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Innovative Strategy for Electrical Calibration Management – Laboratory Sustainability for Metrology 5.0

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***Abstract*—The paper presents an innovative strategic approach for achieving improved sustainability practices within the Laboratory for Electrical Measurements (LEM) at Ss. Cyril and Methodius University in Skopje, an accredited electrical calibration laboratory. A systematic evaluation of LEM's existing strategic documents, including the Quality Policy and Quality Manual, was conducted against the UN Sustainable Development Goals (SDGs) using the EU SDG Mapper toolkit. Initial analysis revealed that the initial Quality Policy did not address any UN SDGs, and the initial Quality Manual only partially addressed few SDGs. Therefore, a thorough revision of LEM's strategic documents and procedures was undertaken to align them with the three aspects of laboratory sustainability: environmental, social, and governance. An effectiveness review of the revised documents, including the new Quality and Sustainability Policy, Quality and Sustainability Manual, and the newly adopted Access Policy to LEM Research Infrastructure, demonstrate a significant improvement in LEM's contribution to a wider range of UN SDGs. This innovative approach, integrating ISO/IEC 17025:2017 quality assurance with a focus on UN SDGs, supports LEM's strategic evolution towards Metrology 5.0 and long-term sustainability.**

Keywords—laboratory sustainability, Metrology 5.0, Industry 5.0, UN SDGs, electrical calibration

I. INTRODUCTION

Industry and more generally corporate sustainability is increasingly shaped by regulatory frameworks like ESG (Environmental, Social, and Governance), [1], which the United Nations (UN) promotes through its seventeen Sustainable Development Goals (SDGs), [2]. ESG was initially developed to measure the industry's/company's responsibility in three key areas: environmental impact, social responsibility, and governance practices. The goal was to enhance sustainable practices and increase transparency, helping to prevent "greenwashing" by requiring companies to disclose their actions. Sustainability has become particularly vital for Small and Medium-sized Enterprises (SMEs) operating as testing, inspection, and calibration laboratories, i.e. conformity assessment bodies (CABs). Given the global risks of climate change, the laboratories must adopt protocols that minimize their environmental footprint, [3]. The IPCC GHG Protocol offers a thorough framework to help them achieve these objectives, [4]. To move beyond the narrow definition of sustainability, a more fundamental perspective is needed: a laboratory is truly sustainable only if it can remain economically viable in the long term while also respecting the environment and the rights of its workers and society. The laboratory sustainability aspects are also closely related to the overall transformation from Industry 4.0 to Industry 5.0: the re-humanization of the race towards automation, [5]. It is the recognition that both robotic/automated/digital advances and the human questioning/insight/innovation/ creativity are of equal value in the manufacturing process. Each industrial revolution induces a spin for a new metrology revolution, thus bringing the Metrology 5.0 for which the laboratories have to be prepared, [6]. The orientation towards laboratory sustainability directly contributes to evolvement of Metrology 5.0 and the laboratory of the future, [7]. Laboratories are best equipped to define how sustainability applies to their unique situation, demanding sound entrepreneurial judgment, ability to adapt to client expectations, and efficient resources use, building on three core principles, [3]:

- *Continuity through value creation*: a laboratory sustainability hinges on its ongoing ability to create value, i.e. consistently delivering technical excellence while fostering trust with clients and society.
- *Freedom to adapt*: laboratories operate in diverse environments. Therefore, sustainability efforts must be shaped internally, guided by their specific business models, market signals, and stakeholder priorities.
- *Ownership of strategy*: genuine sustainability comes when each CAB takes responsibility for its own objectives and priorities aligning with its core mission.

An innovative example of developed methodological approach for the modeling and assessment of environmental sustainability of measurements as part of ICT is presented in [7]. The environmental sustainability as an additional criterion for the measurement design is imposed in [8] through comparative analysis of different case study scenarios of electrical resistance measurements.

This contribution presents an innovative strategic approach for achieving improved sustainability practices in the Laboratory for Electrical Measurements (LEM) [10], an accredited calibration laboratory for electrical instruments according to EN ISO/IEC 17025:2017, [11], at the Ss. Cyril and Methodius University in Skopje (UKIM), Faculty of Electrical Engineering and Information Technologies (FEEIT). The LEM serves as a research infrastructure, in particular for the education and research purposes [12]. The systematic and thorough evaluation of the maturity of the current-state-of-the-art towards sustainability in LEM, is conducted through benchmarking of the existing laboratory strategic documents: the Quality Policy, the Quality Manual and other quality and competence assurance procedures and documented information in compliance to EN ISO/IEC 17025:2017, against the different UN SDGs. The evaluation is done by deployment of the validated on-line tool EU SDG Mapper, [13]. Some partial initial maturity evaluation results are presented previously in [6], [14], while the extended analysis results are given here. The obtained maturity analysis outcomes and identified sustainability issues, form a basis for introduction of innovative strategic measures on systematic laboratory management level, such as a thorough revision of the strategic documents and procedures, thus directly affecting the continual laboratory operations and practices, followed by

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an iterative check on the achieved improvement towards long-term and continual laboratory sustainability.

II. Conceptual Aspects of Laboratory Sustainability

Laboratory sustainability demands a comprehensive perspective involving environmental protection, guaranteeing ethical treatment and well-being of workers, cultivating a positive community relationship, and implementing a governance model that ensures both accountability and resilience. Crucially, true sustainability is not simply about meeting regulations, but about ongoing practices that create value and earn social legitimacy. Without a balanced commitment to all these areas, a CAB cannot genuinely be considered sustainable. Different original approaches, such as fuzzy logic, [15] and the more recent integration of AI, [16], are introduced to evaluate a laboratory's readiness for sustainable transformation. Innovative scientific efforts are given to make labs sustainable, with specific focus on their fields of activities, [17], [18], [19] and [20]. This is also internationally accepted by several initiatives/networks, such as the MyGreenLab in the USA, [21] or the Sustainable European Laboratories network (SELs) in Europe, [22]. My Green Lab®, [21] categorises laboratory sustainability into 14 focus areas:

1. Community: working together
2. Waste Reduction: minimising waste volumes
3. Resource Management: well-planned material management
4. Purchasing: sustainable purchasing processes
5. Green Chemistry: using more eco-friendly chemicals
6. Water: Reducing water consumption
7. Plug Load: minimising the energy consumption of laboratory devices
8. Fume Hoods: reducing the energy consumption of laboratory fume hoods
9. Cold Storage: reducing the energy consumption of refrigerating equipment and rooms
10. Large Equipment: analysing the largest consumers of the laboratory's equipment
11. Infrastructure Energy: optimising ventilation, air conditions, lighting, and so on
12. Travel: eco-friendly commuting routes and business trips
13. Field Work: incorporating field research in the strategy
14. Animal Research: efficient, animal-friendly biological research.

For gaining improved sustainability, diverse holistically interrelated practices in the laboratory have to be implemented, considering different ground inputs:

- the scope of laboratory activities,
- the current laboratory practices, habits and level of awareness of the employed personnel,
- the available laboratory resources (infrastructure, equipment, personnel, information),
- the inputs to and outputs from the laboratory, and
- the overall operations environment of the laboratory (national/regional/global context, regulatory requirements, culture, traditions and mentality,...)

Overall, there are three major aspects in the multi-dimensional laboratory transformation for Metrology 5.0 by strategic practicing of sustainability, [15] as in Figure 1:

- Environmental aspect - a strategic orientation towards reducing waste, improving energy efficiency, and optimising resource use which lowers operational costs, improves performance, and strengthens client trust.
- Social aspect - practices creating work environments where people can grow, contribute, and remain engaged.
- Governance aspect - good governance supporting the long-term sustainability by enabling consistent decision-making.

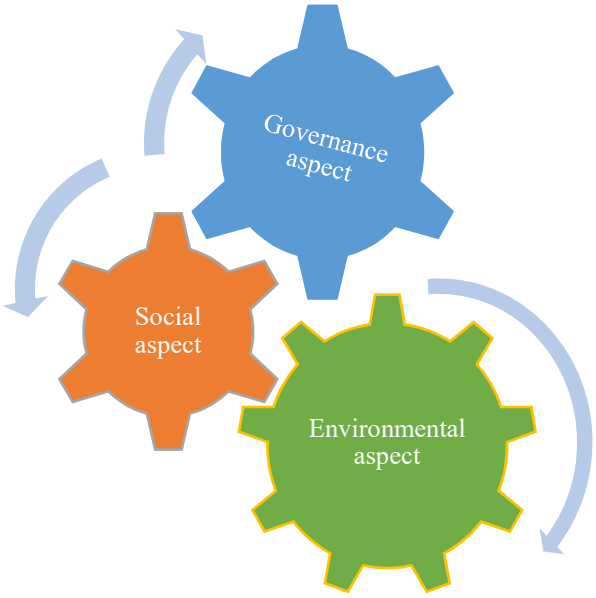


Fig. 1. Three aspects of laboratory transformation towards Metrology 5.0 through long-term sustainability

III. Innovative Circular Model and Toolkits for Introduction of Strategic Reorientiation towards Laboratory Sustainability

Some comprehensible methodologies are published, for introduction of laboratory sustainability practices contributing to increased achievement of the UN SDGs, [22], [23] and [24].

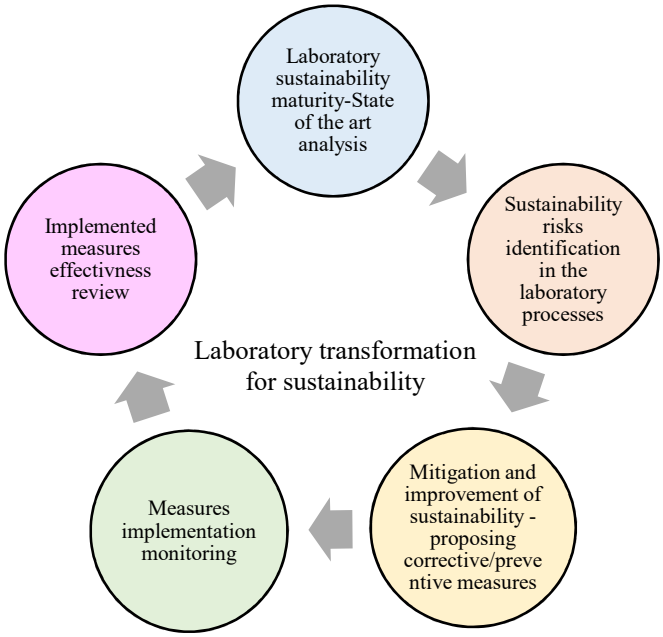


Fig. 2. Circular methodlogy for long-term laboratory sustainability

In this contribution a circular methodology is proposed based on continual improvement for establishing long-term sustainability, as illustrated in Figure 2. The process begins

with an assessment of the lab maturity, which includes a mapping and gap analysis, as outlined in [6]. The primary tool used to assess the maturity of LEM in terms of sustainability is a custom-developed questionnaire, [6], designed specifically for this purpose. It gathers information on the most significant environmental impacts of the laboratory, incorporating the FMEA methodology to apply risk-based thinking [25]. The gap analysis findings delivered that the key measure for achieving a visible and long-term impact on lab sustainability is to address the laboratory's strategic documents, such as the Quality Policy and the Quality Manual and the other laboratory procedures and documented information. For an integrated evaluation approach of the three aspects of laboratory sustainability maturity in LEM a specific publicly available on-line toolkit KnowSDGs [13] is deployed for assessment of the strategic laboratory documents against the UN SDGs. KnowSDGs (Knowledge base for the SDGs) is a web platform designed to support evidence-based SDGs implementation. It offers tools and organized knowledge on policies, indicators, methods, and data [26], [27]. The platform uses text mining and natural language processing to analyze uploaded policy documents, linking them to relevant SDGs and targets via keywords [26], [27]. The SDG Mapper tool within KnowSDGs identifies pertinent SDGs in the texts, then visualizes the prevalence of different SDGs, and indicators, illustrating how documents address the SDGs, as in Figure 3.

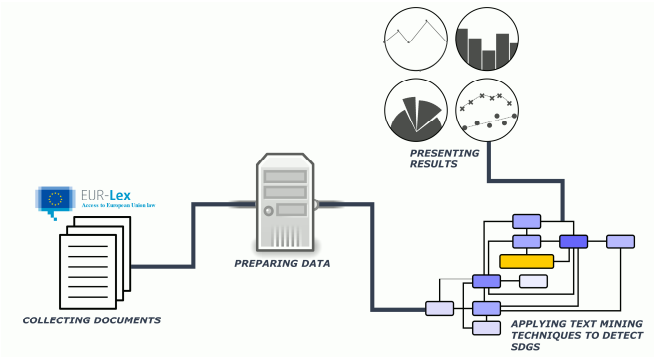


Fig. 3. EU KnowSDGs – SDGs Mapper flow-chart [13]

IV. Transformation towards Laboratory Sustainability-Case Study of LEM

Supporting a range of teaching, research, and application activities, the Laboratory for Electrical Measurements (LEM) shown in Figure 4 is an accredited calibration laboratory for instruments measuring electromagnetic quantities.

LEM has maintained its accreditation since 2015, initially under ISO/IEC 17025:2005, and later transitioning to the ISO/IEC 17025:2017 standard in 2019. After conducting the through initial maturity analysis with baseline results presented in [6], [14] and [20], it has been concluded that the following strategic documents of the laboratory accredited quality assurance system, have to be revised:

- the LEM Quality Policy,
- the LEM Quality Manual,
- other quality and competence assurance procedures, and
- the rest of relevant documented information in compliance to EN ISO/IEC 17025:2017.



Fig. 4. Laboratory for Electrical Measurements - case study for strategic transformation towards sustainability

V. Results of Initial Analysis

In the Figures 5 and 6 some of the results compliance of the existing strategic management documents of LEM towards the UN SDGs derived by the KnowSDGs toolkit are given. The SDGs Mapper tool, provided that the analyzed LEM Quality Policy, issued in September 2023, did not address at all any of the UN SDGs. The second strategic document which was subjected to the SDGs mapping was the accredited LEM Quality Manual, issue from September 2023. The results in Figure 5 indicate that the issue of the LEM Quality Manual analyzed in September 2023 addresses the following SDGs:

4-Quality Education (33%),
8-Decent work and economic growth (33%) and
9-Industry, innovation and infrastructure (33%).

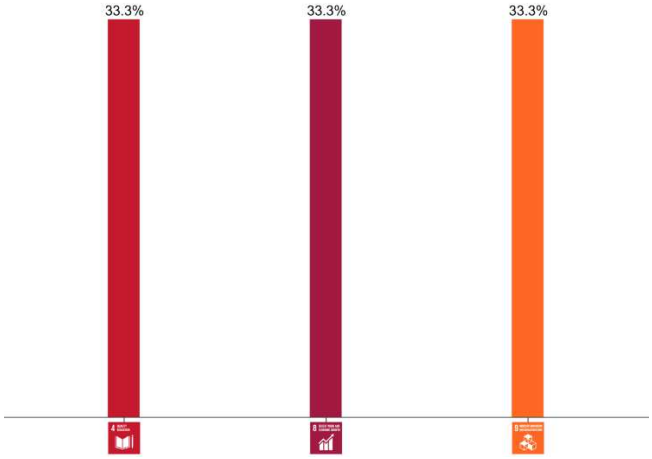


Fig. 5. Relevant UN SDGs addressed by the LEM Quality Manual from September 2023 obtained by KnowSDGs toolkit

The main SDGs targets addressed by the initial issue from September 2023 of the LEM Quality Manual, as in Fig. 6 are:

4.4 - by 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship,

8.2 - achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labor-intensive sectors,

8.3 - promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization

and growth of micro-, small- and medium-sized enterprises, including through access to financial services, and

9.5 - enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending.

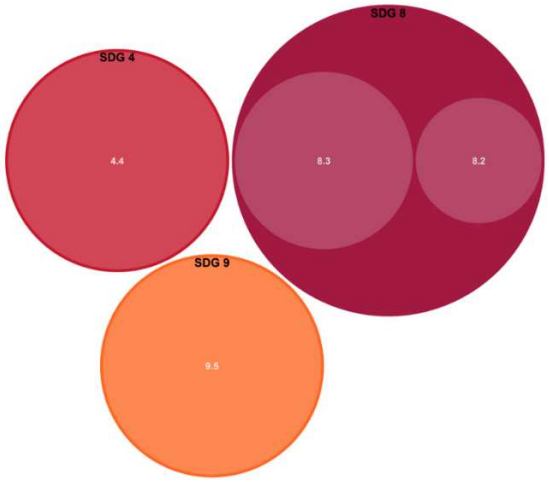


Fig. 6. SDGs targets addressed by the LEM Quality Manual from September 2023 obtained by KnowSDGs toolkit

The SDGs mapping of the rest of the LEM management documentation derived that in none of the analyzed procedures or relevant documents, the UN SDGs are addressed. This induces the necessary measure to conduct a thorough review of the content of the overall LEM quality assurance documentation to align to the principles of the three aspects of the laboratory sustainability. Some of the content changes of the LEM's Quality and Sustainability Policy and the LEMS' Quality and Sustainability Manual are presented in [6].

Furthermore, for enhancing the different sustainability aspects in the laboratory practice in September 2023 LEM has implemented and adopted another strategic document the LEM's Laboratory Infrastructure Access Policy, based on the principles of "open science" and "open access", [28] to laboratory infrastructures, [14], [29], [30].

VI. Effectiveness Review of the Measures Conducted for Advanced Laboratory Sustainability Management

The results of effectiveness of the review of the new LEM Quality and Sustainability Policy, the Quality and Sustainability Manual and the newly adopted Access Policy to LEM Research Infrastructure, for support of the UN SDGs, derived by the KnowSDGs toolkit, are presented in [6].

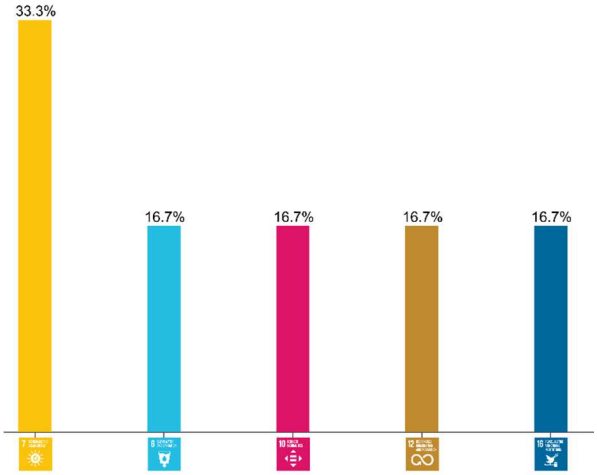


Fig. 7. Relevant UN SDGs addressed by the revised PR 8.6 Procedure for Improvement from July 2025 obtained by KnowSDGs toolkit

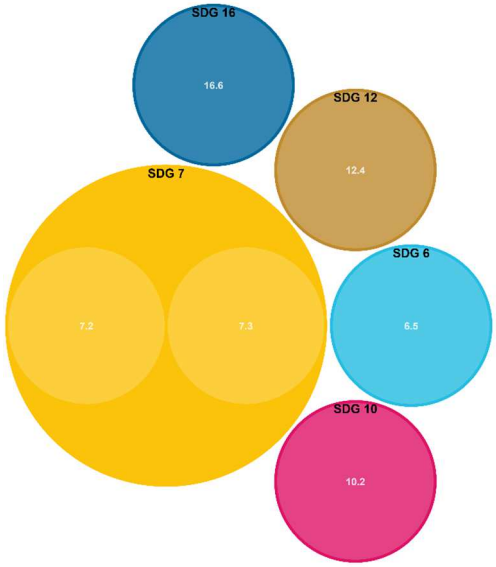


Fig. 8. SDGs targets addressed by the revised PR 8.6 Procedure for Improvement from July 2025 obtained by KnowSDGs toolkit

In the Figures from 7 to 10 a selection of effectiveness results of the revised strategic management procedures of LEM towards the UN SDGs derived by the KnowSDGs toolkit are displayed.

The qualitative and quantitative results of the review of the strategic measures undertaken to establish sustainable laboratory management at LEM clearly demonstrate the laboratory's contribution to the UN SDGs. Table I provides a comparative overview of the initial and final status of LEM's contribution to the SDG targets, obtained by using the KnowSDGs toolkit. The positive increment of LEM's strategic evolution is demonstrated in the EU SDGs Mapper tool results.

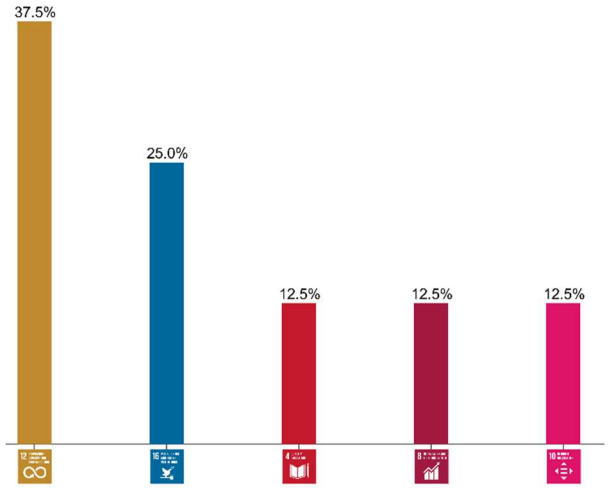


Fig. 9. Relevant UN SDGs addressed by the revised PR 8.9 Procedure for Management Review from July 2025 obtained by KnowSDGs toolkit

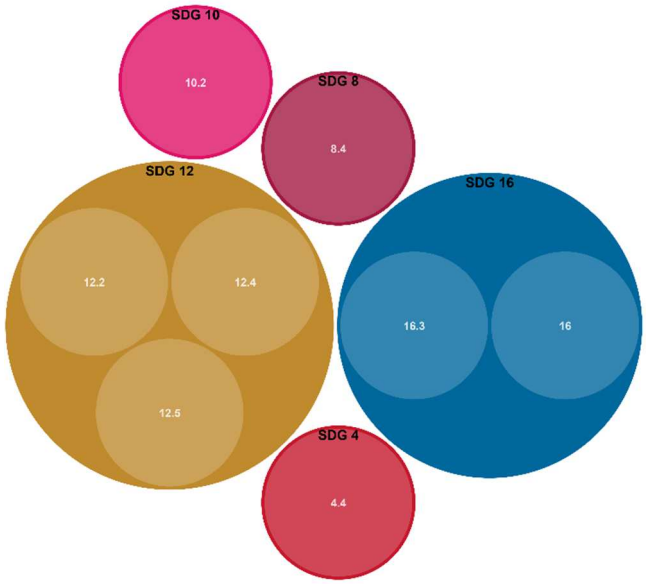


Fig. 10. SDGs targets addressed by the revised PR 8.9 Procedure for Management Review from July 2025 obtained by KnowSDGs toolkit

VII. Quantitative Framework to Assess the Laboratory Contribution to the UN SDGs

After introduction of the strategic laboratory governance reorientation through essential content intervention in the major LEM policies and documents, the process of practical implementation has begun. From Table I it can be concluded that while the initial issues of the laboratories strategic management documents addressed the UN SDGs with very low level, the newly issued strategic documents address all three aspects of laboratory sustainability with visible impact. The integration of ISO/IEC 17025:2017 quality assurance and a focus on UN SDGs has significantly enhanced LEM's contribution to the UN's strategic development goals. The level of contribution to the SDGs is planned to be measured through quantitative Key Performance Indicators (KPIs) in the three dimensions: environmental, social and governance. Following the recommendations from [3], some of the major KPIs to be followed annually are given in Table II. The selection of the KPIs are aligned to the specifics of LEM as electrical calibration laboratory.

TABLE I. Effectivness of the revision of the LEM strategic documents towards Metrology 5.0 for support of the UN SDGs

LEM Strategic document	**Initial issue from September 2023**	**Revised Issue from April 2024 until July 2025**
	Supported of UN SDGs	***Addressed UN SDGs targets***
Quality Policy (revised issue Quality and Sustainability Policy)	none	10, 16
	none	10.3, and overall 16
Quality Manual (revised issue Quality and Sustainability Manual)	4, 8, 9	4, 7, 8, 9, 10, 12, 13, 16
	4.4, 8.2, 8.3, 9.5	4.3, 4.4, 7.1, 7.2, 7.3, 8.2, 8.3, 9.5, 10.3, 12.4, 12.5, 12.8, and overall 13 and 16
Access Policy to LEM Research Infrastructure Addressed UN SDGs targets (new lab doc)	/	1, 9, 17
	/	1.4, 4.3, 4.4, 9.5, 17.6
PR 6.2 Procedure for Requesting Competence, Selection, Training, Supervision, Authorization and Monitoring of Personnel Competence	none	7, 12
	none	7.2, 12.4
PR 6.4 Procedure for Handling of Equipment: Handling, Transport, Storage, Use, Maintenance Planning, Equipment Calibration and Ensuring Metrological Traceability	none	12
	none	12.4
PR 6.6 Procedure for Procurement of Products and Services	none	12
	none	12
PR 7.4 Procedure for Handling Calibration and Testing Samples	none	12
	none	12.4
PR 8.5 Procedure for Risks and Opportunities Management	none	6, 10, 12
	none	6.5, 10.2, 12.4
PR 8.6 Procedure for Improvement	none	6, 7, 10, 12, 16
	none	6.5, 7.2, 7.3, 10.2, 12.4, 16.6
PR 8.8 Procedure for Internal Audit	none	4, 8, 10, 12, 16
	none	4.4, 8.4, 10.2, 12.2, 12.4, 12.5, 16.3, 16
PR 8.9 Procedure for Management Review	none	4, 8, 10, 12, 16
	none	4.4, 8.4, 10.2, 12.2, 12.4, 12.5, 16.3, 16

VIII. Conclusions

In the paper an innovative approach for strategic laboratory transformation towards sustainability is presented. Based on thorough initial analysis for laboratory sustainability, the LEM has significantly improved its contribution to the UN SDGs through strategic reformulation of its management documents. Initially, the LEM Quality Policy did not address any UN SDGs, and the Quality Manual only minimally supported some SDGs. A comprehensive review and revision of the LEM's strategic documents were undertaken to align with the three aspects of laboratory sustainability: environmental, social, and governance. The EU KnowSDGs Mapper toolkit was instrumental in assessing the lab maturity against the UN SDGs. The revised documents, such as the new Quality and Sustainability Policy, Quality and Sustainability Manual, and the newly adopted Access Policy to LEM Research Infrastructure, but also several other operational laboratory procedures now visibly impact a wider range of UN SDGs. This demonstrates a positive development

of LEM's strategic approach towards Metrology 5.0 and long-term sustainability by integrating ISO/IEC 17025:2017 quality assurance with the UN SDGs. The presented circular methodology is universal and can be applied in other labs tending to orient towards sustainability and Metrology 5.0.

TABLE II. LABORATORY ACTIVITIES KPIS FOR QUANTITATIVE TRACKING OF SUSTAINBILITY PERFORMANCE

Sustain-ability Dimen-sion	Indicator	Description	Measurement Unit
Envirnonment	Total energy consumption	Energy used annually in all operations	kWh/year
	Waste generation	Total waste generated annually	kg/year
	Waste recovery rate	Percentage of waste reused, recycled, or recovered	%
	Avoided travel	Number of business trips replaced by virtual alternatives	Number of trips
Social	Training per employee	Annual training hours provided per staff member	Hours/person/year
	Health and safety incidents	Events impacting the safety or well-being of staff	Number/year
	Participation in feedback tools	Engagement in internal surveys or similar instruments	% of workforce
Governance	Role clarity	Share of roles with clearly defined responsibilities	% of positions
	Audit planning based on risk	Use of risk-based criteria to determine audit priorities	Yes/No
	Defined impartiality safeguards	Existence of internal mechanisms for impartiality assurance	Yes/No
	Risk register update frequency	Regular review and update of the organisational risk register	Number/year

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A Flexible Thermoelectric Power Source for Sustainable and Conformable Applications

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***Abstract*—This work investigates flexible thermoelectric generators for energy harvesting of thermal gradients across wearable and industrial applications. In the first phase, prototypes with 4, 8, and 12 thermoelectric generators of bismuth telluride (Bi_2Te_3) assembled in series are characterized on a controlled hot-plate temperature. The increase in the number of generators increased the output voltage and is linearly related to the thermal gradient. Twelve elements were then reassembled in series on a flexible stripboard and tested under controlled airflow (0, 0.5, and 1 $m \cdot s^{-1}$). Variable airflow significantly enhanced convective heat transfer, as confirmed by dual-thermocouple heat-flux measurements. In open circuit and forced air flow, the conformable device delivered around 27 mV/0.07 nW near human body temperature and about 150 mV/2.3 nW under harsh conditions (120°C). Load-sweep characterization (5 Ω – 20 MΩ) identified a maximum-power point near 2.5 kΩ, yielding 1 µW. The airflow influences the performance, which is confirmed by thermal flux measurements. Overall, the results validate the feasibility of making a flexible thermoelectric generator that can bend to a radius of 6 cm and operate at temperatures up to 120°C.**

Keywords—Energy harvesting, flexible TEG, low power devices, thermoelectric generator, wearable applications

I. Introduction

The use of conventional energy sources, such as fossil fuels, is increasingly recognized as unsustainable, not only due to the progressive depletion of available resources but also because of their significant environmental impacts, including air, water, and soil pollution, as well as global warming [1]. The adoption of new materials for transducers [2,3] and renewable energy sources, combined with substantial improvements in the efficiency of the devices and systems they power, represents one of the key strategies for addressing these global challenges [4,5]. Within this framework, there is an increased focus on developing and optimizing the implementation of this energy harvesting solution with a reduced environmental footprint [6].

In addition to large-scale renewable integration and efficiency improvements, the use of low-intensity renewable sources through energy harvesting offers a sustainable route to power low-power autonomous systems. This approach is particularly promising for wearable, implantable, and IoT devices, where reducing battery dependence is crucial and a rapidly growing body of research is driving continuous innovation and technological advancements [7]. Common energy-harvesting methods include vibration, thermoelectric, photovoltaic, RF, and piezoelectric generators [8-10], which can often be combined in hybrid configurations [11].

In particular, thermoelectric generators have attracted growing attention as a strategy to enhance energy efficiency by directly converting waste heat into electrical power. Recent advances in material design, aimed at optimizing thermal conductivity, maximizing conversion efficiency, and improving mechanical robustness, are increasingly enabling TEGs to perform reliably and effectively under real-world operating conditions [12]. Thermoelectric generators have been applied in various fields, from industrial waste heat recovery to transportation [13-16], and are increasingly explored in combination with other renewable technologies included their integration with fuel cells to recover heat from electrochemical conversion and their hybrid use with solar or geothermal systems, where TEGs convert residual thermal energy into additional power, thereby enhancing overall efficiency and system sustainability [17-20].

Flexible and wearable thermoelectric generators (respectively f-TEGs and w-TEGs) represent the evolution of traditional TEGs and have gained growing attention as body-heat harvesters for powering biomedical sensors, such as electrocardiograms or wireless RF devices. Different architectures have been developed, including early 2D film-based structures, 3D-flexible w-TEGs, and stretchable 3D configurations. A central challenge remains improving the deformability of both the thermoelectric materials and the overall device [21].

This study investigated the design and characterization of a prototype thermoelectric generator fabricated on a flexible and conformable substrate. Such a configuration enables effective integration on curved or irregular surfaces, thereby expanding its range of potential applications. The innovative solution proposed here was evaluated under different operating conditions, spanning low temperatures relevant to biomedical applications and high temperatures representative of industrial environments. Tests were also performed with and without forced air flow to quantify the role of convective

cooling in shaping the thermal gradient across the device and its impact on energy conversion performance.

The output power was found to be sufficient to sustainably operate low-power sensors, such as those used for monitoring biological or physiological parameters, like temperature, in wearable biomedical systems. In industrial contexts, where substantially larger temperature gradients than those achievable on the human body are available, the same technology can deliver enhanced power generation, making it a promising solution for the autonomous operation of distributed process-monitoring sensors. This paper proposes a characterization of f-TEGs as a function of the number of TEGs elements and environmental testing on flat and curved surfaces.

II. Architecture and Working Principle

Thermoelectric generators are solid-state devices that directly convert a temperature gradient into electrical energy through the Seebeck effect. A TEG typically consists of multiple pairs of thermoelectric (TE) elements connected electrically in series and thermally in parallel. One side of the device is maintained at a lower temperature (cold side, T_c), while the opposite side is exposed to a heat source (hot side, $T_h = T_c + \Delta T$). This temperature difference leads to a gradient in the concentration of charge carriers-holes in p-type materials and electrons in n-type materials. The higher carrier concentration at the hot side drives diffusion toward the cold side, thereby generating a potential difference across the device.

The effect that provides a thermoelectric conversion is the Seebeck effect. In the presence of a temperature gradient, electrons can flow from the hot side to the cold side, causing an electrical current as shown in Fig.1. This means a coupling between electrical and thermal phenomena, known as the Seebeck effect.

The Seebeck effect is a phenomenon in which the induced output voltage V_T is proportional to the thermal gradient (T_h - T_c) [22]:

$$V_T = S(T_h - T_c) \tag{1}$$

where S is the Seebeck coefficient, a characteristic of the material. The electrostatic potential generated by a single p- or n-type element is extremely low; therefore, dozens or even hundreds of couples are typically connected in series.

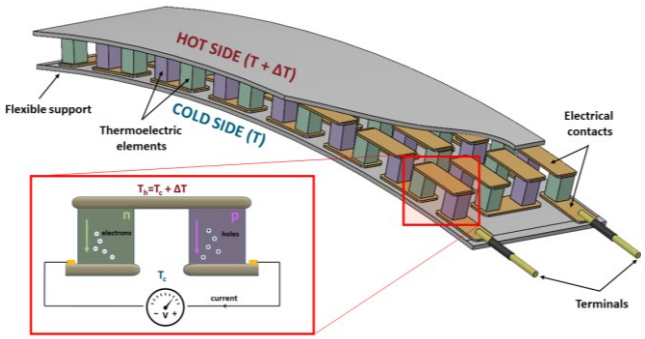


Fig. 1. A flexible TEG with in evidence the principle of thermoelectric generation.

TEGs from an electrical point of view can be modeled as a voltage generator in series with a source resistor (R_T) [23], as shown in Fig. 2.

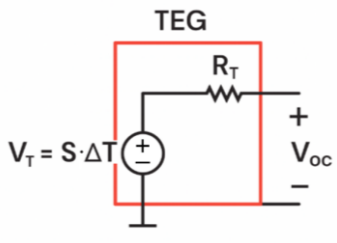


Fig. 2. Equivalent model of TEG.

The temperature difference between the hot side and the cold side generates a heat flux that can be expressed, under steady-state one-dimensional conditions, by Fourier's law of heat conduction:

$$\dot{Q}_{cond} = kA\frac{(T_h - T_c)}{t} \tag{2}$$

where $\dot{Q}_{cond}$ is the rate of heat transfer, k is the thermal conductivity of the material, A is the surface area, and t is the thickness of the material [24].

When the cold-side surface of the TEG is exposed to an air stream at temperature T_{air}, the temperature of the fluid sufficiently far from the surface of the TEG, heat is removed by convection according to the following relation:

$$\dot{Q}_{conv} = hA(T_c - T_{air}) \tag{3}$$

where h is the convection heat transfer coefficient. This reduces the cold-side temperature and, in turn, increases the conductive heat flux and, in parallel, enhances the electrical output of the device via the Seebeck effect.

III. Setups and Experimental Steps

In the first experiment, different prototypes were developed, each featuring an increasing number of thermoelectric couples mounted in series on a rigid support. These couples, made of bismuth telluride (Bi_2Te_3), were unsoldered from commercially available SP1848-27145SA thermoelectric generator (TEG) modules.

The characterization focused on output voltage under variable thermal gradients at temperatures typical of the human body, tested under static conditions (no airflow). The measurement setup consists of a temperature-controlled hot plate (Digital Stirring Hot Plates HS30/HS30A [25]), a digital multimeter (HP Agilent Keysight 34410A DMM Multimeter, 6.5-digit [26]), and a thermal camera (FLIR T560sc [27]).

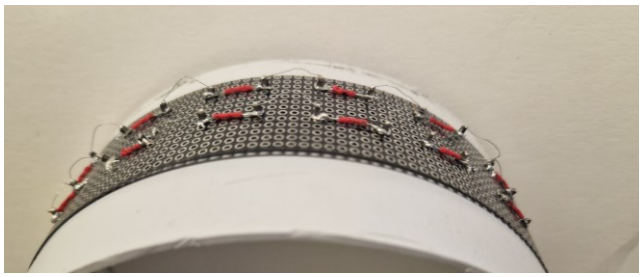


Fig. 3. Twelve TEG on a flexible surface.

In the second part, twelve thermoelectric elements were assembled onto a bendable stripboard (0.4 mm flexible protoboard PTBF2030 with 1 mm holes and 2.54 mm pitch), maintaining their series electrical connection, to fabricate a bendable thermoelectric generator. The device, shown in Fig. 3, has dimensions of 14 cm × 1.5 cm × 2 mm (length × width × thickness). This new configuration preserved the enhanced output of the rigid prototype while introducing mechanical adaptability for potential wearable and conformable applications. When tested on a surface with a 6 cm radius of curvature, it exhibited excellent compliance, adapting to the surface without any damage or plastic deformation of the supporting material. Moreover, after tens of bending cycles, no significant changes were observed in its electrical output performance. This point will be addressed in future studies.

The f-TEG was characterized using a procedure similar to that applied to the rigid devices, with additional emphasis on two aspects: the effect of variable airflow and performance under higher thermal gradients.

The experimental setup, based on the same instruments used previously, was extended to include a system for generating and controlling convective cooling, with measurements of air temperature and airflow rate: a small fan (12V DC Brushless Cooling Fan, 40mm) and an anemometer (Kane" KANE101 [28]). The complete instrumentation is shown in Fig. 4.

The final experiment was conducted to evaluate the voltage and power output as a function of the load and thermal flux conditions. The setup, shown in Fig. 5, consisted of the following instrumentation: a digital multimeter (Agilent 34401A [29]) (for voltage); a digital multimeter (Keysight 34465A [30]) (for current); a data logger (Almemo 2590 Ahlborn [31]) with thermocouples (for measuring thermal flux, room temperature, and hot plate temperature); a hot plate (Ika RH Basic 2 [32] (set to 70 °C, with room temperature at 19 °C); a programmable resistance box (IET PRS-330 [33]); a small fan (4 W, 1000 rpm).

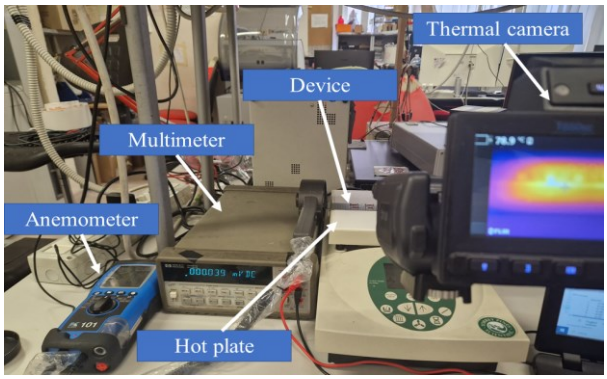


Fig. 4. The setup of the first two experimental phases.

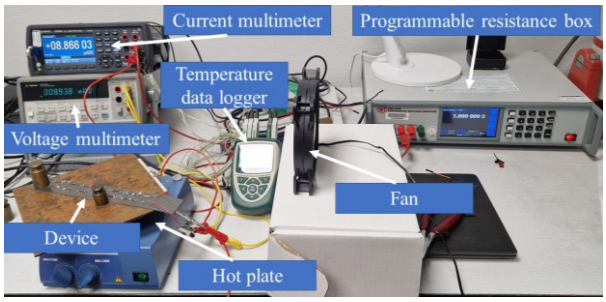


Fig. 5. The setup of the third experimental phase.

IV. Experimental Results

To evaluate the effect of the variable thermal gradients on the voltage output, three samples were fabricated. The prototypes consisted of 4, 8, and 12 thermoelectric couples mounted on a rigid support, respectively. The hot plate temperature was varied from 30°C to 40°C in 2°C increments, while the room temperature was maintained at 27°C. Fig. 6 reports the average output voltage as a function of the temperature gradient, with error bars denoting the standard uncertain from 10 measurements taken at each step. The output voltage increases almost in proportion to the number of thermoelectric elements. The twelve-element device achieved the best performance, delivering higher output voltage due to the greater number of thermoelectric couples connected in series.

The twelve thermoelectric elements were reassembled on a flexible stripboard to form an f-TEG. Its performance was evaluated under variable airflow (0, 0.5, and 1 m/s), with results reported in Fig. 7, up to high temperature gradients representative of industrial conditions. The inset highlights lower gradients typical of the human body. Error bars show standard uncertainty (n = 10).

Studying variable airflow is essential, as airflow strongly modulates convective heat dissipation and, consequently, TEG performance, enhancing the output voltage, as evidenced by our results. We considered conditions representative of wearable devices (e.g., quasi-steady airflow during running or cycling) and industrial environments (e.g., natural convection around motor shafts). The results quantify the impact of airflow on the f-TEG output voltage across operating conditions.

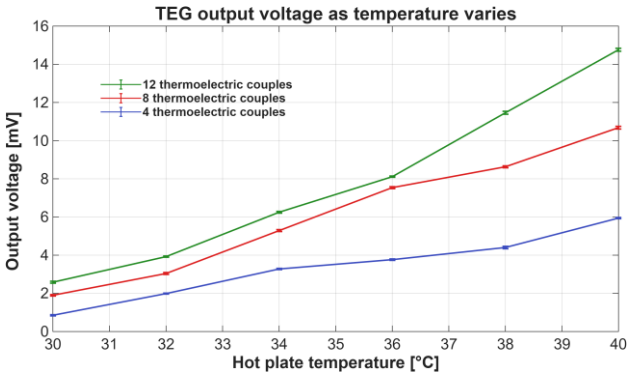


Fig. 6. Output voltage of TEGs with varying numbers of couples. Max standard uncertainty = 0.078 mV.

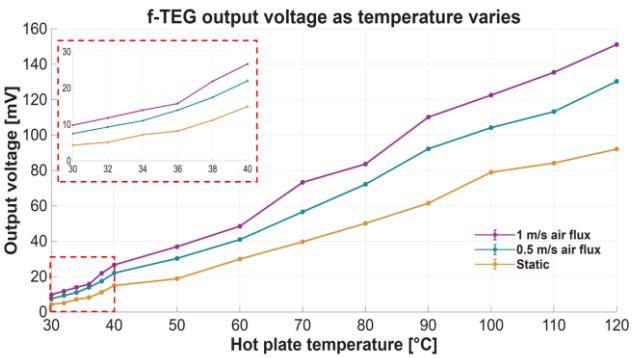


Fig. 7. f-TEG output vs. airflow. The insert shows the f-TEG output at low temperature gradients. Max standard uncertainty = 0.136 mV.

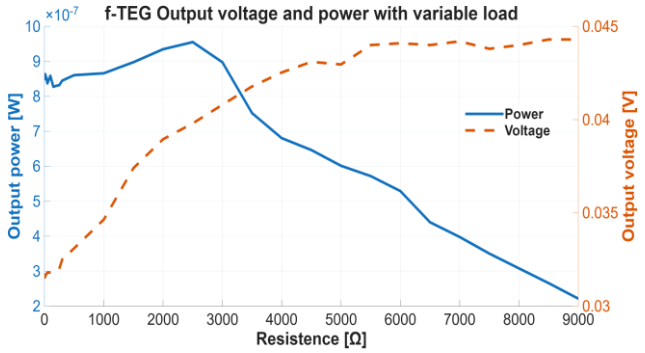


Fig. 8. f-TEG output voltage and power as a function of load resistance.

The f-TEG was characterized in the lab by measuring voltage and current as a function of load, with a ΔT of 51 °C, in order to identify the optimal load for maximum power transfer, a critical aspect for low-power energy-harvesting devices to maximize delivered power. The load resistance was swept from 5 Ω to 20 MΩ. For each value, ten voltage–current measurements were recorded. As shown in Fig. 8, the largest voltage variation occurs for loads between 5 Ω and 9 kΩ. In particular, it shows a power maximum at 2.5 kΩ of approximately 1 µW, nearly three orders of magnitude higher than under impedance mismatch.

To gauge the effect of airflow on heat transfer, heat flux was measured while airflow was varied by moving the fan closer to the device, with the fan speed held constant at 1000 rpm. Temperatures on the hot and cold sides of the device were acquired simultaneously using a dual-thermocouple setup. The heat flux was computed using (2), and the results are summarized in Table I. Heat flux rises with airflow as the fan–device distance decreases.

TABLE I. HEAT FLUX UNDER DIFFERENT AIRFLOW INTENSITIES

	Without air flow	With air flow (fan at 25 cm)	With air flow (fan at 15 cm)
Heat flux [W·m⁻²]	997.9	1231.0	1469.1

The flexible TEG's output is intrinsically very low: without impedance matching, it reaches ~27 mV/0.075 nW at low ΔT and ~150 mV/2.3 nW at high ΔT, well below the needs of sensors and their conditioning circuits. Practical operation thus requires auxiliary solutions and/or design improvements (e.g., more thermoelectric couples, higher-performance materials), and critically a DC–DC step-up converter to provide stable rails (e.g., 3.3 or 5 V) [34]. A thermistor, like Semitec 504GT-2 [35], consumes about 0.66 µW at low temperature and about 4.8 µW at high temperature. Even without impedance matching, assuming a 25 ms electrical readout, the f-TEG can support this by taking one sample roughly every 3.6 minutes in low-temperature conditions or every 52 s in high-temperature conditions. Under best-case scenarios, with proper impedance matching, available power can reach 1 µW, three orders of magnitude higher than in scenarios where maximum power transfer conditions are not reached, enabling much higher sampling rates and improved overall efficiency.

V. CONCLUSION

This work presents a study on a conformable thermoelectric generator, designed for sustainable applications in both industrial scenarios (high ΔT) and wearable technologies (low ΔT). Airflow tests (0–1 m/s) indicate a significant performance gain, consistent with the measured increase in heat flux. Load-dependent electrical characterization identifies a maximum-power point at ~2.5 kΩ (~1 µW), providing usable power for wearable electronics. Overall, the results validate the proposed approach and highlight convective management, thermal interfacing, and power conditioning as key levers for real-world optimization. The lifecycle of the device and the evolution of its electrical characteristics as the number of bending cycles increases are currently under investigation. The study is ongoing and involves extensive characterization and the design of a flexible MEMS device.

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Sustainability of Telemedicine: A Comparative Analysis with In-Person Visitation

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***Abstract*—Telemedicine is often regarded as a sustainable alternative to in-person consultations, primarily due to the reduction in patient travel. However, this is only a partial perspective, as it overlooks other sources of environmental impact, such as energy consumption from devices, data transmission, and digital infrastructures. This study introduces a method to compare the environmental impact of remote and traditional consultations in telemonitoring scenarios. The proposed method integrates Life Cycle Assessment (LCA) principles with the Guide to the Expression of Uncertainty in Measurement (GUM) and Monte Carlo simulations, in order to provide probability distributions of the impact. This approach differs from traditional ones, which typically report sustainability estimations as single-point values. The case study shows that the sustainability of medical consultations is influenced by variables such as travel distance and the duration of the visit. The findings indicate that, under specific circumstances, either remote or in-person consultations may represent the more sustainable option. Consequently, telemedicine should not be regarded as intrinsically more sustainable, but rather as context-dependent.**

***Index Terms*—Carbon Footprint, Environmental Impact, Health 5.0, Life-Cycle Assessment, Measurement, Sustainability, Telemedicine, Uncertainty**

I. Introduction

Health 5.0 represents an innovative vision for healthcare that integrates advanced technologies to address global challenges such as population aging, equitable access to care, and sustainability. This concept goes beyond digital health by proposing a healthcare ecosystem that not only optimizes treatments but also promotes efficient use of resources. Leveraging technologies from *Industry 5.0*, this approach aims to improve access, enhance operational efficiency, and reduce the environmental footprint within healthcare systems [1], [2].

Building on the principles of *Industry 5.0*, the core characteristics of *Health 5.0* can be defined by three main principles: healthcare systems must be *human-centric*, *resilient*, and *sustainable* [3].

The human-centric approach prioritizes patient well-being by tailoring healthcare solutions to individual needs, using technology to enhance accessibility and promote personalized care [4], [5]. Resilience refers to the system's ability to adapt to and recover from disruptions, such as technological failures or public health emergencies, ensuring continuity of care through flexible infrastructures [6], [7]. Sustainability refers to minimizing the environmental impact of healthcare systems by optimizing resource use, reducing waste, and lowering emissions [8].

While the principles of human-centricity and resilience have been extensively explored in the literature [9], [10], the sustainability dimension remains the least addressed. This gap is particularly concerning given the increasing environmental pressures associated with modern healthcare delivery.

In a nutshell, sustainability in Health 5.0 involves minimizing environmental impact while ensuring equitable access to healthcare services. Although there is growing interest in assessing sustainability [11], there is a lack of rigorous methodologies to estimate the environmental impact of healthcare technologies and services. For instance, consider the case of telemedicine, defined as *"the use of electronic information and communications technologies to provide and support health care when distance separates the participants"* [12]. Although telemedicine is commonly considered a sustainable solution, particularly for its potential to reduce greenhouse gas (GHG) emissions by avoiding patient travel [13], [14], this view provides only a partial picture of its environmental impact. Remote healthcare relies on digital infrastructures, continuous data exchange, and prolonged device usage, all of which contribute to energy consumption and associated emissions.

In light of this, this work presents a measurement method for comparing remote and in-person consultations, taking as a case study typical visits carried out for patient monitoring in

the context of a specific diagnosis or condition. The analysis focuses solely on the consultation component, without including any medical devices specific to the monitored condition.

The proposed method follows the principles outlined in the *Guide to the Expression of Uncertainty in Measurement (GUM)* [15] and integrates the *Life Cycle Assessment (LCA)* methodology, as regulated by the International Organization for Standardization (ISO), particularly through the ISO 14040 standards [16]. This analysis serves as a preliminary assessment, aimed at identifying the conditions under which one consultation mode is more environmentally sustainable than the other, providing a basis for further research in this field.

The paper is organized as follows. Section II presents the methodology employed in this study. Section III illustrates the application of this methodology through a case study focused on patient monitoring. Finally, Section IV provides the conclusions, highlighting the key findings and suggesting potential directions for future improvements in the environmental impact assessment of telemedicine systems.

II. Method

The environmental impact of consultations is estimated using the LCA approach, with the Carbon Footprint adopted as the measurand. The Carbon Footprint refers to the total amount of GHG emissions over a defined period, expressed in kilograms of $CO_{2,eq}$, which is the unit used to compare the radiative forcing of a GHG to that of carbon dioxide [17].

In the LCA framework, two main contributions to emissions can be distinguished:

- *Embodied footprint*, which accounts for the emissions related to the manufacturing, distribution, and end-of-life of products and devices;
- *Operational footprint*, which refers to the emissions generated during the actual use phase.

In the context of medical consultations, the embodied component of devices such as laptops, modems, or even cars cannot be meaningfully attributed to a single visit, since these items are typically available and used regardless of the consultation. For this reason, this work focuses exclusively on the operational phase, where each item directly associated with the consultation contributes to the total emissions.

To improve the reliability of the results, the LCA framework is enhanced by following the guidelines of the GUM, especially the Supplement I, applying Monte Carlo simulations [15]. This approach makes it possible to express the outcomes as probability density functions (PDFs) rather than single-point values, thereby strengthening the statistical significance of the comparison.

Overall, in line with the methodological framework proposed in [18], the measurement of the environmental impact of the consultations is articulated into four main steps, outlined in Figure 1:

1) *Checklist definition*: A detailed checklist identifies the items contributing to the operational impact of both remote and in-person consultations.
2) *Impact estimation*: The operational emissions of each item are estimated using appropriate conversion factors (e.g., distance-to-emissions for travel, energy-to-emissions for devices and data transmission). Each contribution is represented by a PDF to account for variability in input parameters such as conversion factors, device power ratings, and data transmission rates.
3) *Impact aggregation*: The PDFs of all items are combined for each consultation mode through Monte Carlo simulations, resulting in two aggregate distributions: one for in-person visits and one for remote visits. From each distribution, a coverage interval associated with a specific coverage level is derived, representing the measurement outcome of the environmental impact of a single consultation.
4) *Sustainability Balance*: Finally, the two consultation modes are compared by calculating the *Carbon Footprint Balance*, defined as the difference between in-person and remote emissions. A positive balance indicates lower emissions for telemedicine, while a negative value indicates a lower impact for in-person visits.

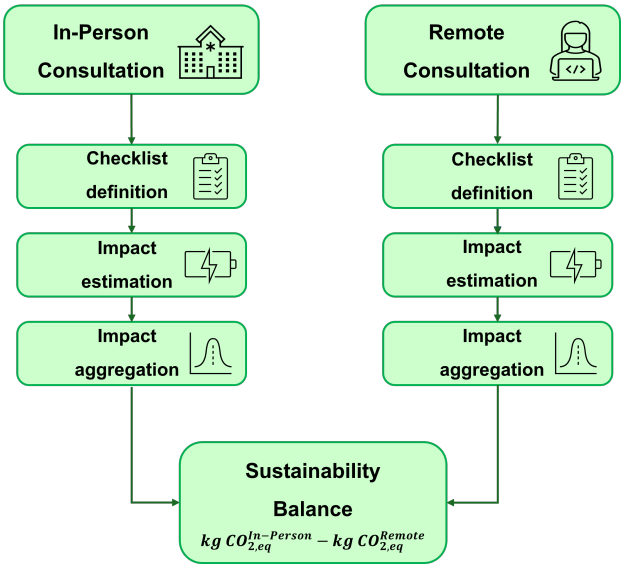


Fig. 1. Representation of the four main steps of the described methodology

III. Case Study

The case study considers a representative scenario involving a one-hour medical consultation for patient monitoring, comparing the environmental impacts of remote and in-person modes under equivalent conditions. By fixing the consultation time to one hour, the only variable left to influence the balance between the two modes is the travel distance between doctor and patient. In this study, three representative scenarios are analyzed:

- *Scenario 1*: doctor–patient distance of 0.5 km,
- *Scenario 2*: doctor–patient distance of 1.0 km,
- *Scenario 3*: doctor–patient distance of 2.0 km.

For all scenarios, travel distances were doubled in the calculations to account for round trips, ensuring that total travel-related emissions reflect both outbound and return journeys.

A. Checklist definition

As the first step, a checklist has been defined to identify the items contributing to the operational impact of each consultation type, and it is summarized in Table I. In this case study, each item has been specified to ensure consistency and reproducibility of the analysis

- For in-person consultations, the patient's travel is assumed to take place with the most used compact car in Italy in 2024, namely a petrol Fiat Panda [19];
- For both modes, laptops are assumed to belong to the mid-range category, which is considered representative for typical clinical and patient use;
- For remote consultations, the videoconferencing platform is fixed to Microsoft Teams;
- Modems are assumed to be standard consumer devices commonly available on the market.

This level of detail ensures that the impact is linked to realistic and widely used technologies. At the same time, the methodology remains flexible: different parameters can be adopted to adapt the analysis to other case studies.

TABLE I
CHECKLIST OF ITEMS CONTRIBUTING TO OPERATIONAL IMPACT
(P = PATIENT, D = DOCTOR)

Item	In-person	Remote
Car (Fiat Panda, petrol)	Operational (P)	–
Laptop (Mid-range)	Operational (D)	Operational (P, D)
Videoconferencing (Teams)	–	Operational (P, D)
Modem (Standard)	–	Operational (P, D)

The doctor's commute is excluded from the analysis, as it is assumed to occur regardless of the consultation mode. The modem is considered only in remote consultations, where its usage increases due to patient-specific data transmission. In contrast, during in-person visits, its constant background consumption is not attributed to the consultation.

It is important to note that this case study serves as an example of the methodology's application, and the results may vary if different items are considered. However, the methodology remains flexible and can be adapted to other contexts.

B. Impact estimation

The evaluation of the operational impact requires two complementary steps. First, assumptions are made regarding the main quantities involved in each consultation scenario, such as travel distance, device power demand, energy consumption, and data transmission rates. Second, these quantities are converted into emissions through appropriate emission factors, each represented by a probability distribution to reflect the variability and uncertainty of the underlying parameters.

- *Car*: The conversion from distance traveled (km) to emissions is based on the kilometric emission factor of the petrol Fiat Panda [20]. Since minimum and maximum emission values are available, a uniform PDF has been associated to represent the range of possible values. In this case study, the impact of car use is evaluated for different doctor–patient travel distances, in order to explore how the variability of this parameter affects the relative sustainability of in-person and remote consultations.
- *Laptop*: The power demand of mid-range laptops is modeled through a uniform PDF, defined over the typical operating range of this device category. The corresponding energy consumption (kWh) is computed for a one-hour consultation. Emissions are then obtained by applying the Italian electricity emission factor for 2024, derived from monthly data provided by the Electricity Maps platform [21]. A yearly average value has been calculated, together with the associated standard uncertainty, and the resulting factor has been represented by a normal PDF. This allows the model to account for both the mean emission intensity of the Italian energy mix and its natural variability over time.
- *Modem*: The operational consumption is modeled starting from the power demand of standard consumer devices. A uniform PDF is assigned to represent the variability of commonly reported power values. From this, the energy consumption is calculated over the one-hour consultation, and subsequently converted into emissions by applying the Italian electricity emission factor.
- Videoconferencing platform: The total data transmitted is derived from the session duration and the bandwidth required by Microsoft Teams in its best-performance configuration. Bandwidth values are modeled with a uniform PDF based on the lower and upper limits reported by the provider [22]. The conversion from data (GB) to energy is based on the energy intensity of videoconferencing traffic, for which a uniform PDF has been adopted using the reported minimum and maximum values (kWh/GB) [23]. The resulting energy is then converted into emissions using the Italian electricity emission factor.

For the sake of transparency and reproducibility, the conversion factors adopted in the analysis are summarized in Table II. The table reports the reference units together with the numerical parameters defining the PDFs associated with each conversion factor.

TABLE II
CONVERSION AND EMISSION FACTORS ADOPTED IN THE CASE STUDY.

Factor	Unit	PDF parameters
km $\rightarrow$ $CO_{2,eq}$	kg $CO_{2,eq}$/km	0.132 ÷ 0.135 (Uniform)
kWh $\rightarrow$ $CO_{2,eq}$	kg $CO_{2,eq}$/kWh	0.310 $\pm$ 0.015 (Normal)
GB $\rightarrow$ kWh	kWh/GB	0.209 ÷ 0.212 (Uniform)

C. Impact aggregation

The obtained PDFs representing the operational Carbon Footprint of each item were aggregated through Monte Carlo simulations with 10^6 iterations [15]. This procedure makes it possible to derive the total environmental impact of each consultation mode, both remote and in-person, under the different travel distance scenarios defined in the case study. For both consultation modes, the coverage intervals associated with a coverage level of 95 % have been calculated for each scenario. The results are summarized in Table III.

TABLE III
COVERAGE INTERVALS (95 % COVERAGE LEVEL) OF THE TOTAL CARBON FOOTPRINT FOR IN-PERSON AND REMOTE CONSULTATIONS

Consultation [1h]	**Carbon Footprint** [kg $CO_{2,eq}$]
In-person (0.5 km)	[0.14 ÷ 0.15]
In-person (1.0 km)	[0.27 ÷ 0.29]
In-person (2.0 km)	[0.54 ÷ 0.56]
Remote	[0.17 ÷ 0.29]

D. Sustainability Balance

The *Carbon Footprint Balance* between remote and in-person consultations is defined as:

$$\text{Balance} = \text{kg CO}_{2,\text{eq}}^{\text{In-Person}} - \text{kg CO}_{2,\text{eq}}^{\text{Remote}}$$

A positive balance indicates a lower impact for remote consultations, whereas a negative value favors the in-person mode.

Figure 2 presents the results for the selected case study, which considers a one-hour consultation evaluated under three different travel distance scenarios. The distances reported correspond to a one-way trip but are doubled to account for round-trip emissions. The outcomes can be interpreted as follows:

- *Scenario 1 – 0.5 km:* In-person is more sustainable.
- *Scenario 2 – 1.0 km:* Impacts are comparable.
- *Scenario 3 – 2.0 km:* Remote is more sustainable.

It is important to stress that these results are not of general validity, but rather emerge from the specific assumptions of the present case study. In particular, the analysis refers to a single car model, a given videoconferencing platform, a fixed internet connection speed, and country-specific conversion factors for energy and transport. Different boundary conditions could significantly affect the balance between remote and in-person consultations.

Overall, the case study demonstrates that telemedicine cannot be regarded as inherently more sustainable: its environmental advantage emerges only when the avoided travel distance is large enough to offset the footprint of digital infrastructures and devices. At short distances, in-person visits remain preferable, while intermediate situations lead to comparable impacts. These findings highlight both the potential and the limitations of telemedicine from an environmental perspective, and underline the need for further analyses that explore a wider variety of transport modes, technologies, and geographical contexts. The proposed methodology, which combines the LCA method with GUM principles and Monte Carlo simulations, provides a robust framework to support such future investigations and to inform decision-making in the context of Health 5.0.

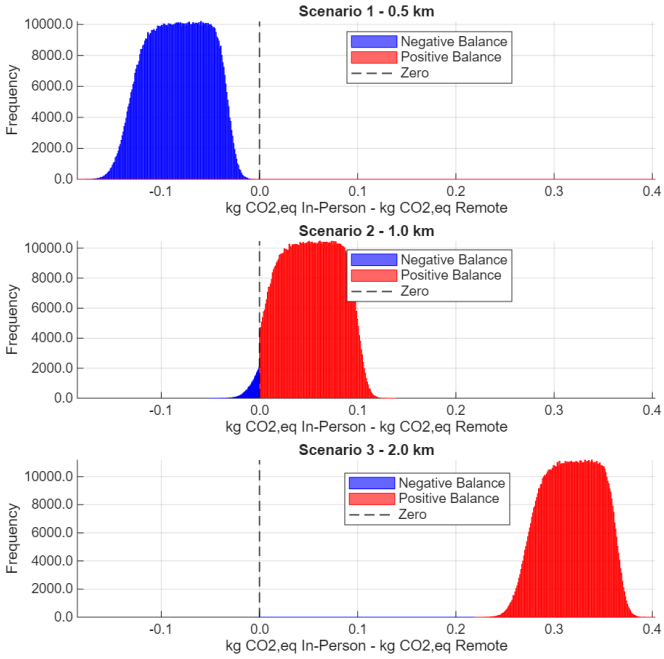


Fig. 2. Carbon Footprint Balance distributions [kg $CO_{2,eq}$] for one-hour consultations across three different travel distance scenarios.

IV. CONCLUSION

This work presented a preliminary comparison between remote and in-person medical consultations, assessed in terms of their environmental impact. The proposed methodology combines Life Cycle Assessment (LCA) with the Guide to the Expression of Uncertainty in Measurement (GUM) and Monte Carlo simulations, allowing the Carbon Footprint of each mode to be expressed as probability distributions rather than as single deterministic values.

The case study has shown that the relative sustainability of the two consultation modes depends strongly on contextual factors. In particular, short travel distances favor in-person visits, long distances favor telemedicine, while intermediate conditions lead to comparable results. These findings confirm that telemedicine cannot be considered inherently more sustainable, but only conditionally advantageous when certain boundary conditions are met.

The main limitations of the study lie in the simplifying assumptions adopted, such as the use of a specific car model, a single videoconferencing platform, fixed internet parameters, and country-specific conversion factors. Future work will extend the analysis to a wider variety of transport modes, digital infrastructures, and geographical contexts, as well as to scenarios involving the embodied impact of dedicated medical

devices, which may be considered in future assessments when specific medical devices are involved, with impacts allocated over the full duration of the monitoring plan.

In conclusion, the results highlight both the potential and the limitations of telemedicine in contributing to sustainable healthcare. The proposed framework offers a transparent and statistically robust tool to support evidence-based decision-making in Health 5.0 and to guide future research on the environmental footprint of digital healthcare services.

ACKNOWLEDGMENT

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Intelligent Indoor Air Quality System with Web-Application Based Monitoring and Real-Time Response to Household Pollutants Through a Dynamic Control System

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***Abstract*— While pollution and degradation of outdoor air are widely discussed, indoor air quality (IAQ) is often overlooked. Households are frequently perceived as safe environments, yet they often harbor unseen air quality risks. This paper aims to raise awareness and address this issue by developing a low-cost, real-time IAQ monitoring and dynamic air purification system designed to inform users and protect them from associated health risks. The proposed system integrates multiple sensors on an Arduino platform to measure key IAQ parameters: temperature, humidity, CO, eCO2, TVOC and $PM_{2.5}$. The Raspberry Pi processes these readings using a dynamic weighting algorithm that considers both exposure duration and usage context. This information is then displayed in real-time via a user-friendly web application. To address poor air quality, the system incorporates a responsive control unit equipped with carbon and High-Efficiency Particulate Air Filter (HEPA) filters. These filters are dynamically activated with varying intensity based on individual pollutant levels and overall air quality score. Experimental testing explored common indoor scenarios—cooking, ventilation, and cleaning. Results showed that frying with olive and vegetable oils generated the highest $PM_{2.5}$ emissions, while rapeseed oil produced the lowest. Combined use of extractor fans and open windows yielded the greatest reduction and fastest dissipation of pollutants post-exposure. VOC analysis revealed that cleaning sprays caused the highest peaks but dissipated quickly, whereas floor cleaners had lower peaks but longer persistence. These findings offer practical guidance for changes in behavior and policy, underscoring the broader importance of IAQ monitoring.**

Keywords—Indoor Air Quality (IAQ), Real-Time Air Quality Monitoring, Dynamic Air Purification and Embedded Sensors.

I. INTRODUCTION

Indoor air quality (IAQ) is a critical aspect of sustainable building design and public health, as people spend approximately 80–90% of their time indoors [1]. Recent studies [1], [2] indicate that indoor air pollution can pose equal or greater health risks than outdoor pollution. Poor IAQ has been linked to respiratory illnesses, reduced productivity, and overall well-being issues, making it imperative to monitor and improve air quality inside homes, schools, and workplaces. This need is further underscored by major European Union (EU) initiatives that align environmental sustainability with human health. The European Green Deal, for example, emphasizes the creation of green and healthy buildings as part of its climate-neutral strategy, and the EU's "Renovation Wave" strategy aims to at least double the rate of energy-efficient building renovations by 2030 [3]. These policies, along with updates to the Energy Performance of Buildings Directive (EPBD) mandating Nearly Zero-Energy Building (NZEB) standards, seek to decarbonize the built environment while safeguarding occupant well-being [4]. A tighter building envelope and improved energy efficiency can inadvertently lead to pollutant accumulation if ventilation is insufficient. Thus, European directives increasingly recognize that sustainable buildings must also maintain healthy IAQ as a co-priority. As a case in point, Ireland's climate action plan has set ambitious retrofit targets (e.g. upgrading 500,000 homes to high energy efficiency by 2030) [4]. This retrofit wave is driven by decarbonization goals, but it raises concerns about IAQ: homeowners often worry that insulating and sealing their houses could degrade indoor environment quality [4]. Recent studies in Ireland confirm that while deep energy retrofits improve energy performance, they can have mixed effects on IAQ if not accompanied by adequate ventilation [4]. For instance, one field study found that post-retrofit, indoor CO_2 levels generally decreased (indicating better ventilation), yet fine particulate ($PM_{2.5}$) and formaldehyde concentrations increased in many homes – likely due to tightened buildings without commensurate ventilation, along with ongoing indoor pollutant sources [4]. Such findings reinforce the policy mandate: achieving climate and energy targets must go hand-in-hand with IAQ monitoring and control measures so that sustainability and public health remain aligned.

In response to growing awareness, a variety of IAQ monitoring and purification technologies have emerged commercially and in research. High-end environmental monitoring stations provide accurate measurements of pollutants, and consumer-grade IAQ monitors (from simple CO_2 sensors to multi-sensor devices) are increasingly available. Modern buildings are also beginning to incorporate sensors for "demand-controlled" ventilation as recommended by standards. However, current solutions exhibit significant limitations in cost, scope, and capability. Professional IAQ monitoring equipment is often prohibitively expensive, while affordable low-cost sensors face challenges with data accuracy, stability, and calibration [5]. Many off-the-shelf IAQ devices only cover a limited range of pollutants (often focusing on one indicator like CO_2 or particulate matter) and may miss other important contaminants. For example, low-cost particle counters can detect gross changes or events but struggle to measure low concentrations and are affected by environmental factors like humidity [5], [6]. Another gap is the lack of dynamic control in most commercial systems – they tend to monitor and display IAQ data passively, leaving it to occupants to take action (e.g. open a window or switch on a purifier). Typical home air purifiers and heating, ventilation and air-conditioning (HVAC) systems, if present, often operate at fixed settings or simple timer schedules without real-time optimization. This means they may waste energy by running when not needed, or conversely, fail to

ramp up in time to mitigate pollution spikes. The result is suboptimal IAQ management that neither ensures consistently clean air nor minimizes energy use. Scalability is also a concern: deploying a dense network of IAQ sensors across multiple rooms or buildings can be technically complex and costly, especially if each node requires power and maintenance [1]. In research settings, numerous smart IAQ solutions have been prototyped to tackle these issues – for instance, wireless sensor networks for real-time IAQ monitoring using gas sensors [1], [7], and AI-driven control algorithms that adjust ventilation or purification based on sensor data [8]. These efforts demonstrate the feasibility of integrated IAQ management, but many existing approaches still lack one or more features such as affordability, multi-pollutant coverage, real-time responsiveness, or scalability.

The proposed system focuses on primarily monitoring two key indicators of indoor air quality: fine particulate matter ($PM_{2.5}$), and volatile organic compounds (VOCs). These pollutants were selected based on their relevance in residential environments and their recognition in both health literature and building standards [4], [9], [10], [11]. $PM_{2.5}$ is mainly generated through cooking and combustion activities and is strongly associated with respiratory and cardiovascular health risks [10]. VOCs are commonly emitted from cleaning products, and paints, with chronic exposure linked to irritation, allergies, and in some cases, carcinogenicity. These parameters are also frequently used in European retrofit studies and air quality guidelines, including those assessing post-retrofit IAQ performance in Ireland [4]. By targeting this pollutant duo, the system ensures coverage of particulate, chemical, and ventilation-related IAQ dimensions, aligning with best practices in both health protection and building performance evaluation.

This work utilizes a low-cost, real-time IAQ monitoring and purification system that integrates multi-pollutant sensing, visualization, and intelligent pollutant mitigation. The system is built around a network of affordable sensors, which are calibrated and combined to provide a comprehensive view of indoor air in real time. Users can access this information through a user-friendly interface (such as a smartphone app or web dashboard), promoting transparency and awareness of indoor air conditions at any moment. In addition, the system closes the loop between sensing and control by employing an intelligent filtration mechanism: it can automatically activate or adjust air purification devices in response to detected pollution events. For example, if the $PM_{2.5}$ concentration spikes due to cooking emissions, the system could ramp up a HEPA-filter air purifier or an exhaust fan to quickly reduce particle levels. This dynamic, demand-driven control contrasts with the static operation of typical HVAC or purifier systems. By only running filtration or ventilation at the intensity and time needed, the system improves IAQ while avoiding unnecessary energy consumption. By leveraging low-cost IoT hardware and open-source software, the deployment cost is kept low, which supports scalability (multiple units can be placed in different rooms or dwellings without exorbitant expense). The architecture is modular – additional sensors or actuators can be incorporated as needed – and it can be integrated into existing smart home platforms or building management systems. This flexibility means the system can fit both small residential settings and larger commercial or educational buildings, scaling from a single-room device to a network of devices covering an entire facility. Overall, the system directly addresses the limitations of current IAQ approaches: it monitors a broad range of pollutants relevant to indoor health, provides real-time feedback and visualization, and importantly, acts on the data through intelligent filtration control. By doing so, it ensures that improvements in energy efficiency (as buildings become more airtight and energy-conscious) do not come at the expense of occupant health.

TABLE I. SELECTED IAQ MONITORING SENSORS

Sensor	***Parameter Measured***	***Cost***	***Rationale***
BME280	Temperature, Humidity	€6.93	Miniaturized, low-power sensor; high accuracy over wide temperature range
SGP30	eCO_2, TVOC	€14.29	Compact affordable gas sensor
MQ135	CO	€6.50	Economical multi pollutant sensor
PMS5003	$PM_{2.5}$	€17.52	Optical laser sensor offering adequate resolution on dust particles at low-cost.

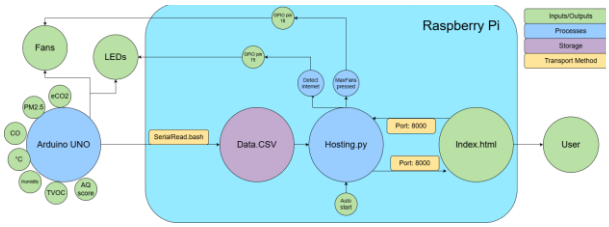


Fig. 1. Proposed system design

II. PROPOSED SYSTEM DESIGN

The proposed system as shown in Fig. 1 was developed with three core principles in mind: affordability, modularity and responsiveness. These principles guide each component of the design – ensuring it can be deployed in diverse household settings and respond in real-time to pollutant events. The system integrates an array of sensors connected to an Arduino platform, which then output the raw data via serial communication to the Raspberry Pi. This data is logged into a Comma-Separated Values (CSV) file and used for responsive control of the fans and two LEDs through Arduino. A web server hosts the visual interface, enabling user-friendly access through an integrated web application.

A. Sensing Unit: Selection Criteria & Calibration

A key design goal was to detect a representative range of indoor pollutants with minimal cost. The selected pollutants—$PM_{2.5}$, VOCs, CO, eCO_2, temperature, and humidity—were chosen due to their prevalence in domestic environments and documented health impacts as previously outlined. The sensors listed in Table I were chosen to measure these parameters reliably and cost-effectively. Although the focus of analysis was on $PM_{2.5}$ and VOCs, temperature and humidity were included due to their influence on sensor accuracy and pollutant behaviour. These parameters remained relatively stable during tests, providing reassurance about consistency in readings. Similarly, CO and eCO_2 were monitored to provide ventilation and combustion-related context, though no concerning levels were observed during

the household activities simulated. The inclusion of these sensors thus supports a more comprehensive IAQ profile without compromising on system affordability or safety.

The sensors were interfaced to an Arduino UNO Minima R4 using I²C for the BME280 and SGP30, analog input for the MQ135, and UART serial communication for the PMS5003. Sensor readings are transmitted in .CSV format to a Raspberry Pi via USB serial communication, which processes the sensor data and enables user interaction via a web-based interface.

The MQ135 was calibrated by completing a 48 hour "burn in" period to stabilize the sensor, followed by determining the baseline resistance, R_0, in clean air. This was measured at 314.55Ω which was then used to measure the CO value using the provided logarithmic equation from the datasheet. The SGP30 was initialized with the Adafruit libraries, self-calibrates during run time and was configured for humidity compensation. The BME280 utilized the Adafruit library which applies built-in factory calibration. The PMS5003 comes calibrated from factory and was configured using the included library.

B. Proposed Algorithms

Traditional IAQ systems often rely on static thresholding, which can trigger false alarms or miss events depending on occupancy and external conditions. To address this, the system integrates the following three adaptive algorithms:

1. Air Quality Scoring Algorithm: Sensor values were first measured and then normalized to a 0-100 scale. Each value is then assigned a dynamic weight using a context-sensitive function that considers factors such as room type (e.g. kitchen vs bedroom), time of day (cooking time vs. sleep hours), external environment, current activity and pollutant severity. These weights were determined through literature informed reasoning [12], [13] and realistic exposure scenarios. For example, $PM_{2.5}$ carries its highest weight during cooking and in the kitchen, as previous study [12] highlights its significant accumulation during frying and grilling. CO carries an extremely high weight during sleeping hours in the bedroom as significant CO exposure over prolonged periods of time can be fatal. TVOC receives its highest weighting during cooking and cleaning in the kitchen and bathroom respectively as both activities can result in significant increase in VOC levels. These weighted values are then combined and normalized again to produce an overall air quality score ranging from 0-100, as shown in Fig. 2.

2. Short-Term Exposure Index: To assess cumulative risk, the system maintains a 5-hour rolling average for each raw sensor in its native units and measurement range. Each pollutant and overall air quality score is compared against predefined safety thresholds based on the health risk that pollutant poses. This index reflects the occupant's likely exposure and is mapped to qualitative descriptors (Low, Medium, High). This method is aligned with IAQ health guidelines, which emphasize time-weighted pollutant exposure [14]. The integration step in Fig. 2 feeds into this process resulting in the derived exposure value.

3. Control System Activation: Based on pollutant-specific thresholds and overall IAQ score, the system dynamically controls air purification. It activates filtration system equipped with carbon and HEPA filters at three levels (Off, Medium, High), balancing responsiveness with energy efficiency. When the PWM value reaches a defined threshold, the system initiates the corresponding control response, such as fan activation or LED alerts, as illustrated in the control system layer of Fig. 2.

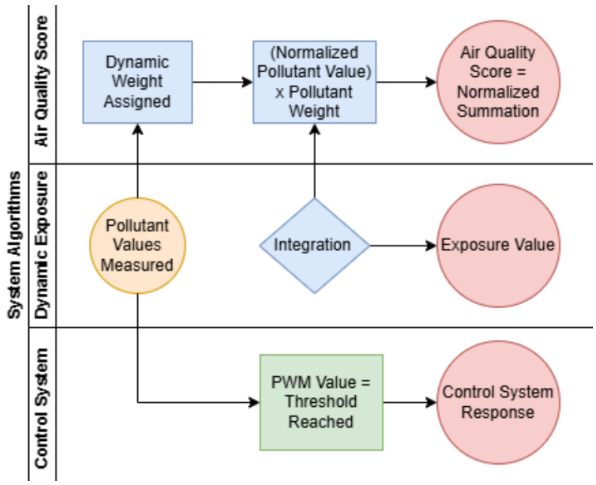


Fig. 2. System algorithm flow for air quality assessment and control. The figure illustrates three key layers: pollutant measurement and dynamic weighting (Air Quality Score), exposure integration and threshold evaluation (Dynamic Exposure), and responsive actuation based on Pulse Width Modulation (PWM) thresholds (Control System).

The proposed algorithms ensure that the system is context-aware, proactively prevents pollutant levels from reaching dangerous thresholds and provides simple, user-friendly metrics to communicate exposure.

C. Web Application

Sensor data is transferred via USB serial communication from the Arduino to the Raspberry Pi. This data feeds a real-time dashboard that displays individual parameters, pollutant graphs, and system control options. The web application also includes a power saving mode, which overrides the fan speed to zero. The front-end interface is developed using a combination of JavaScript and HTML.

III. Experiment Design And Methodology

To evaluate the effectiveness of the proposed system and to better understand typical indoor pollutant sources, a series of controlled experiments were conducted. These tests simulated common household activities in order to identify key pollution events and assess corresponding mitigation strategies. Each experiment was designed to capture variations in indoor air quality under different conditions such as cooking, cleaning, and ventilation scenarios. The system recorded the following environmental metrics during each test: temperature, humidity, TVOC, equivalent CO_2 (eCO_2), CO, and $PM_{2.5}$. All sensor data were logged in real time in CSV format using a datalogger, with the system connected to a laptop for continuous monitoring and subsequent analysis.

A. Frying Oils

Four different cooking oils were tested in a controlled experiment to assess the effect of frying on indoor air quality. The aim was to evaluate both the types and levels of pollutants released, and to determine whether the choice of oil influences pollutant concentrations. The oils tested were olive, vegetable,

sunflower and rapeseed. Each test was conducted in the same kitchen environment, with the air quality monitoring system placed a meter from the frying pan to simulate the typical distance of an occupant during cooking. The following procedure was designed to isolate the effects of different oils on pollutant generation by standardizing cooking duration, intensity, and food type:

- 5 minutes pre-test recording to establish a stable baseline of the background IAQ conditions.
- 3 minutes oil heating on high to ensure all oils reach a consistent frying temperature.
- 5 minutes of frying (potatoes of 1 inch thickness with consistent surface area) to provide a uniform cooking task across tests to generate comparable emissions.
- 30 minutes post-test recording to capture the pollutant dissipation profile and evaluate lingering effects of the emission events.

B. Ventilation Methods

Alongside the frying oil tests, each experiment was repeated using a set of different ventilation strategies to evaluate their effectiveness in reducing peak pollutant levels and accelerating pollutant dissipation. These methods were selected to reflect common household ventilation practices and to assess how practical interventions influence indoor air quality. The ventilation modes tested were:

- None – represents a sealed environment with no active ventilation, simulating poor IAQ conditions.
- Windows and Doors – simulates passive ventilation through natural airflow.
- Extractor Fan – represents active mechanical ventilation commonly available over stovetops.
- Both – combines natural and mechanical ventilation for maximum extraction efficiency.

The experimental procedure remained consistent with that used in *Test A* (frying oils), with the only variation being the application of these ventilation methods. This ensured fair comparison across conditions while isolating the impact of ventilation on pollutant behaviour.

C. Cleaning Products

Household cleaning activities, particularly those involving sprays and floor cleaners, often release unsafe levels of VOCs. This test series aimed to assess the significance of VOC emissions from typical cleaning products and evaluate how long these pollutants persist in indoor air under realistic usage conditions. Three representative cleaning scenarios were selected to reflect common household practices, each targeting different spaces and application methods:

- Bathroom cleaning spray (In a confined bathroom with all surfaces sprayed)
- Floor cleaner mopping test (In a household hallway with the entire floor surface mopped)
- Combined kitchen cleaning (Spray and Mopping)

Each test was designed to replicate everyday cleaning routines as closely as possible. A 5-minute pre-test period established a VOC baseline, followed by product use, and 30-minute post-test recording to capture pollutant persistence and decay.

D. Control System

To evaluate the responsiveness and accuracy of the control system, a controlled emission test was conducted under standardized conditions. The entire device incorporating carbon and HEPA filters was enclosed within a large, transparent test chamber to simulate a confined indoor space. The test run followed the following procedure:

- A 5-minute pre-test recording period was initiated to establish baseline air quality conditions within the sealed chamber.
- At the 5-minute mark, a candle was lit, then extinguished inside the chamber to generate a predictable and rapid spike in particulate and gas-phase pollutants, particularly $PM_{2.5}$.
- The system then continued to operate under observation for a 30-minute post-event period, during which sensor data, air quality score, and control system response were logged.

IV. Results And Discussion

The system performed reliably throughout all test scenarios, showcasing highly sensitive and responsive data acquisition across the full range of monitored pollutants. Each test was analyzed using Python for data visualization. While detailed analysis focuses on $PM_{2.5}$ and VOCs due to their significant fluctuations and health relevance, other recorded parameters such as CO, CO_2, temperature, and humidity were also monitored. CO and CO_2 levels remained within safe threshold with CO failing to exceed 9ppm and CO_2 remaining below 900ppm, aligning with the low-combustion, household-safe scenarios used. Temperature (average 19°C) and humidity (55-65%), included to account for sensor performance and pollutant behaviour, showed minimal variation across tests, reaffirming consistency and data reliability. The following subsections summarize key findings. The graphs provided include thresholds marked Good or Healthy (Green), Poor (Yellow), Very Poor or Potentially Hazardous (Red).

A. Frying Oils

The frying oils experiment revealed that cooking with different oils leads to notable variations in indoor pollutant levels—specifically in $PM_{2.5}$. All tested oils generated a significant increase in $PM_{2.5}$ concentrations during the heating and frying phases compared to baseline, though peak values varied. Fig. 3 presents $PM_{2.5}$ levels over time for vegetable, sunflower, olive, and rapeseed oils under no ventilation. The red line at 250 µg/m³ in the graph corresponds to the "Very Poor" threshold used in AQI systems to indicate short-term exposure risks. Among all the tested oils, vegetable oil produced the highest increase peak concentration at 372 $\mu g/m^3$ closely followed by Olive oil at 334 $\mu g/m^3$. Both values significantly exceeded the healthy thresholds (Green) (250 µg/m³) and maintained these levels for extended durations— 13 minutes for vegetable oil and 15 minutes for olive oil. Sunflower and Rapeseed oils briefly crossed the "Very poor" threshold (Red) with peak increase values of 268 $\mu g/m^3$ and 241 $\mu g/m^3$ respectively. To evaluate how long the pollutants remained in the air after frying, a 30-minute post-test decay analysis was conducted. Rapeseed oil, which had the lowest peak, showed the most

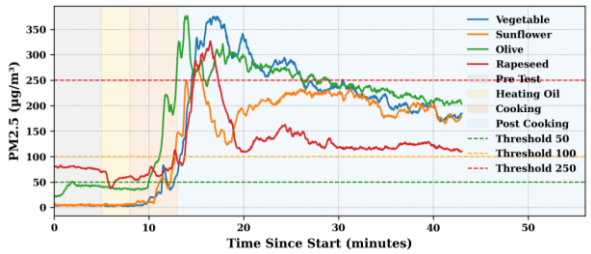


Fig. 3. $PM_{2.5}$ concentrations during frying with different oils without ventilation.

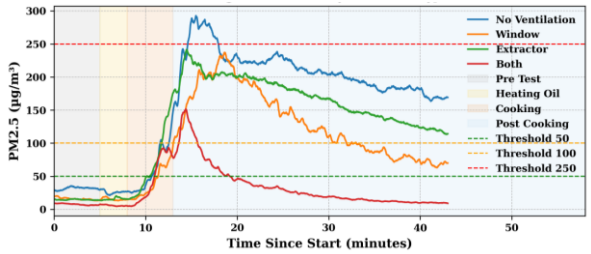


Fig. 4. Average $PM_{2.5}$ concentrations during frying across all oil types under different ventilation conditions.

rapid dissipation, with a decay rate of 66.7%. In contrast, vegetable oil, despite its high initial concentration, exhibited a slower rate of decay. The average decay in $PM_{2.5}$ concentration over the 30-minute post-test period across the four oils was 49.6%.

These results demonstrate that the choice of cooking oil plays a significant role in both the intensity and duration of indoor particulate pollution during frying, especially in environments without adequate ventilation.

B. Ventilation Methods

To evaluate the effect of ventilation on pollutant reduction, each cooking oil test was repeated under four different ventilation conditions: no ventilation, windows and doors open, extractor fan only, and both methods combined. Fig. 4 presents the average $PM_{2.5}$ levels across all oils for each ventilation type, underscoring the significant impact of ventilation on both peak pollutant levels and post-test decay. In the absence of any ventilation, $PM_{2.5}$ concentrations peaked at 372 µg/m³ (vegetable), 293 µg/m³ (mean) and remained above the "Very poor" threshold (250 µg/m³) for approximately 13 minutes (vegetable), 4 minutes (mean). This condition represented the worst-case scenario, with limited dissipation and an average post-test decay of just 49.6% over 30 minutes. The introduction of passive ventilation (opening windows and doors) resulted in a substantial improvement. Peak $PM_{2.5}$ levels were noticeably reduced, falling just below the "Very Poor" category, and the average decay rate improved significantly to 74.9%, indicating faster pollutant clearance. When using only the extractor fan, peak values remained similar to the passive ventilation scenario; however, the average decay rate was slightly lower. This suggests that while extractor fans may help during active cooking, their impact on post-exposure dissipation is more limited compared to natural airflow. The most effective strategy combined both passive and mechanical ventilation. This approach reduced peak $PM_{2.5}$ levels to 151 µg/m³ (mean), a far safer range, and achieved the highest average decay rate of 93.3% during the post-test

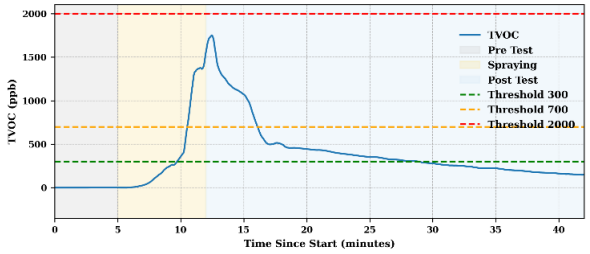


Fig. 5. TVOC levels during bathroom spraying.

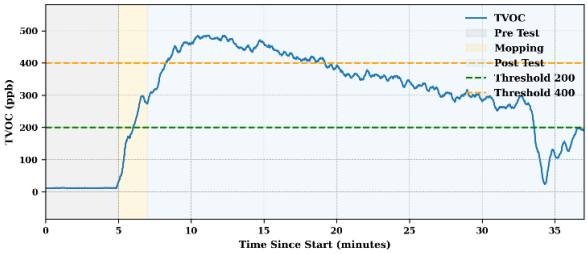


Fig. 6. TVOC levels during hall mopping.

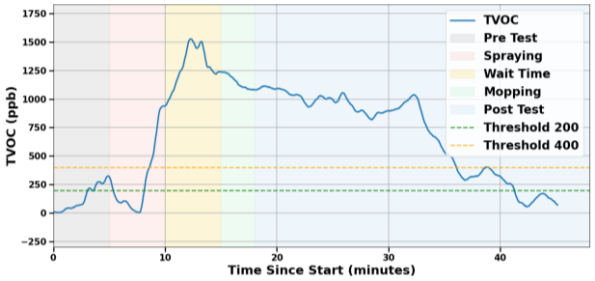


Fig. 7. TVOC levels during cleaning spray & mopping.

period. Notably, this combined method kept pollutant levels close to or within the "Good or Healthy (Green)" air quality range throughout most of the test window.

C. Cleaning Products

The impact of household cleaning products on indoor air quality was evaluated through three controlled test scenarios: bathroom spraying, hallway mopping, and a combined cleaning procedure in the kitchen. All scenarios revealed notable spikes in TVOC concentrations, but with distinct emission patterns depending on the activity and product used.

The bathroom spray test, shown in Fig. 5, resulted in a rapid and pronounced increase in TVOCs, with a peak reaching 1750 ppb shortly after spraying began. While this remains just below the severe advisory threshold ("Very Poor" -Red) of 2000 ppb, it still indicates a substantial and acute emission event, especially in a confined environment. The decay, however, was relatively swift, with levels dropping significantly within 10 -15 minutes after spraying ended. In contrast, Fig. 6 illustrates TVOC levels during the hallway mopping test using a common floor cleaner (Flash Lavender all-purpose floor cleaner). The concentration gradually increased during the mopping phase, peaking at approximately 470 ppb, and then dissipated slowly over the following 30 minutes. While this emission level is "Poor (Yellow)", it reflects the persistence of VOCs from surfaces post-application, with TVOC values remaining above the 200-ppb threshold well into the post-test period. The combined cleaning test, involving both spraying and mopping as shown in Fig. 7, produced sustained high TVOC

levels with an extended plateau around 1,200 ppb, and a secondary peak during the mopping phase. This scenario resulted in the longest overall exposure, indicating that sequential or combined use of cleaning products can compound pollutant effects, both in intensity and duration. These results underscore the importance of careful cleaning product use and adequate ventilation during cleaning activities. While sprays introduce immediate and intense pollution spikes, mopping leads to slower, more persistent emissions. In practice, the combined effects may significantly elevate occupant exposure, particularly when cleaning occurs in succession or in enclosed environments.

D. Control System Testing

The results of the control system testing are presented in Fig. 8, which compares $PM_{2.5}$ concentration over time with and without active fan control. Both test conditions began with similar baseline levels and a controlled pollutant introduction via a candle lit and extinguished at the 5-minute mark, as outlined in the methodology. In the 'No Fans condition', $PM_{2.5}$ concentrations spiked sharply to over 800 µg/m³, remaining above 250 µg/m³ (Potentially Hazardous - Red) for the duration of the test. Dissipation of pollutants occurred gradually and incompletely, with levels still exceeding 400 µg/m³ at the 30-minute mark. In contrast, the 'With Fans condition' demonstrated rapid activation of the control system immediately following the pollutant spike. The system responded by increasing fan intensity, resulting in a rapid decline in $PM_{2.5}$ concentration. Within approximately 5 minutes post-activation, levels dropped below 50 µg/m³ and continued to decline shortly after. The pollutant concentration remained near baseline for the remainder of the test. This trend is further illustrated in Fig. 9, which shows the fan speed dynamically scaling in response to $PM_{2.5}$ concentration, with maximum intensity triggered as thresholds (Red and Yellow) are exceeded and gradually reduced as air quality improves.

V. Conclusion

This work successfully developed and validated an intelligent air quality monitoring and mitigation system tailored to everyday household use. Through the integration of real-time sensing alongside custom built for purpose algorithms it provides meaningful air quality score, user-friendly exposure index and reacts in real-time to reduce and even prevent reduced air quality. Additionally, investigative testing into household events uncovered the reality behind some common household events and the air quality they leave behind. This work has provided a low-cost user-friendly system to measure, mitigate and educate users and raise awareness into the reality of their household air quality.

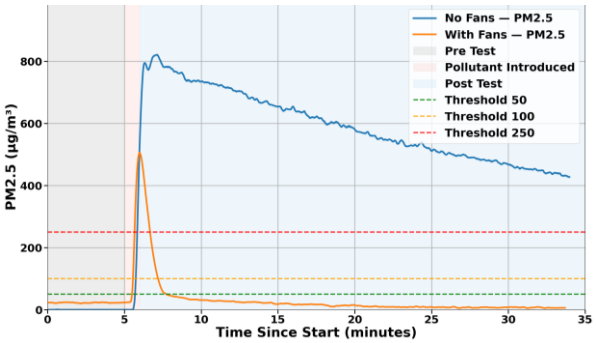


Fig. 8. $PM_{2.5}$ levels over time with and without fan control. A candle was lit and extinguished at 5 minutes to introduce pollutants. Active fan response significantly reduced peak levels and accelerated dissipation.

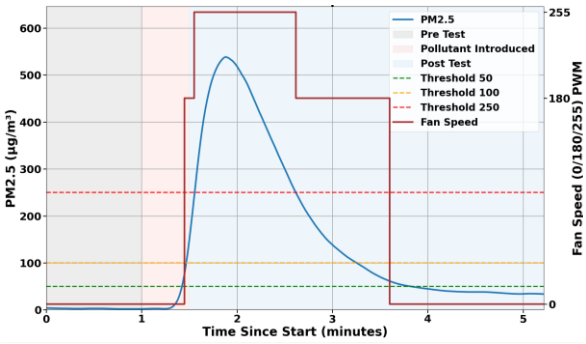


Fig. 9. $PM_{2.5}$ concentration and fan speed over time following pollutant introduction (candle extinguished at 1 min). The control unit adjusts fan intensity in real time, reaching maximum speed above 250 µg/m³ and gradually reducing as air quality improves.

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Machine Learning for Air Quality Monitoring with Low-Cost Sensors: Evaluating Calibration Approaches Through Relative Expanded Uncertainty

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***Abstract*—**The current paper introduces machine learning (ML) as a method that supports field calibration of low-cost air quality sensors and their networks. The ML methodology initially focuses on individual/ad-hoc sensor node calibration, but it is then developed towards a global calibration approach, where one calibration function is trained to serve the needs of calibration of all nodes belonging to an AQ monitoring network. To achieve more meaningful results in terms of operational requirements, the evaluation of this calibration is based on statistical metrics such as the root mean squared error (RMSE) and coefficient of determination (R^2), but also on the relative expanded uncertainty (REU). The latter is defined in the European Directive 2008/50/EC and is incorporated into the ISO standards CEN/TS 17660-1 (2021) and CEN/TS 17660-2 (2024), and it offers a more standardized and interpretable metric for uncertainty evaluation. REU quantifies the uncertainty between LCS and reference measurements based on co-located and simultaneous observations. The ML-oriented approach achieves REU values for PM_{10} below 50% across all tested configurations and below 25% specifically when sufficient training data are available (≥60% train-test split for this experimental setting) and pollutant concentrations exceed 30 μg/m³. Critically, global calibration demonstrates superior performance in data-sparse scenarios, a common constraint in operational sensor network deployments. Our results highlight the importance of adopting REU as a unified performance metric and demonstrate the benefits of global calibration for scalable, transferable AQ sensor network deployment.

Keywords—machine learning, air quality, urban environment, relative expanded uncertainty, global calibration

I. INTRODUCTION

Air quality (AQ) monitoring has been transformed by the rise of low-cost sensors (LCS), which is based on the advances made in miniaturized sensor elements and Internet of Things (IoT) technologies [1]. From its infant phase to its maturity, this scientific field has become quite popular among the scientific community as well as among citizens.

However, the proliferation of LCS deployments has exposed critical gaps in standardization and interoperability. The heterogeneity of sensor technologies, combined with sensitivity to environmental factors such as humidity, temperature, and atmospheric composition, creates systematic biases that vary spatially and temporally. This variability undermines confidence in data from individual sensors and necessitates robust calibration frameworks applicable across diverse deployment contexts.

On this basis, a common pitfall of these LCS systems is evident: their lower measurement quality, compared to standard reference instruments that provide the highest quality AQ data. To address this challenge, machine learning (ML) assisted calibration has emerged as an effective way to learn the calibration function and deploy the LCS applying this correction algorithm. This approach has been proven particularly advantageous where field-based calibration is required, like in cases where a heterogeneous network is already employed and operates under real world conditions.

While ML models can substantially improve sensor accuracy, challenges in generalizability and standardization remain [2]. Recent reviews [3, 4] underscore the state-of-the-art in field calibration – from simple linear fits to advanced ML models – and the growing consensus that ML-assisted calibration is now the *de facto* standard for improving LCS data quality on-site. To improve the performance of the individual sensors as well as of their networks, a few methods have been suggested for their calibration, with emphasis on their field-operational calibration. [5] provide a comprehensive survey of ML-based quality control for LCS, covering traditional regressions, deep learning, and hybrid approaches for sensor calibration. On this basis, certain criteria, commonly used for the assessment of the success of these calibration methods have been applied, including RMSE, the coefficient of determination (R^2), etc. Generally, evaluating the behaviour of a computational calibration requires a suite of metrics to understand it thoroughly. Metrics including linearity, errors, uncertainty, distribution, and variance are often used interchangeably to evaluate calibration performance. However, a comprehensive assessment should include at least one metric from each category and emphasize parameters affecting overall sensor network performance and measurement quality.

While metrics like the RMSE and R^2 provide useful initial indicators, they frequently mask poor performance at low concentration ranges—precisely where regulatory thresholds and public health action levels operate. This gap motivated the incorporation of relative expanded uncertainty (REU) into the CEN/TS standards, providing a measurement-centric metric that directly relates to regulatory requirements and field performance. More specifically, the first technical

standard (TS) published for LCS, was a CEN standard (CEN/TS 17660-1, 2021) [6], focusing on the performance evaluation of air quality sensor systems for gaseous pollutants. The second TS that followed was a CEN standard (CEN/TS 17660-2, 2024) for particulate matter in ambient air [7].

These standards provide detailed procedures for calibration and testing of LCS and state the criteria according to which such sensor systems may be classified. A cornerstone of the aforementioned TS is the use of the relative expanded uncertainty (REU) as a criterion for the classification into three categories, as follows:

- Category 1 sensors (REU < 25% for PM_{10}) are suitable for complementary monitoring alongside regulatory reference instruments and can contribute to network-level assessments.
- Category 2 sensors (25% ≤ REU < 50% for PM_{10}) are appropriate for indicative monitoring, providing spatial context and identifying pollution hotspots but requiring reference validation for regulatory decision-making (this is Class 1 sensors according to CEN/TS).
- Category 3 sensors (REU ≥ 50% for PM_{10}) provide only qualitative trend information and are unsuitable for enforcement purposes (this is Class 2 sensors according to CEN/TS if 50% ≤ REU < 100%).

This certification allows for categorizing sensors according to the relative expanded uncertainty of the measurement, which varies per pollutant, as is defined in the relevant annex of the Air Quality Framework Directive (2008/50/EC).

On this basis, the use of the REU as the main criterion for ML-powered operational sensor network calibration has naturally emerged in literature, within which the authors were among the first to contribute.

In this study, we (1) compare a global (network-wide) calibration framework with the conventional ad-hoc (individual-sensor) approach, and (2) evaluate two REU calculation methods — one based on a single reference value and another spanning the full measurement range.

In the rest of the paper, we are going to introduce the concept of the REU and the ML calibration methodology, followed by exemplified results and their discussion, leading to the conclusions.

II. Materials And Methods

A. Dataset

A comprehensive public dataset was employed for the computational experiment to be presented. The dataset [8] provides raw measurements from multiple LCSs collocated with reference or equivalent-to-reference instruments. The data collection took place in three European cities (Antwerp, Oslo, Zagreb) with different time intervals. The experiment was divided into three distinct periods. Initially, for each city all the nodes were collocated with a single reference instrument (1st collocation period). Afterwards, the sensors were deployed in the city web with some of them being collocated with different reference analysers (deployment period). Finally, the nodes were once again collocated with the initial reference instrument at the same site as the first collocation period (2nd collocation). In this study, we focused on the calibration of PM sensors where each LCS device included a nephelometer (PMS5003, 6 bins and manufacturer estimations for PM_1, $PM_{2.5}$ and PM_{10}) and an optical particle counter (OPC-N3, 24 bins and manufacturer estimations for PM_1, $PM_{2.5}$ and PM_{10}). During the deployment period, six collocation pairs were established in Oslo and nine in Antwerp. In Antwerp, all equivalent-to-reference measurements were obtained using the Palas Fidas 200, an optical particle counter (OPC). In contrast, the Oslo sites employed a more heterogeneous set of reference instruments: three sites were equipped with TEOM 1405F-FDMS (tapered element oscillating microbalance with filter dynamics measurement system), one site with a Fidas 200S, and one with an Andersen FH62IR beta attenuation monitor. Based on these configurations, we focused on the field calibration of Antwerp's low-cost sensor networks (LCSNs) because it is the largest of the three datasets. LCS measurements were aggregated at the hourly resolution to evaluate and compare the performance of two calibration strategies, namely ad-hoc calibration (site-specific) and global calibration (cross-site).

B. Relative expanded uncertainty

There are two approaches to calculate the REU. On the one hand, REU can be calculated at a predefined value such as the limit value (LV) or at the upper assessment value (UAT) or at the lower assessment value (LAT) following the equation:

$$U_r(y_i) = 2\left(\frac{RSS}{n-2} - u^2(x_i) + [b_0 + (b_1 - 1)L]^2\right)^{\left(\frac{1}{2}\right)} \quad (1)$$

Where L could be any of the above values.

On the other hand, REU can be calculated for the full range of available measurements making use of the following equations [9].

$$U_r(y_i) = 100\,\frac{2\left(\frac{RSS}{n-2} - u^2(x_i) + [b_0 + (b_1 - 1)x_i]^2\right)^{\left(\frac{1}{2}\right)}}{y_i} \quad (2)$$

$$RSS = \sum_{j=1}^{n} \left(y_{i,j} - b_0 - b_1 x_{i,j}\right)^2 \quad (3)$$

In this case $U_r(y_i)$, is the REU, $u^2(x_i)$, is the between reference system uncertainty of the standard method here set equal to 0.67 for PM_{10} and $PM_{2.5}$. RSS represents the sum of (relative) residuals, x_i is the average result of the reference method over period i (e.g. daily averages), and y_i is the average result of the sensor system over period i. The terms b_0 and b_1 correspond to the coefficients of the regression equation $y = b_1 x + b_0$. Finally, n is the number of measurements.

Following the first approach leads to a single value to determine the uncertainty between the calibrated and the reference measurements but offers less information compared to the second approach where it is possible to

understand the weaknesses of a calibration system for a specific range. The main advantages of employing REU as a metric, are that it 1) quantifies the uncertainty relative to real measurements on the field, 2) provides a robust way to compare results from studies and 3) allows for direct assessment via the ISO standards showcasing the calculation and regulations are already in place.

A critical distinction exists between single-point REU calculations (at regulatory thresholds like the 50 µg/m³ limit value for PM_{10}) and full-range REU analysis. Single-point REU can be artificially favourable if calibration performs well near the threshold but poorly at other concentration ranges. Full-range REU, calculated across all observed concentrations, provides a more comprehensive performance characterization and reveals systematic biases that may only manifest at specific concentration regimes—for example, high bias at low background concentrations or non-linear response at high episodic pollution events.

C. Calibration approaches

1) Ad-hoc/individual calibration strategy

The ad-hoc, or site-specific, calibration approach establishes an individual correction function for each LCS using data from its direct collocation with a reference instrument. For instance, [9] collocated low-cost $PM_{2.5}$ sensors with a reference beta-attenuation monitor for 10 months in India and found raw sensor readings had very low R^2 (~0.4), but after local calibration the R^2 improved to ~0.99 with greatly reduced error. The calibration model is derived exclusively from the paired measurements at a given site and is therefore adapted to the local conditions of that location and deployment period. Another study [10] emphasizes that LCS "require calibration and validation in their specific deployment site using expensive reference instruments" before use. While this method is relatively straightforward and can achieve satisfactory accuracy at the calibration site however it lacks generalizability, as the resulting calibration function cannot be reliably transferred to other locations or newly deployed sensors [11]. In summary, ML models are typically context-specific without adaptation, their calibration accuracy "fails to generalize to new, unseen data".

2) Global/network-wide calibration framework

The global calibration strategy integrates measurements from all collocated sensor–reference pairs within the LCSN into a tall dataset. In this framework, data from different collocated pairs (LCS and reference) are employed and concatenated into a single aggregated matrix. A global calibration model is then trained on this pooled dataset, thereby indirectly capturing spatiotemporal variability and enabling transferability across sites and sensor types. This design ensures that the framework is inherently extensible, as additional nodes can be seamlessly incorporated into the global calibration, without requiring the development of site-specific models. Building on this, [12] showed that a random forest global model could eliminate the need for separate per-sensor calibrations and still achieve decent accuracy at new sites (e.g. global model R^2 0.65 for NO_2 at unseen location). [13] co-located sensors at multiple reference stations, developed regression models with humidity correction at each site, and then applied the best model city-wide. The chosen model, a multi-linear regression, yielded reduced mean bias errors and RMSE. Once deployed across the whole city network, this calibration identified local PM_{10} hotspots that the sparse official monitors had missed. Overall, these network-wide calibration frameworks show promise in achieving more *transferable* corrections. They use pooled data from many collocations to train models that generalize better than single-site models, enabling consistent calibration of a distributed sensor network.

3) Spatiotemporal cross-validation (STCV) scheme

To rigorously evaluate the generalization capacity of the global calibration, a spatiotemporal cross-validation (STCV) procedure is employed. Under STCV, the test set consists of measurements collected at a designated evaluation site strictly after a specified timestamp, while the training set comprises data from all other sites strictly prior to that timestamp. This simultaneous isolation in both the spatial and temporal domains ensures that the model is neither exposed to the evaluation site during training nor provided with future information. Excluding historical data from the evaluation site validates the model's capacity to operate on unseen locations and on newly inserted sensors, while excluding future observations prevents exploitation of temporal autocorrelation. Collectively, STCV provides a robust validation protocol that demonstrates the feasibility of deploying the global calibration function to novel sites and sensors under real-world conditions.

III. Results and Discussion

To evaluate the applicability of the proposed global calibration framework, its performance was systematically compared against that of the ad-hoc (site-specific) calibration. In both cases, the Light Gradient Boosting Machine (LightGBM) algorithm was employed as the calibration function. LightGBM is based on gradient boosting, which builds an ensemble of decision trees sequentially — each new tree tries to correct the errors of the previous ones [14]. All available input features—namely the raw particle number bins and mass concentrations from both Plantower PMS5003 and Alphasense OPC-N3 sensors—were included to establish the final performance. The experiments were repeated across multiple train–test splits to assess robustness (Fig. 1).

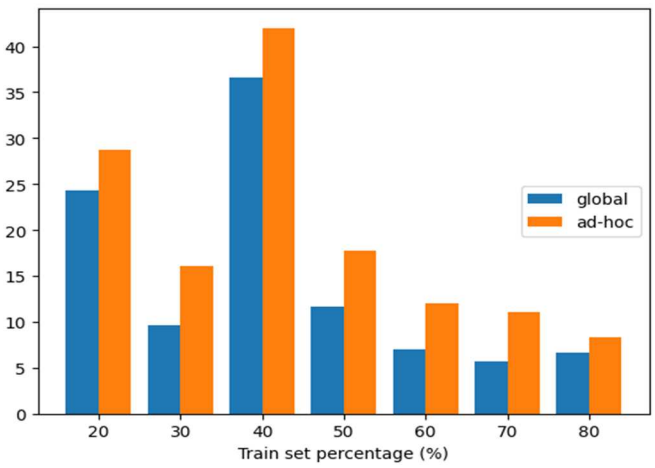


Fig. 1: Relative expanded uncertainty (REU, y-axis) at the limit value for PM_{10} LCS deployed across the Antwerp testbed, evaluated over several train-test splits (x-axis).

Fig. 1 illustrates the PM_{10} calibration results for the Antwerp LCSN and reveals a critical inflection point in the train-test split ratio. When training data were limited, the global calibration consistently outperformed the ad-hoc approach. For all splits, the REU at the LV=50 µg/m^3 remained below 25 %, meeting the criteria for complementary use alongside reference measurements (the daily LV of 50 µg/m^3 has been recently reduced to 45 µg/m^3 according to Directive (EU) 2024/2881, but is used here as a threshold for comparability with other relevant previous studies). As the amount of training data increased, the performance of both approaches improved, and with sufficiently large datasets their results converged, yielding nearly identical calibration accuracy. The contrast between single-point REU (Fig. 1) and full-range REU (Fig. 2-3) deserves careful interpretation. At the 20% training split, ad-hoc calibration (Fig. 2) exhibits performance degradation below 20 µg/m³ (and for some nodes above 50 µg/m³), with REU values exceeding 50% in these ranges. The mixed-shape error pattern of the REU plots, demonstrates low homogeneity in the calibration results across sensor nodes. In contrast, global calibration (Fig. 3) presents a more uniform shape of the REU plots, though still elevated at concentration extremes.

For the global calibration framework, two nodes (for concentrations above ~40 µg/m³) and three additional nodes (for concentrations above ~65 µg/m³) achieve Category 1 performance, continuously, in their upper concentration range, i.e. a total of five nodes. For the ad-hoc calibration, the total of nodes achieving similar performance is only two (for concentrations above ~50 µg/m³), with three additional ones demonstrating low but not stable REU values in their upper concentration range. This has profound implications for regulatory monitoring near ambient PM_{10} levels, where precise low-concentration measurements are essential for detecting compliance with the new EU limit reductions (45 µg/m³ from 50 µg/m³).

When the train-test split is 60-40 both ad-hoc and global calibration REU is within the acceptable range. Therefore, REU calculated at the LV alone can be misleading and the analytical behaviour on the full range of values is more appropriate to understand the behaviour of the calibration.

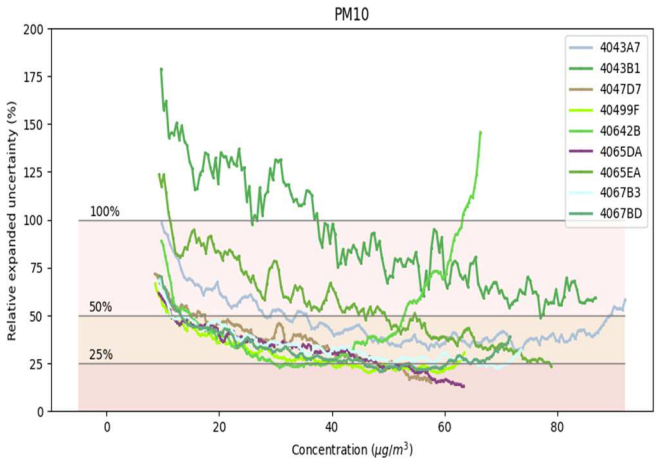


Fig. 2. REU plots over the full range of measurements (daily) for the ad-hoc/individual calibration corresponding to the 20 % orange bar in Fig. 1.

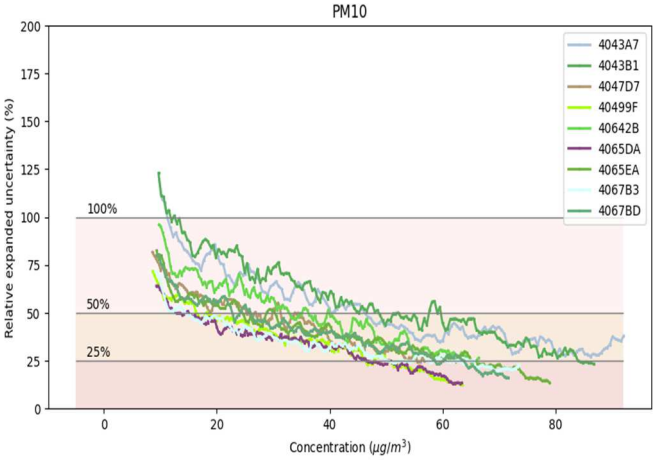


Fig. 3. REU plots over the full range of measurements (daily) for the global/network-wide calibration corresponding to the 20 % blue bar in Fig. 1.

IV. CONCLUSIONS

This study compared two PM_{10} LCS calibration strategies: ad-hoc (site-specific) and global (network-wide) approaches. Using data from large-scale LCSNs collocated with multiple reference instruments in European cities, we demonstrated that global calibration is feasible and, under data-sparse conditions, can outperform ad-hoc approaches. Importantly, both strategies achieved relative expanded uncertainty (REU) values below 25 % at the EU limit value for PM_{10}, satisfying the criteria for complementary use alongside reference methods.

A key finding is that evaluating REU solely at the limit value is insufficient for fully characterizing calibration performance. Full-range REU analysis provides a more informative perspective, revealing calibration weaknesses at specific concentration levels and across different sensors. While ad-hoc calibration remains effective when sufficient collocation data are available, global calibration offers enhanced stability across sites and improved scalability, making it particularly suitable for heterogeneous networks and for the integration of new sensors.

The results relate with ongoing discussions within CEN working groups regarding appropriate REU thresholds for different application classes. The convergence of ad-hoc and global performance at high data volumes suggests that REU thresholds could potentially be tiered based on available training data volume. This would facilitate sensor network deployment while establishing clear performance commitments as data accumulate and training/testing percentages can be altered.

The results of this study have direct relevance for air quality management and the deployment of sensor networks in urban environments. Global calibration provides a scalable solution that allows new sensors to be integrated into existing networks without the need for extensive site-specific collocations, thereby reducing operational costs and logistical complexity. The use of REU as a standardized evaluation metric further enables comparability across studies and alignment with European regulatory frameworks. Together, these advances facilitate the wider adoption of LCS as complementary tools to regulatory monitoring, supporting both policymakers and local authorities in achieving higher-

resolution air quality assessments and empowering communities with reliable environmental data.

The superiority of global calibration has relevance for developing countries and resource-constrained municipalities where extensive collocation studies are infeasible. By enabling knowledge transfer from reference-rich environments (like European cities with established regulatory monitoring) to new deployment regions, global calibration frameworks could democratize access to reliable environmental monitoring without proportional increases in operational costs.

Overall, this work highlights the value of global calibration frameworks in enabling robust and transferable correction functions for LCSNs, while reinforcing the importance of REU as a standard metric for calibration assessment. Future research should explore the integration of additional spatiotemporal features, advanced ensemble models, and long-term deployments to further validate the transferability of global calibration across diverse environments and pollutants.

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A Life Cycle Assessment of photovoltaic integration in future South Tyrol's energy scenarios

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Abstract—This study assesses the environmental performance of future energy scenarios involving increased renewable energy sources penetration, using the Life Cycle Assessment methodology. Standardized under the ISO 14000 series, life cycle assessment is a globally recognized approach for evaluating the environmental impacts of products or services throughout their entire life cycle. It considers both inputs from nature (such as materials, energy, and water) and outputs to the environment, including emissions and waste. This work aims to provide a comprehensive overview of how the environmental impacts may evolve in the transition from a fossil-fueled-based energy system to one dominated by renewable energy sources taking as reference a region in the northern Italy. A cradle-to-gate perspective is adopted, including resource extraction, manufacturing, and the operational phase of electricity generation and distribution. Environmental burdens are quantified across several midpoint indicators, including acidification, freshwater eutrophication, ecotoxicity, climate change potential, land transformation, and resource scarcity. The results highlight the potential of the energy transition paradigm to significantly reduce CO_2 emissions, while also drawing attention to the importance of monitoring other environmental impact categories (particularly those related to material use and resource availability) to ensure a truly sustainable transformation.

Keywords—life cycle assessment, energy transition, photovoltaic electricity production, grid integration sustainability

I. INTRODUCTION

The global shift toward renewable energy sources (RES) represents one of the most urgent challenges of our time. In particular, the energy system requires a deep revision both in its structure and its management to meet decarbonization targets [1–3].

The primary strategy adopted worldwide to decarbonize the energy sector is to increase the share of energy generated from RES, which offers clear advantages, especially in mitigating greenhouse gas (GHG) emissions. However, if not accompanied by comprehensive environmental impact assessments, this strategy risks being short-sighted. In the medium to long term, it may lead to the emergence of other types of impacts (social, economic, environmental, and political), potentially undermining the sustainability of the transition.

As energy systems evolve to integrate higher shares of RES, it becomes increasingly important to evaluate their environmental performance in future scenarios through robust and standardized methodologies that can deliver reliable, comparable, and transparent results.

The life cycle assessment (LCA), standardized under the ISO 14000 series [4] is the most widely used framework for evaluating the environmental impacts of products or services, and consists of four main phases: goal and scope definition, outlining the study's system boundaries, functional unit, and methodology; life cycle inventory (LCI), quantifying inputs from (materials, energy) and outputs to (emissions, waste) the environment; life cycle impact assessment (LCIA), evaluating potential environmental impacts; interpretation and analysis of the results.

In the literature, LCA is extensively used to assess the environmental impacts of various energy technologies, particularly photovoltaics (PV), although so far fewer studies have focused on energy systems as a whole and the broader environmental consequences of the transition itself. Most LCA studies on energy system scenarios found in the literature are conducted at the national level [5–12], with only a few addressing regional [13,14] or supranational scales [12].

The approaches commonly adopted are cradle-to-gate [8,9,13,14], which includes the environmental impacts from raw material extraction to energy production, and cradle-to-grave [5–7,10–12], which also considers the decommissioning and end-of-life phases of the different technologies.

Due to the complexity of this type of analysis, primary data on materials and energy inflows and outflows that go into the LCI are difficult to collect; therefore, for energy systems LCA, most of the time, secondary data are used, derived from third-parties databases, the most used one being the Ecoinvent database [5,6,8,9,12–14].

Regarding the LCIA methods and categories, a greater variety is observed. The most frequently used method is ReCiPe [6,10,12,13], followed by TRACI [7], CML-IA [11,13], Impact 2002+ [8], and the ILCD 2011 Midpoint+ method [9]. Consequently, the impact categories and indicators vary from study to study, depending on the chosen assessment method.

Most of these LCA studies on energy scenarios assess the environmental impacts in terms of different energy technologies, while only rarely is the grid infrastructure included [13,14]. However, as the share of RES in the electricity mix increases, grid infrastructure requires careful planning to avoid additional environmental impacts.

This analysis was part of the SustainGRID | Sviluppo di un framework di modellazione ed analisi dell'impatto del fotovoltaico nella rete elettrica dell'Alto Adige project financed by Fusion Grant 2022.

Therefore, this analysis aims to evaluate the environmental impacts of different energy scenarios, characterized by an increasing penetration of PV, in order to understand how it may affect the overall environmental performance, as well as quantify the contribution of the grid infrastructure. As a real case study, the South Tyrol region in northern Italy has been taken as reference, applying a cradle-to-gate approach. This choice is motivated by the fact that the decommissioning phase of energy technologies is not yet well developed across all sectors, and its inclusion would introduce a significant degree of uncertainty in the final results.

For the LCI, both primary data (related to the operational phase of energy production and distribution) and secondary data from the Ecoinvent database [15] have been used.

This analysis applies the environmental footprint (EF) method for LCIA, which enables the estimation of multiple environmental indicators, thereby supporting a comprehensive overview of the results.

Compared to existing literature, this work originates from the initiative of a local energy distribution system operator (DSO), who expressed the need to adopt a broader and long-term perspective in energy and grid planning and management. Therefore, the results of the analysis support the identification of current and future environmental hotspots, guiding low-impact development of energy production and distribution in future energy scenarios.

The paper is organized as follows: Section II provides the theoretical background and the main assumptions of the LCA analysis, following the steps recommended by ISO 14000 standards; Section III discusses the results and their implications for sustainable energy planning; finally, Section IV concludes the paper and provides recommendations for future research directions.

II. Methodology

A. Goal and scope

The analysis aims to assess the environmental performance of various PV development scenarios aligned with the energy and climate targets of South Tyrol, an Alpine region in northern Italy.

The scenarios are summarized in TABLE I, showing the electricity produced and distributed for each energy technology involved.

TABLE I. Distributed energy in South Tyrol for the different scenarios considered in this analysis.

	2022 [GWh]	**2030 [GWh]**	**2040 [GWh]**
Pumped-hydro storage	2.98	2.98	2.98
Hydro power (reservoir)	329.54	329.54	329.54
Hydro power (run-of-river)	314.17	314.17	314.17
Cogeneration (biogas)	9.29	4.18	4.18
Cogeneration (natural gas)	54.23	24.40	0
Cogeneration (wood chips)	72.52	32.63	32.63
Cogeneration (waste incineration)	76.33	76.33	76.33
PV	132.99	357.60	507.05
Total	*992.24*	*1142.03*	*1267.08*

The 2022 scenario represents the baseline, and the corresponding data on energy produced and distributed along the transmission and distribution grid are provided by the local DSO.

The 2030 scenario is based on Italy's national energy and climate plan [16], which targets a 55% reduction in CO_2 emissions. This target is achieved by proportionally reducing electricity from combustion-based power plants (natural gas, biogas, and wood). Electricity from cogeneration using municipal waste is maintained at a constant level, assuming continued waste processing needs in future years. Hydropower remains unchanged from the 2022 baseline, while PV increases according to the Italian "Aree Idonee" Decree [17], which sets a minimum RES capacity of approximately 804 MW in South Tyrol, nearly all covered by PV installations.

In the 2040 scenario, representing a RES-based energy system, natural gas is entirely phased out, while biogas and wood cogeneration remain at 2030 levels. Given South Tyrol's alpine geography, these cogeneration systems are expected to continue meeting energy needs in remote areas and valleys. Hydropower and municipal waste cogeneration remain unchanged. PV generation increases further compared to 2030, based on the 2040 scenario from the Italian transmission system operator (TSO), Terna [18].

All scenarios are assessed using a cradle-to-gate approach, and the functional unit is 1 kWh of AC energy generated and distributed along the transmission and distribution grid. Therefore, the grid losses are considered from high voltage (HV) to low voltage (LV) networks via transformer substations (HV/MV and MV/LV).

B. Life Cycle Inventory (LCI)

Primary data are used for the operational phase and determined as explained in the previous section. For raw material extraction and manufacturing, secondary data from the Ecoinvent [15] background database are used for all the technologies included in the scenarios.

The grid infrastructure losses are determined based on secondary data from the Italian electricity mix available in Ecoinvent. Three types of transformation losses are considered: MV/LV transformer losses of around 2.3%, applied to distributed energy from HV and MV networks; MV line losses of 0.3%, applied to distributed energy from HV and MV networks; and LV line losses equal to 2.1%, applied to total distributed energy, including PV, which is assumed to be connected only to the LV grid. The impacts related to the initial life cycle stages of the grid infrastructure are included in the model, assuming a certain number of kilometers of infrastructure per kWh of distributed energy as provided by the Ecoinvent.

C. Life Cycle Impact Assessment (LCIA)

The LCIA is performed through the software openLCA version 2.0.3 [19], following the EF method, from which eight different midpoint impact categories are derived.

In general terms, the impact of a specific category is estimated with the following formula

$$I_c = \sum_{i=1}^{n} (Q_i \times CF_{i,c}) \qquad (1)$$

where I_c is the impact of category c, Q_i is the amount of the flow i and $CF_{i,c}$ is the characterization factor for the flow i in the category c. For example, the global warming potential (GWP 100) impact category represents GHG emissions expressed in kg $CO_{2,eq}$ and is determined by multiplying the amount of a specific GHG by its characterization factor equivalent to its potential GWP at 100 years.

Human health impacts are assessed with human toxicity (HT), subdivided into carcinogenic and non-carcinogenic effects, which measures the potential influence of pollutants absorbed through air, water, and soil, quantified in comparative toxic unit for humans (CTUh), and particulate matter (PM), which quantifies the negative effects of PM emissions and their precursors (e.g., NO_x, SO_2), represented as disease incidence per kg of $PM_{2.5}$ emissions.

Additional categories included in this analysis to assess impacts on soil, water, and natural resources are land use (LU), which addresses the environmental consequences of occupying, changing, and managing land for human use, and the unit of measurement depends on the impact assessment method used; water use (WU), which considers water availability or scarcity in the region where the activity occurs, measured in m^3; and abiotic resource depletion potential (ADP), which covers non-biological resource use and is subdivided into ADP-fossil, quantified in MJ, and ADP-metals/minerals, measured in kg Sb_{eq}.

III. Results

In this section, the LCIA results are discussed in detail to compare the environmental performance of the different scenarios. The results are provided in TABLE II for all the impact categories and scenarios considered.

TABLE II. Scenarios' results of the impact categories considered in this analysis for 1 kWh of AC distributed electricity.

	2022	**2030**	**2040**
GWP 100 [kg $CO_{2,eq}$]	0.066	0.050	0.041
HT carcinogenic [CTUh]	$4.4 \cdot 10^{-11}$	$4.8 \cdot 10^{-11}$	$5.4 \cdot 10^{-11}$
HT non-carcinogenic [CTUh]	$1.2 \cdot 10^{-9}$	$1.7 \cdot 10^{-9}$	$2.1 \cdot 10^{-9}$
PM [disease incidence]	$3.2 \cdot 10^{-9}$	$2.9 \cdot 10^{-9}$	$3.3 \cdot 10^{-9}$
LU [-]	3.3	1.3	1.3
WU [m^3 world eq.]	1.2	0.4	0.4
ADP-fossil [MJ]	0.9	0.7	0.5
ADP-metals/minerals [kg Sb eq.]	$0.8 \cdot 10^{-6}$	$1.7 \cdot 10^{-6}$	$2.2 \cdot 10^{-6}$

TABLE II shows that the energy transition driven by increased PV penetration results in a reduction in most environmental impact categories considered.

Comparing the current 2022 scenario with the 2030 scenario, where PV generation rises from 133 to 358 GWh, an impact decrease is observed in categories such as GWP 100, LU, WU, and ADP-fossil. Conversely, some impacts increase, including ADP-metals/minerals, and HT, both carcinogenic and non-carcinogenic. These trends become even more pronounced in the 2040 scenario, where PV generation is expected to exceed 500 GWh.

Fig. 1 compares the distribution of environmental impacts by energy technology for the 2022 (a) and 2030 (b) scenarios, to clearly highlight the main contributors to each impact category.

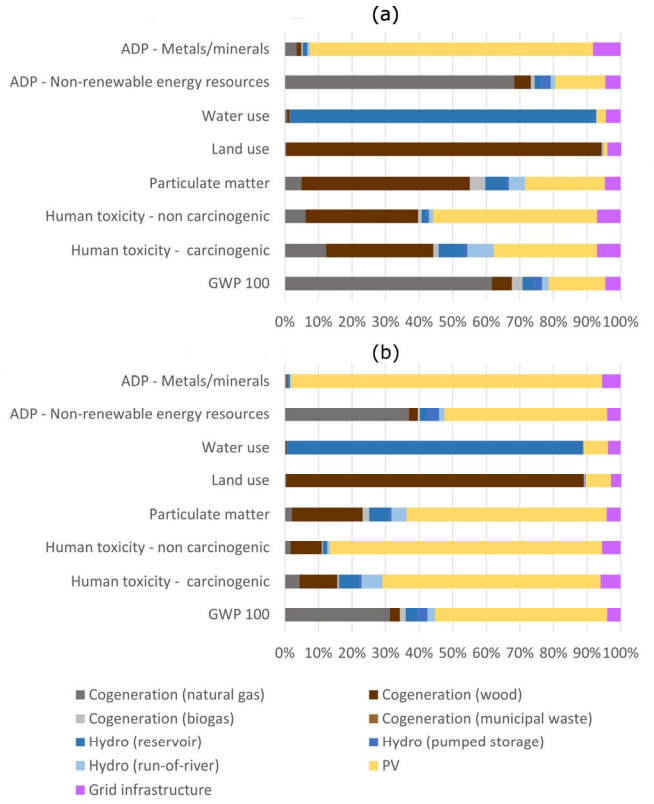


Fig. 1. Environmental impacts distribution in terms of energy generation technology of the 2022 scenario (a) and the 2030 scenario (b).

In the 2022 scenario, natural gas cogeneration is the main contributor to GWP 100 (62 %) and ADP-fossil (68 %). Wood-based cogeneration primarily affects HT (32 %), PM (50 %), and LU (94 %). Hydropower, especially reservoir-based, accounts for 91 % of the WU impact, while PV technology contributes 84 % to ADP-metals/minerals and 49 % to HT-non-carcinogenic. The grid infrastructure contributes, on average, 5.6 % to total impacts, with the highest share in ADP-metals/minerals (8 %) and the lowest in LU and WU (4.4 %).

In the 2030 scenario, the impact of PV becomes more prominent due to the significant reduction in electricity from cogeneration plants. Wood cogeneration and reservoir hydropower remain the main contributors to LU and WU, respectively. Natural gas cogeneration still contributes over 30 % to GWP 100 and ADP-fossil.

In the 2040 scenario, PV technology emerges as the dominant source of impact across nearly all categories. Hydropower and wood cogeneration continue to lead in WU and LU, respectively. Grid infrastructure impacts decrease to an average of 4.3 %.

From a life cycle perspective, Fig. 2 illustrates the distribution of GWP 100 impacts by technology and life cycle stage for the 2022 (a) and 2030 (b) scenarios.

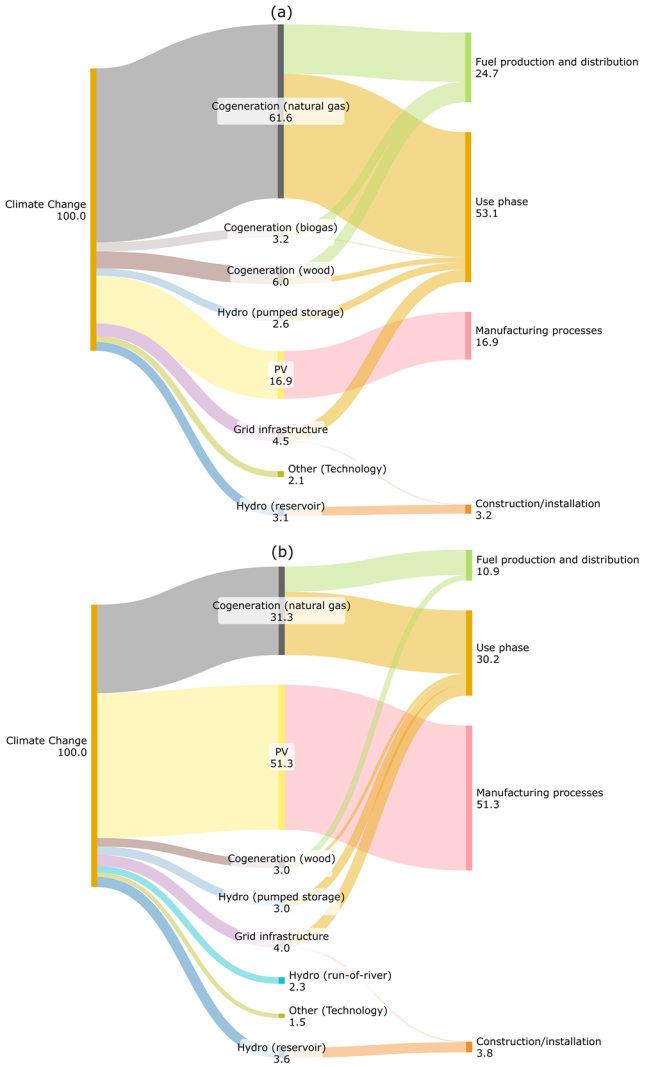


Fig. 2. Climate change impacts distribution of 1 kWh of AC distributed electricity, in terms of technologies and life cycle stages for the 2022 scenario (a) and the 2030 scenario (b).

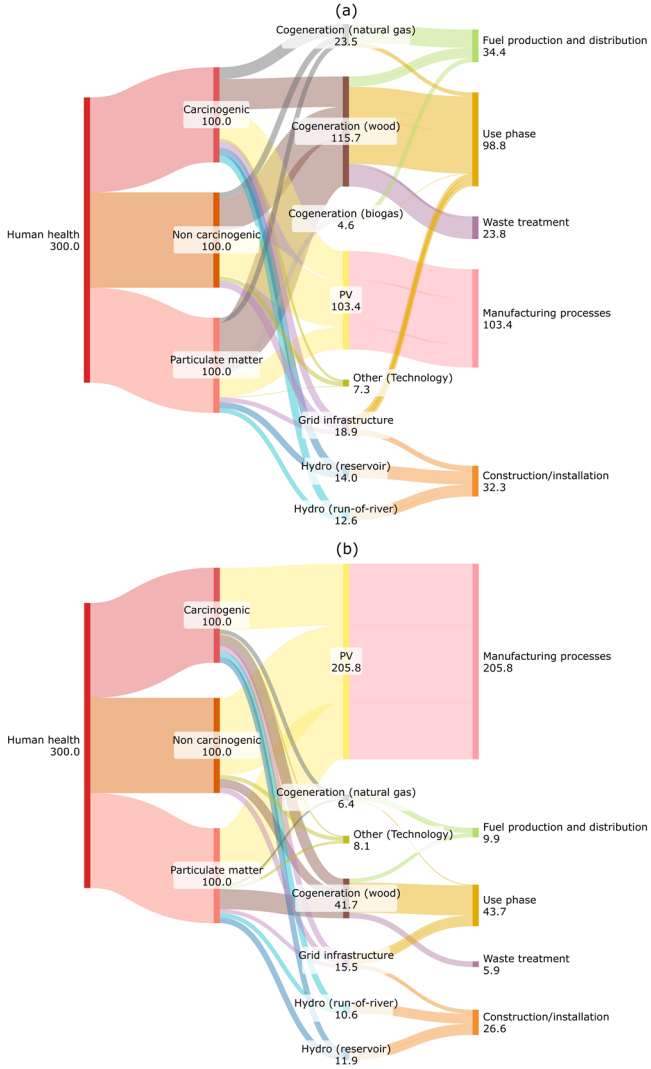


Fig. 3. Human health impacts distribution of 1 kWh of AC distributed electricity, in terms of technologies and life cycle stages for the 2022 scenario (a) and 2030 scenario (b).

In 2022 scenario, the use phase of natural gas cogeneration is the primary source of impact, accounting for over half of the total life cycle impacts in this category. Fuel production and distribution represents the second major source, with natural gas cogeneration contributing approximately 18 %. All PV-related impacts originate from the manufacturing phase, particularly the PV module, which alone accounts for 13 %. Hydropower reservoirs contribute mainly through their construction phase, while the grid infrastructure accounts for 4.5 % of impacts, primarily during the use phase due to the mix of energy flowing through it.

In the 2030 scenario, PV technology becomes the dominant contributor to GWP 100, responsible for over half of the impacts, followed by natural gas cogeneration at 31.3 %. As in 2022, the main contributors by life cycle stage are the manufacturing of PV components and the use phase of natural gas cogeneration. The grid infrastructure contributes around 4.4 %.

In the 2040 scenario, the role of PV manufacturing becomes even more significant, representing over 80 % of total impacts in this category. The grid infrastructure contributes less than 5 %.

The overall human health impacts for the 2022 (a) and 2030 (b) scenarios, along with their distribution across technologies and life cycle stages, are illustrated in Fig. 3. Human health is primarily affected by the use phase of wood cogeneration and the manufacturing processes of PV system components. In the 2022 scenario, wood cogeneration contributes approximately 24.1 % to HT-carcinogenic, 12.3 % to HT-non-carcinogenic, and 44.7 % to PM. Ash waste treatment from wood combustion adds 21.2 % to HT-non-carcinogenic. PV manufacturing accounts for 30.8 % of HT-carcinogenic, 48.9 % of HT-non-carcinogenic, and 23.7 % of PM. These impacts are mainly due to the PV module, followed by the inverter, balance-of-system (BOS), and mounting structures. The grid infrastructure contributes 7 % to HT and 4.7 % to PM, mostly during the use phase.

In the 2030 scenario, PV technology becomes the dominant contributor, responsible for 65.1 % of HT-carcinogenic, 81.1 % of HT-non-carcinogenic, and 59.4 % of PM. As in 2022, these impacts stem from the PV manufacturing process, followed by the inverter, BOS, and mounting structure. The grid infrastructure contributes 5.9 %

to HT-carcinogenic, 5.5 % to HT-non-carcinogenic, and 4.1 % to PM.

In the 2040 scenario, the contribution of PV manufacturing increases further, reaching 74.7 % for HT-carcinogenic, 86.3 % for HT-non-carcinogenic, and 68.4 % for PM. The grid infrastructure accounts for 5.4 % of HT-carcinogenic, 4.9 % of HT-non-carcinogenic, and 3.9 % of PM.

The impacts on soil, water, and natural resources in terms of technology and life cycle stages for the 2022 (a) and 2030 (b) scenarios are illustrated in Fig. 4.

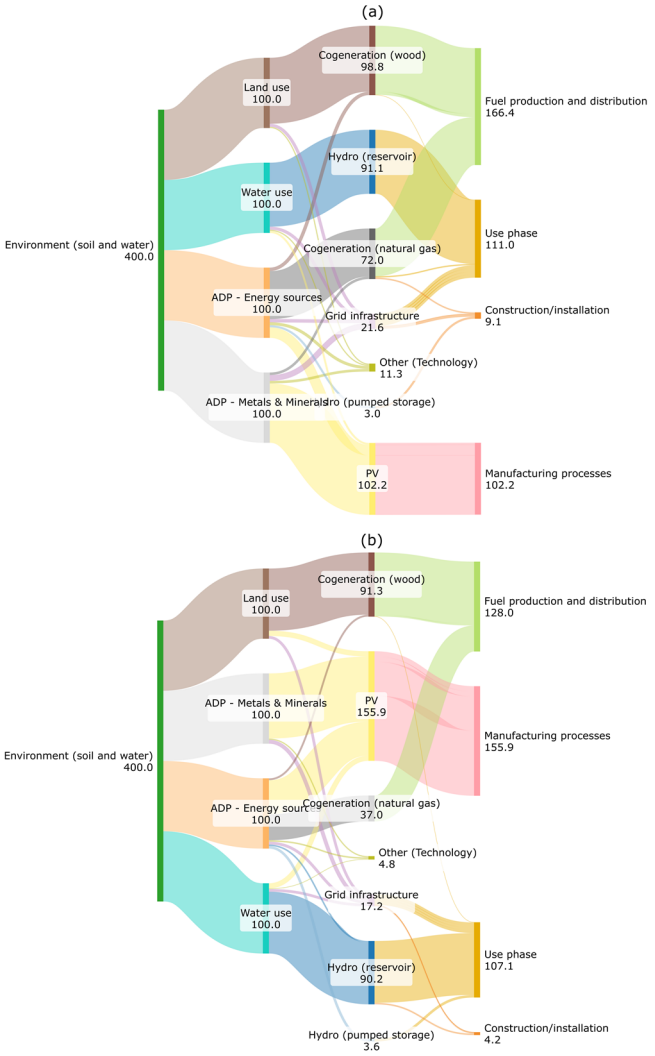


Fig. 4. Impacts distribution on soil, water and natural resources of 1 kWh of AC distributed electricity, in terms of technologies and life cycle stages for the 2022 scenario (a) and 2030 scenario (b).

It is possible to observe that, in this case, each midpoint impact category is clearly dominated by a specific technology and life cycle stage.

In the 2022 scenario, LU is primarily affected (93.9 %) by the fuel production and distribution of wood cogeneration. WU impacts are mainly due to the use phase of reservoir hydropower (91.1 %). ADP-fossil is influenced by the fuel production and distribution of natural gas cogeneration (68.1 %). Finally, ADP-metals/minerals is largely driven by the manufacturing processes of PV system components (84.4 %), subdivided into PV module manufacturing (34.5 %), inverter manufacturing (29.4 %), and BOS manufacturing (19.7 %). The grid infrastructure contributes approximately 4.4 % to LU and WU, 4.5 % to ADP-fossil, and 8.2 % to ADP-metals/minerals, respectively.

A similar distribution of impacts is observed in the 2030 and 2040 future scenarios.

IV. Conclusions

The environmental LCA of current and future energy scenarios in South Tyrol is conducted using the openLCA software and the Ecoinvent database.

Three scenarios are considered: a 2022 baseline, to assess the environmental performance of the current energy mix; a 2030 scenario, based on future local energy targets reached by adding a certain amount of PV; and a 2040 scenario, to evaluate the performance of a fully RES-based distributed energy mix. In all these scenarios, a cradle-to-gate approach is applied to all power generation technologies, as well as to MV and LV grid infrastructure. For the use phase, primary data are used to represent the amount of distributed electricity per technology. For the raw material extraction and manufacturing phases, secondary data from the Ecoinvent database are applied.

LCA results are evaluated using eight midpoint impact categories, derived from the EF method. The results of this study confirm that the energy transition toward a RES-based system is an effective environmental strategy to reduce the overall impacts of the energy sector. However, there remains a risk that some impacts may worsen if mitigation strategies are not implemented. For example, while combustion-based power plants currently dominate the GWP category, in future RES-based scenarios, PV technology becomes more influential due to its energy-intensive manufacturing processes. This outcome, however, is influenced by the energy mixes from the database, which do not account for future changes for the background processes. Moreover, the increasing penetration of PV may shift future priorities from reducing emissions to preserving the raw materials required for its production, a concern that is already emerging in recent years. From this perspective, recycling has proven to be an effective strategy to reduce environmental impacts, particularly by avoiding emissions during the extraction and production phases.

On average, the contribution of the grid infrastructure to the overall environmental impacts is around 5%-6%, and the use phase is the life cycle stage that contributes the most due to the energy type that flows through it.

To address the limitations of this study, future research should adopt a prospective LCA approach that accounts for changes in background inventories, allowing for the increasing penetration of RES in the electricity mix used for background processes. Additionally, a more detailed modeling of the grid infrastructure (considering its evolution, regional characteristics, and material composition) would help better capture its environmental relevance and support more accurate impact assessments in future scenarios.

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Probabilistic Models for Photovoltaic Production Forecasting: A Case Study at the Politecnico di Torino Campus

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***Abstract*—Forecasting energy production from renewable sources is essential for the effective management of electricity transmission grids. However, the intrinsic dependence of these sources on meteorological conditions introduces significant uncertainty. If the characteristics of a photovoltaic (PV) plant are known, deterministic models allow production to be estimated with a reasonable degree of accuracy. When these characteristics are unknown, these techniques cannot be used.**
Assuming the availability of historical data relating to generated power and meteorological data measured in the vicinity of the plant (such as irradiance and temperature), energy production can be estimated using probabilistic models. This paper, therefore, presents an analysis of this specific case at the Politecnico di Torino Campus. Established and recently developed Recurrent Neural Networks (RNNs) were trained on consumptive data to evaluate their strengths and limitations. The results were then analyzed to determine future actions with forecasting data.

***Index Terms*—Bidirectional Long Short Term Memory, Energy, Long Short Term Memory, Neural Networks, Photovoltaic Systems, Recurrent Neural Networks, Renewable Energy Sources, Solar Energy, Solar Power Generation.**

I. Introduction

RENEWABLE ENERGY PRODUCTION is a key point for making the modern society development compatible with the environment. Among the main technologies are photovoltaic (PV) panels, which convert solar energy into usable electricity, and wind turbines, which harness the energy in the convective motion of air (wind). The challenge of these technologies lies in their discontinuity, as they both depend on atmospheric conditions. The daily production of a PV plant is dependent on its own characteristics, such as the panel technology itself, the mounting angle and orientation of the panel, geographic position, and, of course, the day of the year, on which the Sun's trajectory depends. If these data are known, deterministic models can be created to estimate production. Unfortunately, these are not sufficient, since it also depends on the weather conditions, due to the capability of clouds to reflect into the space a part of the solar power, reducing the irradiance on the panels, and to a lesser extent, the temperature, whose increase reduces the conversion efficiency of the panels.

Deterministic models for PV generation define a straightforward relationship between the electrical output and weather variables, i.e., solar irradiance and module temperature. Unlike diode-based equivalent circuit approaches, which reproduce the entire current–voltage characteristics, these models avoid the need for detailed parameter identification and complex computations [1] [2] [3]. Although circuital representations may enhance accuracy at the device level, their higher complexity does not necessarily yield substantial benefits for large-scale energy forecasting. For this reason, simplified proportional models relying on irradiance and temperature are generally regarded as the most effective trade-off between accuracy and computational efficiency [4].

Since deterministic models require manual setup and detailed knowledge of the characteristics of the plant—which are not always available—this study adopts probabilistic models based on machine learning. It is considered a scenario in which such characteristics are entirely unknown, and only a small quantity of measured data is available. The goal is to understand the behavior of the Politecnico di Torino campus plant by relating Global Tilted Irradiance (GTI), G, and ambient temperature, T_a, to the produced power, P_{AC}. These insights will then be helpful in further developing such systems.

Typically, research papers present the methodology before the case study. In this work, however, the opposite approach was adopted: the plant characteristics and the available data are described first, followed by the methodology, including the data preprocessing steps. This order is designed to present a workflow tailored to the type of data available in the case study. By first outlining the context, as well as the nature, quality, and length of the dataset, the reader gains a more intuitive understanding of the data-processing pipeline, which ultimately prepares the data for use as input to probabilistic

models. The whole paper is then organized as follows. Section II discusses some of the more recent papers on the topic. Follows Section III, which reports the case study, and Section IV, which describes the proposed methodology. Subsequently, Section V presents the experimental results, while Section VI draws the conclusions.

II. Probabilistic Models for Forecasting the Photovoltaic Production Profile

In [5], two different Machine Learning (ML) approaches, Gaussian Process Regression (GPR) and Support Vector Machine (SVM), were tested to forecast the PV power using data coming from [6]. The time of day, solar PV panel temperature, solar flux, relative humidity, and ambient temperature were used as input variables. Matern 5/2 GPR obtained the best results, with a Root Mean Square Error (RMSE) of 7.967 kW, a Mean Average Error (MAE) of 5.3025 kW, and a Coefficient of Determination (R^2) of 0.98.

Another research on PV production is presented in [7]. Two PV systems, one located inside a research laboratory and the other on the roof of Qatar University, were used to acquire the needed measures for the task. Two ML algorithms, M5P regression tree [8] and Simple Linear Regression [9], were evaluated using RMSE, MAE, Root Mean Absolute Error (RMAE), Root Relative Squared Error (RRSE), and Relative Absolute Error (RAE). In the end, the first one turned out to be the most performing, at the expense of greater complexity.

In [10], Regression Tree (RT), Support Vector Regression (SVR), and Artificial Neural Network (ANN) ML methods were tested for day-ahead PV power predictions. Meteorological and PV operational datasets were acquired over a year at the University of Cyprus (UCY) external testing facility. RMSE, MAE, Mean Absolute Percentage Error (MAPE), and Skill Score (SS) were used to assess the obtained performance. The ANN achieved the best performance, obtaining a MAPE of 0.61%, an RMSE of 10.37W, an nRMSE of 0.76%, and a SS of 92.22%.

Two other popular ML algorithms, Decision Trees (DT) and Random Forest (RF), were tested in [11], always for PV power prediction, using a small dataset of which nine features were considered, including temperature, irradiance, Direct Current (DC) power, and DC voltage. In general, RF was capable of achieving the best results.

A more comprehensive work is [12], where the authors designed a trained Dynamic Bayesian Network (DBN) for forecasting the power production of a 40 MW PV plant composed of 182,880 solar panels. The training dataset contains records from the 10^{th} May 2020 to 9^{th} May 2021 (1 year) meteorological data, operational indicators, sensor data such as inverters temperatures, number of faulty inverter modules, inverter on/off status, curtailment (impossibility to deliver the produced power due to grid saturation) status and historical power data. Considering a one-day-ahead forecasting with a 1-month rolling window, a 69.0397 kW MAE, 137.4292 kW RMSE, 0.0603 Normalized Root Mean Square Error (NRMSE), and 0.94 R^2 were achieved.

III. Case Study

A. Photovoltaic System Description

This photovoltaic installation represents the most significant plant on the Politecnico di Torino campus, with a total installed capacity across multiple rooftops of approximately 1 MW. This system alone contributes 604 kW. The system was commissioned in 2015 and consists of 1,849 modules with a nominal efficiency of 21.1%. The overall installed capacity is 604 kW, with the modules mounted on a shed-type roof at a tilt angle of 30°, oriented southwest with an azimuth of 30° west of south, as shown in Fig. 1. The modules exhibit a thermal power loss coefficient of 0.38%/°C and a Nominal Operating Cell Temperature (NOCT) of 45 °C, in accordance with the specifications of the manufacturer. The system employs a distributed inverter architecture, featuring multiple DC/AC converters rated at 25 kW each. The plant is equipped with a dedicated monitoring infrastructure, including calibrated reference solar cells and three-phase energy meters for the collection of the plant's total production.



Fig. 1. View of the photovoltaic system installed on the rooftop of the Politecnico di Torino canteen.

B. Weather data measurements

The meteorological data are collected from a weather station located on the rooftop of Politecnico di Torino. The system measures global, diffuse, and direct irradiance on the horizontal plane. Global irradiance is monitored with a Class A pyranometer (ISO 9060 standard) operating in the spectral range 300–3000 nm, with a directional error below ± 20 W/m^2 at 1000 W/m^2 and an overall daily uncertainty within $\pm 5\%$ at 95% confidence. Diffuse irradiance is acquired through a second pyranometer equipped with an occultation device to remove the beam component, while direct irradiance is measured by a pyrheliometer aligned with the Sun by an automated tracker. The entire setup is periodically calibrated (every 2–3 years), and the tracking error on the incidence angle remains typically below $\pm 5\%$. Measurements are sampled every minute, averaged over 15-minute intervals, and stored in a local SQL database for further processing.

IV. Methodology

A. Problem Analysis

The problem discussed in this paper is in the form of an n-step prediction model expressed in the form:

$$\mathbf{y}_{t:t+n} = f(\mathbf{x}_{t:t+n}) \tag{1}$$

where:

- $f(\cdot)$ is the prediction function learned by the probabilistic model;
- n is the number of time steps to be predicted;
- $\mathbf{x}_{t:t+n} = [x_t, x_{t+1}, \ldots, x_{t+n}]$ are observations of the targets inputs (GTI G and ambient temperature T_a) over a look-back window k;
- $\mathbf{y}_{t:t+n} = [y_t, y_{t+1}, \ldots, y_{t+n}]$ is the model forecast power production P_{AC} from the plant. Given the relations, the model description can be simplified as follows:

$$\mathbf{P}_{AC} = f(\mathbf{G}, \mathbf{T}_a) \tag{2}$$

The model is trained on a dataset composed of past historical data of length $h > n$.

B. Preprocessing

First, the data was processed to ensure its full usability with probabilistic models. The first step involved a preliminary data correction. Then, to best balance the datasets and conduct reliable tests for different periods of the year, production variations were taken into account on a monthly basis. Subsequently, the data was organized into sequences suitable for the Recurrent Neural Network (RNN) models considered, eventually augmented, and finally normalized.

1) Preliminary data analysis and correction: The dataset time window considered for the task is from October 2022 to September 2025. An initial check was performed to ensure that the GTI was zero in the absence of natural light. For all available days, during the hours without natural light, which in Italy can reasonably be between 11:00 PM and 4:00 AM UTC (Coordinated Universal Time), the GTI values were set to exactly zero. The 15-minute data was then averaged over an hour to provide hourly granularity.

2) Dataset Balance and Monthly Variability: The available dataset was first grouped by the number of full days, which were then split into training, validation, and testing sets with respective percentages of 80%-10%-10%. This split was not randomized across the entire dataset; instead, a split approach based on monthly data was chosen to perform balanced tests and account for variability in seasonal and monthly energy production. Due to connection issues, blackouts, and other reasons, the dataset used for this work has some "holes": that is, it does not contain all the data for all the days present in the interval considered. For this reason, only 602 24-hour sequences are available, which is less than two years. In detail, there are 179 days available in the spring season, 87 days in summer, 111 days in fall, and 225 days in winter. It is worth noting that the winter season, which is typically the period of lowest production in Italy, presents data almost three times higher than the summer season, in which production tends to be higher. The dataset is therefore strongly unbalanced. Subsequently, the days were split between the train, validation, and test datasets based on the aforementioned split percentages.

3) Data Augmentation: After splitting the dataset into training, validation, and testing sets, the training dataset was either used as is or subjected to Data Augmentation (DA) techniques to overcome data limitations partially. Simple stochastic augmentation techniques were employed, including the injection of Gaussian noise and the application of multiplicative scaling factors to the irradiance–power relationship. These perturbations aimed to increase the variability of the training set, thereby facilitating more stable convergence of the probabilistic models.

4) Normalization: The variables of interest were normalized to fall within the range of 0 to 1. The normalization is defined as follows:

$$x_{i_norm} = \frac{x_i - min(x)}{max(x) - min(x)} \tag{3}$$

where x_{i_norm} is the obtained i^{th} normalized value, x_i is the original i^{th} value, $min(x)$ is the minimum value in the dataset, and $max(x)$ is the maximum value in the dataset.

C. Probabilistic Models

Seven different architectures were considered: Vanilla RNN, LSTM [13], GRU [14], BiLSTM [15], BiGRU, minLSTM [16], and minGRU. All of them are very suitable for the task at hand because they are architectures belonging to the family of RNNs, which, unlike normal Feedforward Neural Networks (FNN) or other similar networks, have the characteristic of being able to recur on the same neuron and, therefore, to memorize past inputs in order to make better predictions. While LSTM is a well-established architecture, GRU is a more recent and simplified version, which is, for this reason, usually better suited for analyzing shorter time series. Newer mathematical formulations for LSTM and GRU were presented in [16]. Such versions, called minLSTM and minGRU, have the following key changes concerning their counterpart:

- Hidden state dependencies, i.e., dependencies on previous time steps, have been removed, transforming the process from sequential to parallel.
- Functions for limiting the range of output values in traditional models, such as tanh and sigmoid, have been replaced by linear transformations, making calculations faster and easier.
- Training has been made more stable and efficient on long sequences by not scaling the output based on the sequence length.

These changes made minGRU and minLSTM significantly faster to train and less memory-intensive, while maintaining results comparable to or better than their classical counterparts and in line with more demanding alternatives, such as Transformers [17] and Mamba [18]. BiLSTM and BiGRU are the bidirectional versions of the LSTM and GRU architectures, which means that they process the input sequence not only from the bottom to the top of the network, but also in the opposite direction.

Since minLSTM and minGRU are novel approaches, it was also decided to use the classical LSTM and GRU models to compare the results obtained by the reduced and classical versions in this particular task.

The seven different models were tested, considering $n = 24$, which corresponds to a full day. The following structure has been adopted for all models:

- Stacked m-layer RNN each having a hidden layer of k units and a dropout of $d\%$, where the number of stacked layers m was set from 1 to 4, the size k of the hidden layers were powers of two from $2^4 = 16$ to $2^9 = 512$, and the dropouts d were from 0% to 30% in 5% increments.
- 1 Fully Connected (FC) layer having the same size as the hidden layers neurons, doubled in the case of BiLSTM and BiGRU.

D. Hyperparameters

The following hyperparameters were tested to train the models:

- Learning Rate (LR): 0.5, 0.25, 0.1, 0.075, 0.05, 0.025, 0.01, 0.0075, 0.005, 0.0025, 0.001, 0.0005, 0.0001
- Batch Size (BS): 256, 128, 64, 32, 16, 8.
- Number of epochs: 2000.
- Optimizer: Nadam [19].
- Loss Function: Huber.

After a preliminary analysis of the LR, it was noted that the learning curve was better, and training progressed better, with a learning rate between 0.1 and 0.01. For this reason, several experiments were performed by increasing the LR values around these values. The Huber loss function combines the characteristics of RMSE and MAE, thus penalizing large errors like the former, while being robust to outliers like the latter. Its mathematical formulation is as follows:

$$L_\delta(r) = \begin{cases} \frac{1}{2}(y_i - \hat{y}_i)^2 & \text{if } |y_i - \hat{y}_i| \leq \delta, \\ \delta(|y_i - \hat{y}_i| - \frac{1}{2}\delta) & \text{otherwise.} \end{cases}$$

where y_i is the true observed value at time i, $\hat{y}_i$ is the predicted value at time i, and δ is a positive threshold parameter, controlling the loss transitions from quadratic to linear.

Having a large number of epochs significantly increases training time and, if the network stops learning, may even be unnecessary. To overcome these problems, it was decided to implement an early stopping strategy with the following parameters:

- Metric monitored: Validation Loss.
- Patience (number of epochs without improvement before the training is stopped): 15.
- Delta (minimum performance increase considered meaningful from the baseline): 0.0001.

An LR reduction strategy has also been implemented to try to continue training in case the Validation Loss is not improving:

- Metric monitored: Validation Loss.
- Mode: minimum (the LR is reduced once the monitored metric stops decreasing).
- Factor (proportional reduction factor applied to the LR): 0.5.
- Patience (number of epochs without improvement before the LR is decreased): 4.
- Cooldown (minimum number of epochs to wait before executing another LR reduction): 2.
- Threshold (sensitivity threshold for identifying meaningful updates to the optimal value): 0.0001.

To ensure maximum reproducibility between the different tests performed, a fixed seed was set for the main libraries used: numpy [20], pandas [21], [22], and pytorch [23].

E. Indicators

Several Key Performance Indicators (KPIs) were used to evaluate the performance of the probabilistic model:

- RMSE, which can be obtained by taking the square root of the Mean Squared Error (MSE). It penalizes larger errors more, preventing them from dominating. Its mathematical formulation is as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

  where n is the number of samples (time steps).
- MAE, which measures the average magnitude of the error in a set of predictions. It provides a simple and intuitive measure of how far predictions tend to be from the true values. The lower it is, the better the model performs. It is defined as follows:

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i|$$

- MBE, which indicates whether the model systematically underestimates (positive MBE) or overestimates (negative MBE) the observations. It is essential to note that an MBE of zero does not guarantee accurate model performance, as it merely indicates that the errors tend to cancel out on average. It is defined as follows:

$$\text{MBE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)$$

- R^2, which indicates how well the model fits the data. It ranges from 0 to 1, where zero indicates that the model performs no better than the average prediction, while one indicates that it makes perfect predictions. It is defined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

  where $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$ is the mean of the observed values.

V. Experimental Results

The results obtained are presented in Tables I and II, which displays direct and clipped outputs, i.e., those whose value is constrained between the minimum and maximum energy production values observed during training. The minimum value is set to zero, as energy production is assumed to be always positive. For the clipped values, the upper and lower values returned by the networks are therefore reported within

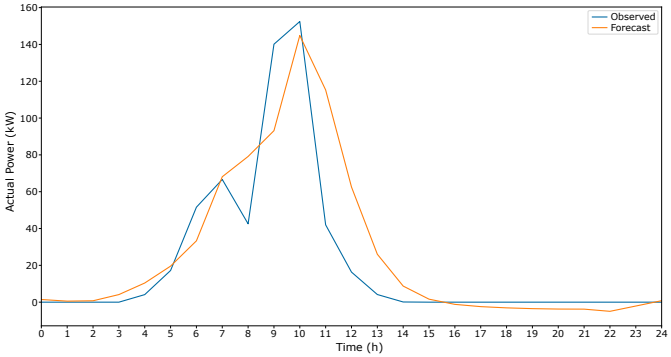


Fig. 2. Predicted LSTM measurements compared to those observed on a cloudy day, without clipping the night hours.

this range. What can be observed is that this effect generally tends to have positive effects on some metrics, but at the same time, it tends to degrade others, particularly the MBE. Therefore, for completeness of information, Tables I and II report both cases. Examining the results, it is evident that LSTM outperformed the other models for all KPIs of interest, followed by GRU and BiGRU.

The hyperparameters used to obtain the best KPI for each probabilistic model are reported in Table III. It can be seen that training benefited mainly from a low BS, especially for a value equal to 16, except in two cases. Furthermore, only a small number of cases have benefited from DA, so this aspect should be further investigated.

An example of a cloudy day forecast performed with the best trained probabilistic model, the LSTM, is shown in Figure 2. It can be seen that the model provides a reliable representation of daily production, even in the harsh case of a cloudy day. However, it lacks accuracy in tracking the actual trend of daily production.

VI. Conclusions

This research work was useful for assessing the behavior of the probabilistic models, particularly RNNs, when trained using a small amount of data. The results obtained are good, but they do not seem sufficient to describe physical behavior as accurately as possible. To address this issue, statistical DA techniques have been attempted, but the results do not demonstrate significant benefits. In the future, the use of these DA techniques could be further explored by attempting to use existing data to generate more plausible and physically based perturbations, such as algorithms to correlate power and irradiance better, estimate cloud passage, estimate the temperature of the plant site based on time and year, and more. This solution comes at the cost of losing the ability to forecast power data without knowing the physical characteristics of the plant, such as its geographic location and panel inclination. Additional input variables could also provide more insight into the time of year, passing clouds, and other factors, allowing networks to better adjust for seasonal variations. Future work will continue to explore this research theme in greater detail and will benefit from the findings presented here.

TABLE I
Comparison of the best KPI obtained with the probabilistic models considered

	Normal Outputs			
Model	**RMSE (kW)**	**MAE (kW)**	**MBE**	**R^2**
Vanilla RNN	52.779	28.898	4.074	0.746
LSTM	**38.602**	**19.50**	**0.084**	**0.864**
GRU	42.879	21.92	-0.142	0.852
BiLSTM	43.856	21.414	2.635	0.824
BiGRU	41.467	23.33	0.919	0.843
minLSTM	46.831	23.69	3.94	0.8
minGRU	49.763	28.429	-0.279	0.774

TABLE II
Comparison of the best KPI obtained with the probabilistic models considered using clipped outputs

	Clipped Outputs			
Model	**RMSE (kW)**	**MAE (kW)**	**MBE**	**R^2**
Vanilla RNN	52.663	28.224	4.748	0.747
LSTM	**38.534**	**19.32**	**0.095**	**0.875**
GRU	42.852	21.349	0.429	0.853
BiLSTM	43.856	21.408	2.641	0.824
BiGRU	41.281	21.862	2.387	0.845
minLSTM	46.826	23.565	4.066	0.8
minGRU	49.761	28.396	-0.247	0.77

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TABLE III
Comparison of the hyperparameters used to obtain the best probabilistic models

Model	**Train Loss**	**Val Loss**	**LR**	**BS**	**SL #**	**HS**	**Dropout**	**DA**
Vanilla RNN	0.31527	0.2428	0.075	16	1	128	0	N
LSTM	**0.06458**	**0.06835**	0.0025	16	2	128	0.2	N
GRU	0.07182	0.07483	0.1	32	2	256	0	N
BiLSTM	0.13462	0.1528	0.05	16	2	128	0.15	Y
BiGRU	0.14299	0.17153	0.075	16	1	128	0	N
minLSTM	0.20751	0.22478	0.075	16	2	256	0.15	Y
minGRU	0.31527	0.2428	0.075	16	2	256	0	N

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Star-Shaped SOI-AlN MEMS Thermoelectric Generators for Enhanced Thermal Gradient Conversion

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***Abstract*— This paper presents a novel MEMS-based thermoelectric generator (TEG) fabricated on an SOI substrate with an embedded AlN dielectric layer. The design exploits residual stress from micromachining to induce a spatial separation between hot and cold regions, thereby enhancing the thermal gradient. This novel design, presented here for the first time, enables the creation of a spatial separation between the hot and cold regions by inducing an upward deflection of the tip of a released structure, thereby maximizing the thermal gradient within the microsystem. The conceived device exhibits a sensitivity of approximately 0.06 mV/°C per unit through the Seebeck effect between a 1.02 µm Al/Cr metallic layer and a 10 µm doped silicon layer, electrically insulated from each other by a 0.5 µm AlN dielectric. It is important to highlight that the adopted fabrication technology not only enables thermoelectric conversion, but also supports the integration of additional functional elements, such as piezoelectric transducers, by exploiting the same AlN layer. This multifunctional use of materials allows for significant optimization in terms of area, material consumption, and fabrication costs. The proposed thermoelectric microsystem has been designed, fabricated, and experimentally characterized, demonstrating the suitability of the MEMS structure for energy harvesting and sensing in various domains, while also considering sustainability aspects in transduction systems, including industrial monitoring, wearable electronics, biomedical systems, and automotive applications.**

Keywords—MEMS, SOI-AlN, Star-Shaped TEGs, Thermal Gradients, Thermoelectric generator.

I. INTRODUCTION

Over the past decade, significant research efforts have been devoted to exploring sustainable solutions in the field of sensors and transducers, using naturally occurring materials and biopolymers [1-4] , while also addressing power budget constraints through low-energy solutions and the development of innovative MEMS designs aimed at reducing the overall power consumption of electronic and sensing systems [5–7]. There is growing demand for low-power and generating sensors also capable of operating autonomously with minimal maintenance by incorporating energy harvesters, converters, and appropriate power conditioning circuits [8,9].

Focusing on thermal energy and temperature gradients, thermoelectric generators (TEGs) are widely used, and the literature shows a growing trend in the development of new materials, designs, topologies, and technologies to improve their performance. The primary objective of recent developments is to increase energy conversion efficiency while minimizing device size [10,11]. Notably, the integration of MEMS, NEMS, and VLSI circuits into compact, low-power devices has been made possible through SOI substrates [12] and CMOS technologies, enabling long-term stability and cost-effective, large-scale manufacturing of portable and wearable electronics [13,14]. From an integration perspective, recent literature reports progress in both transducer design and conditioning circuits [15]. Among integrated-scale transducers, one promising solution involves the use of TEGs. Various studies have focused on enhancing materials [16], exploring three-dimensional structures [17], and developing high-efficiency configurations. For example, in [18], the authors presented a CMOS-MEMS TEG that achieved a linear output of 9.51 mV/K per thermocouple.

The standard 0.35 µm CMOS technology, widely used for integrated electronics, has increasingly been adopted for TEG development. In [19], a CMOS-MEMS TEG comprising 24 thermocouples was fabricated, achieving 67 µV at a 1 K gradient.

Increasing the number of thermocouples enhances the system's performance, as demonstrated in [20], where a generator using over 30000 thermocouples reached 16.7 V and 1.3 µW under a 5 K gradient.

Numerous solutions have been proposed to enhance the features and design of TEG converters. For instance, in [21], micromachined CMOS-based TEGs were fabricated as on-chip power supplies, delivering millivolt-level voltages and approximately 1 µW of power under a 10 K temperature gradient.

Research on TEGs is still expanding, with open directions involving micromachined thermopile optimization, targeted wearable applications, and efforts to increase power density [22]. Technological exploration is also moving beyond CMOS to include alternative platforms, such as SOI-based substrates. In this context, [23] demonstrated a BESOI-based MEMS TEG, which used thermal resistance differences to create localized temperature gradients, achieving approximately 900 µV from both internal and external thermocouples, confirming the feasibility of implementing TEGs using standard MEMS fabrication processes.

This work advances the state of the art by introducing, for the first time, a TEG that exploits spatial temperature separation achieved through the residual stress induced during microfabrication. This stress causes an upward deflection at the tip of a suspended structure, effectively creating distinct hot and cold regions and maximizing the

thermal gradient within the microsystem. Notably, the fabrication process not only enables efficient thermoelectric energy conversion, but also supports the integration of additional functional components, such as piezoelectric transducers, by leveraging the same aluminum nitride (AlN) layer. This multifunctional use of materials leads to substantial gains in terms of area efficiency, reduced material usage, and overall fabrication cost.

II. Working Principle and Device

The MEMS device developed for thermoelectric energy conversion is based on the Seebeck effect occurring between an Al/Cr metallic layer and a doped silicon layer, which are electrically insulated from each other by an AlN dielectric layer. The generated voltage V across a thermoelectric couple is given by [24]:

$$V = \alpha . \Delta T \quad (1)$$

where: α is the Seebeck coefficient (V/K) and $\Delta T = T_{hot} - T_{cold}$ is the temperature difference across the thermocouple. It is clear from the relationship that an increase in temperature difference or gradient leads to an increase in the output voltage.

Unlike other solid-state TEGs reported in the literature, this structure deliberately exploits the residual stress resulting from micromachining processes, typically considered undesirable, to realize a cantilever-based system capable of experiencing two different temperatures between its anchor point and free end. The cantilever tip is specifically designed with a star-shaped geometry, where the arms are elevated due to residual stress and staggered to enhance natural convection, increase the active surface area, disrupt the thermal boundary layer, and promote airflow turbulence, thereby improving thermoelectric conversion efficiency. This approach enables the creation of a larger thermal gradient by spatially separating the hot and cold regions. The system can function both as an energy harvester and as a sensor for detecting thermal gradients.

Another strength of the proposed MEMS lies in the integration of an embedded AlN layer, which can be used not only as an electrical insulator for the TEG but also as a piezoelectric material, allowing the development of a multi-sensing system on the same chip. This integration leads to savings in chip area, production costs, and material usage.

It is worth noting that this technology also enables the implementation of kineto-electric transducers within the same die. Although this aspect goes beyond the scope of the present paper, it clearly demonstrates the added value and versatility of the proposed technology. The designed device (see Fig. 1), appropriately scaled to the micrometer range in order to meet microfabrication constraints while simultaneously increasing the number of devices per die, thus enabling their combination in series, has a length of 4000 µm, a width of approximately 1000 µm, and a beam width of 193 µm. The star-shaped structure, as previously mentioned, was intentionally designed with an asymmetric geometry at its terminal parts, featuring widths of 100 µm and 193 µm. The figure also shows the anchored section and the tip which, due to residual stress, will bend upward once released, thereby increasing the thermal gradient.

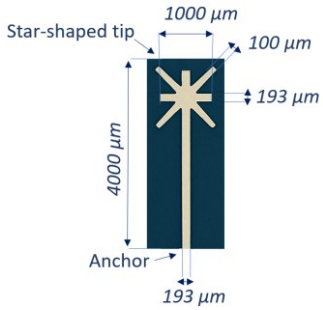
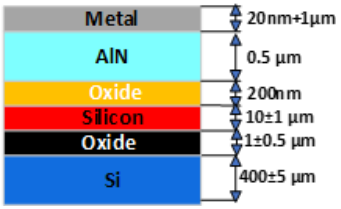


Fig. 1. Schematization of the conceived Star-Shaped SOI-AlN MEMS TEG

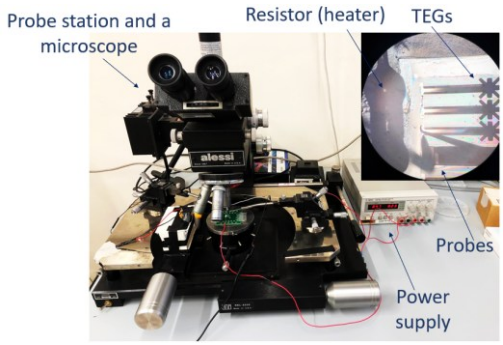
III. Fabrication Technology and Setup

The MEMS fabrication process is based on an SOI (Silicon-on-Insulator) substrate consisting of a 400 µm ± 5 µm thick silicon handle layer, a 1 µm ± 0.5 µm buried oxide layer (used as an etch stop), and a 10 µm ± 1 µm doped top silicon layer as seen in Fig.2(a) [25]. On top of this substrate, a ~0.5 µm thick AlN layer is deposited, electrically isolated by a ~200 nm oxide layer. To establish electrical contact with the top surface of the AlN, a conductive Al/Cr (aluminum/chromium) metal layer, with a thickness of 1 µm + 20 nm, is deposited. The fabrication process uses five photolithographic mask levels and starts with an n-type SOI wafer, where the top silicon layer is doped using a phosphosilicate glass (PSG) film and subsequently annealed at high temperature. After removing the PSG, a 200 nm thermal oxide layer is grown, patterned via lithography, and etched using Reactive Ion Etching (RIE). Next, the AlN layer is deposited and chemically etched to define the active piezoelectric structures. This is followed by the deposition of the Al/Cr metal layer, patterned using a liftoff technique to form the electrical contacts. The top silicon device layer is then etched using Deep Reactive Ion Etching (Deep RIE) with an optimized Inductively Coupled Plasma (ICP) process to prevent undercutting at the buried oxide layer. After applying front-side protection, the wafer is flipped and etched from the backside using an additional mask. The bottom oxide and silicon handle layers are etched through to form via holes. Finally, the buried oxide is selectively removed to release the suspended mechanical structures in the top silicon layer.

The experimental setup involved contacting the DIE using a probe station and a microscope as shown in Fig.2(b). To characterize the device, a resistor of 39 Ω used as a heater was placed at the anchor of the structure. An Agilent E3630A power supply was employed to power the resistor and heat it up. A Fluke VT02 thermometer, with accuracy of ±2% was used to measure the temperature on the MEMS, and the output of the TEG was measured using an HP 34401A digital multimeter with accuracy of ±0.0035%.



(a)



(b)

Fig. 2. Fabrication process of the SOI-AlN MEMS (a), experimental setup, and a zoomed-in view of the fabricated device in the inset. A residual stress-induced tip deflection of approximately 260 µm was measured, resulting from the specific structural design (b).

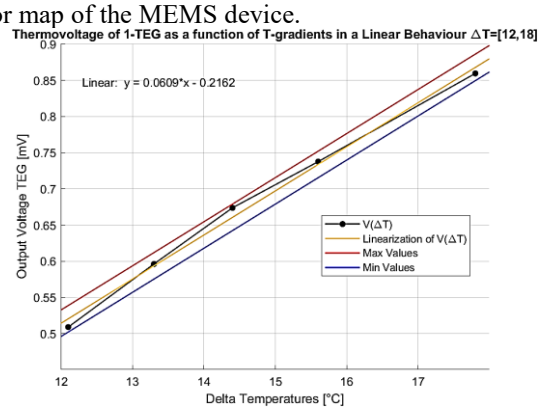
IV. RESULTS AND DISCUSSION

In order to characterize the MEMS device, a single element was analyzed, and the effect of connecting a second element in series was studied. The investigation was carried out using the setup described in Section 3. Repeated 10 measurements were performed, and the mean value and standard deviation were estimated for each operating condition. The temperature was controlled by applying a voltage across the heating resistor, and output voltage measurements were recorded repeatedly.

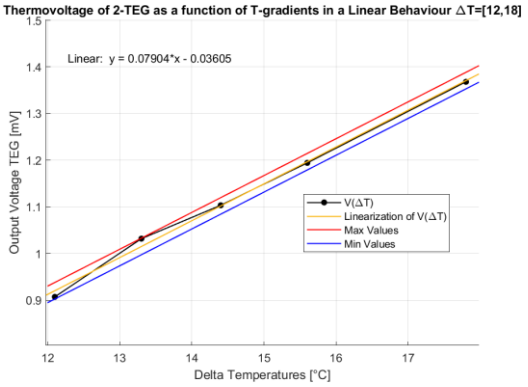
Fig. 3 shows the characterization results for a single TEG element and for two elements connected in series. The range of thermal gradients considered, corresponding to a linear response of the MEMS, is approximately 12–18 °C.

This graph represents the calibration curve, based on the behavior of the TEG. The black markers indicate the data point obtained from the measurements; the yellow line represents the linear interpolation of the measured data, with the corresponding model shown in the graph. The red points indicate the maximum output values observed, while the blue points represent the minimum values.

The obtained results evince a single TEG element exhibits a sensitivity of ~0.06 mV/°C, producing up to 0.85 mV at 18 °C. When two elements are connected in series, the output rises to ~1.37 mV, with an estimated maximum power of ~2 pW. Fig. 4 shows the thermal distribution corresponding to the minimum applied thermal gradient. The heating resistor is clearly visible, as is the temperature color map of the MEMS device.



(a)



(b)

Fig. 3. Calibration diagram of a single TEG (a) and two elements in series(b)

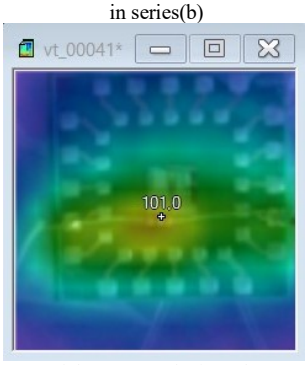
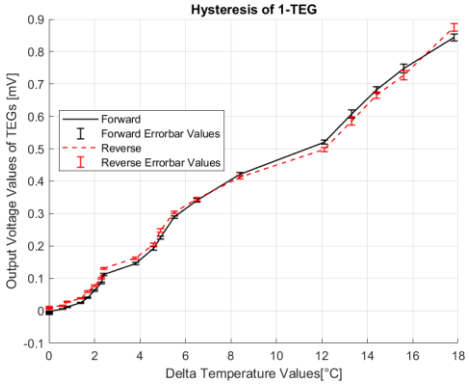
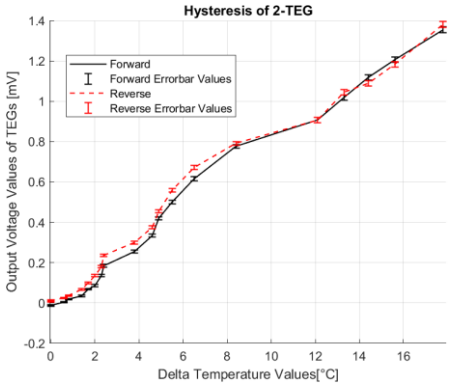


Fig. 4. Color map of the MEMS device when a temperature of approximately 38 °C (~101 °F) is applied. The minimum observed temperature corresponds to 26 °C

In order to investigate possible hysteresis effects associated with the heating and cooling phases of the applied thermal gradient, the analysis was conducted over a gradient range of 0–18 °C. Specifically, Fig. 5 shows the results for a single TEG and for using two devices connected in series. Repeated 10 measurements were taken into account, and the graphs display the mean values, with variability bands of the measured data. The results indicate that the trends observed during the heating and cooling phases are nearly identical, suggesting a high degree of compatibility between the two. These findings demonstrate the suitability of the MEMS structure as a transducer for thermal gradient sensing or for energy harvesting, with potential applications in various fields including industrial monitoring, wearable electronics, biomedical systems, and automotive technologies.



(a)



(b)

Fig. 5. Hysteresis study for a single element (a) and two elements in series (b)

Table 1 presents a comparison of the features of this work with those of previously published MEMS TEG devices.

TABLE I
COMPARISON OF PROPOSED WORK WITH OTHERS

Device / Type	ΔT °C or K	Output Voltage	Output Power	Device Size	Ref.
Two MEMS TEG (Al/Cr–Si with AlN dielectric)	18	1.37 mV	2 pW	0.78 mm²	This work
CMOS-MEMS micro-TEG (polysilicon thermocouples) Measured	1	67 µV 96 µV	0.46 pW 0.94 pW	0.7225 mm²	[19]
Planar thermocouples, MEMS	25	0.9mV	NA	49 (die), 36 (membrane), 0.25 (hole)	[23]
Ultrathin MEMS TEG with Sb_2Te_3/(Cu,Ag,Au,Pt) multilayers	4	0.5mV	NA	~1 µm thick; >46,000 P–N modules in series	[24]
CMOS-MEMS TEGs	3	0.9 mV	0.05 pW	1.5 mm²	[26]

V. CONCLUSION

This research demonstrates the effectiveness of MEMS based thermoelectric generator fabricated on an SOI substrate with an embedded AlN dielectric layer exploiting residual stress to maximize the thermal gradient across the structure. Experimental characterization demonstrated and output voltage of 0.85 mV for a single TEG at maximum temperature difference of 18 °C. When two star-configured TEGs were connected in series, the output increased to approximately 1.37 mV corresponding to a maximum generated power of ~2 pW. The device exhibits a higher thermal gradient per unit area, improved output power density, and strong compatibility with standard SOI MEMS processes. Furthermore, the use of AlN not only supports thermoelectric conversion but also enables the integration of piezoelectric transducers, thereby reducing fabrication complexity and material consumption. These results confirm the suitability of the proposed thermoelectric microsystem for energy harvesting and sensing applications in industrial monitoring, biomedical devices, wearable systems, and automotive technologies.

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A Hybrid 6-DoF Pose Measurement System Using String Potentiometer and Dual IMUs

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***Abstract*—With the advancement of technology, six-degree-of-freedom (6-DoF) pose measurement plays an essential role in spatial metrology, yet existing methods often involve trade-offs between accuracy, cost, and deployment complexity. In particular, optical and inertial systems may require line-of-sight, extensive calibration, or high power consumption, limiting their use in resource-constrained settings. This paper proposes a novel hybrid 6-DoF measurement system that integrates a string potentiometer with dual inertial measurement units (IMUs). By combining cable extension sensing with orientation data through geometric modeling, the system enables real-time pose estimation without the need for external infrastructure. To validate the approach, experiments were conducted on objects with diverse geometries, including linear, angular, and curved features. The results show that the system consistently achieves millimeter-level spatial accuracy under standard indoor conditions, which suggests that the proposed method offers a practical and sustainable alternative for portable 6-DoF tracking. It may also inform the development of low-cost measurement tools in applied metrology.**

***Index Terms*—Low-Cost Pose Measurement, Inertial Measurement Unit (IMU), String Potentiometer, 6-DoF Input**

I. Introduction

Spatial pose measurement tools capable of capturing all six degrees of freedom (6-DoF), comprising 3 translational and 3 rotational axes, are becoming increasingly critical in applications such as precision engineering, structural inspection, and industrial metrology. Accurate 6-DoF measurements enable full pose tracking of tools, surfaces, or mechanical components, which is essential for real-time calibration, geometric analysis, and task execution in complex spatial environments.

Traditional contact-based measurement tools [1]–[3] remain essential in precision metrology but rely on physical contact, linear alignment, and skilled manual operation. Designed mainly for benchtop or factory use, they usually provide only positional or single-axis data, lacking portability and real-time pose feedback [4]. This limitation becomes critical for large-scale or in-field measurements requiring flexible operation and immediate spatial feedback. To overcome these limits, high-performance 6-DoF tracking systems have emerged. Optical systems such as Vicon [5] and OptiTrack [6] achieve sub-millimeter accuracy for motion capture, while electromagnetic trackers eliminate line-of-sight dependence [7]. Inertial measurement units (IMUs) offer compact and low-latency sensing, and hybrid methods like visual–inertial and UWB–IMU fusion enhance robustness under varying conditions [8].

However, these advanced solutions often require costly infrastructure and calibration. Optical systems demand clear sightlines and controlled lighting; electromagnetic systems are affected by magnetic interference [9]; and IMUs suffer from long-term drift [10]. Although hybrid approaches improve accuracy, they increase hardware complexity and power consumption, limiting their use in mobile or outdoor environments [11]. These trade-offs raise concerns about scalability and sustainability.

String potentiometers, also known as cable-extension transducers, offer a low-cost and robust alternative [12]. They convert linear displacement into electrical signals with sub-millimeter resolution, low power, and strong environmental tolerance. Traditionally single-axis, they

TABLE I: Comparison of Contact-Based Tools, Modern 6-DoF Systems, and the Proposed System

Evaluation Dimension	**Contact-Based Tools**	**Modern 6-DoF Systems**	**Proposed System**
Methods	Calipers, CMMs, Laser rangefinders	Vicon, OptiTrack, Hybrid methods	String Pot + Dual IMUs
Pose coverage	✗ Position only	✓ Full 6-DoF	✓ Full 6-DoF
Real-time capability	✗ Manual / offline	✓ Real-time tracking	✓ Real-time update
Portability	✗ Benchtop use only	△ Some portable variants	✓ Handheld, no external snesor
Setup complexity	✓ Simple	✗ Calibration-intensive	✓ Geometry-based setup
Measurement accuracy	△ mm level	✓ Sub-mm (optical best)	△ mm-level validated
Environmental robustness	✓ Insensitive to light/magnetism	✗ Sensitive to LoS / EM	✓ Robust in field
Power consumption	✓ Passive / low	✗ Often high	✓ Low (IMU + sensor)
Cost and scalability	△ Low cost, not scalable	✗ Expensive, complex	✓ Low-cost and scalable

Note: ✓ advantageous performance; ✗ clear limitation; △ partial capability

can be configured in multi-point layouts and fused geometrically for 3D reconstruction [13], without requiring optical markers or fixed infrastructure. However, a single string potentiometer only provides relative displacement and typically represents the sensor's body motion rather than the endpoint [14]. To overcome this, Won et al. [15] developed a hybrid IMU–string encoder system for tool pose estimation using Kalman filtering and fuzzy logic to mitigate drift.

Building upon this concept, we propose a novel hybrid 6-DoF pose measurement system that integrates a single string potentiometer with dual IMUs. This dual-IMU configuration not only captures the global orientation of the cable but also provides local orientation at the device tip, enabling real-time and infrastructure-free pose estimation. The proposed system features a simple architecture and low component cost, while achieving millimeter-level accuracy across diverse spatial configurations. Designed for handheld operation, it is particularly suited for use in unstructured or resource-constrained environments. Table I summarizes the relative advantages and limitations of the referenced measurement methods and the proposed approach. To the best of our knowledge, this is the first implementation of such a dual-IMU and string potentiometer configuration for real-time spatial metrology with experimentally validated accuracy over multiple structural scenarios.

II. Target Pose Estimation

To estimate the 6-DoF pose of the target object in real time, data from two IMUs (one mounted on the cable base, the other on the handheld pen) are combined with cable extension measurements. The estimation process involves a sequence of geometric transformations described below. It should be noted that, all transformations are in the same global coordinate frame, following the right-handed rotation convention.

A. Mapping World Vertical Direction

Let $\mathbf{q}_{\text{wire}}^{\text{init}} \in \mathbb{H}$ denotes the unit quaternion representing the orientation of the wire-mounted IMU with respect to the world frame at the initial calibration time. The world upward unit vector is defined as $\mathbf{u}_w = [0, 0, 1]^T \in \mathbb{R}^3$. The direction of this vector expressed in the local coordinate frame of the wire IMU can be obtained by applying the inverse rotation of $\mathbf{q}_{\text{wire}}^{\text{init}}$:

$$\mathbf{u}_{\text{wire}} = R\left((\mathbf{q}_{\text{wire}}^{\text{init}})^{-1}\right)\mathbf{u}_w, \tag{1}$$

where $R(\mathbf{q}) : \mathbb{H} \to SO(3)$ converts a unit quaternion into a 3×3 rotation matrix.

B. Recovering the Cable Direction

At runtime, the current orientation of the wire IMU is given by quaternion $\mathbf{q}_{\text{wire}}^{\text{now}} \in \mathbb{H}$. By rotating the previously stored vertical direction back to the world frame, the direction of the stretched cable can be estimated as:

$$\mathbf{d} = R\left(\mathbf{q}_{\text{wire}}^{\text{now}}\right)\mathbf{u}_{\text{wire}}, \quad \mathbf{d} \in \mathbb{R}^3. \tag{2}$$

This vector is normalized by construction and indicates the current pulling direction of the cable in world coordinates

C. Computing Cable Endpoint Position

Let $L_1 \in \mathbb{R}$ denote the calibrated cable length, and let $\Delta d \in \mathbb{R}$ represent the real-time incremental extension measured by the string potentiometer. The total length is:

$$L = L_1 + \Delta d. \tag{3}$$

Then, the position of the cable's endpoint is given by:

$$\mathbf{p}_{\text{wire}} = L\,\mathbf{d}, \quad \mathbf{p}_{\text{wire}} \in \mathbb{R}^3. \tag{4}$$

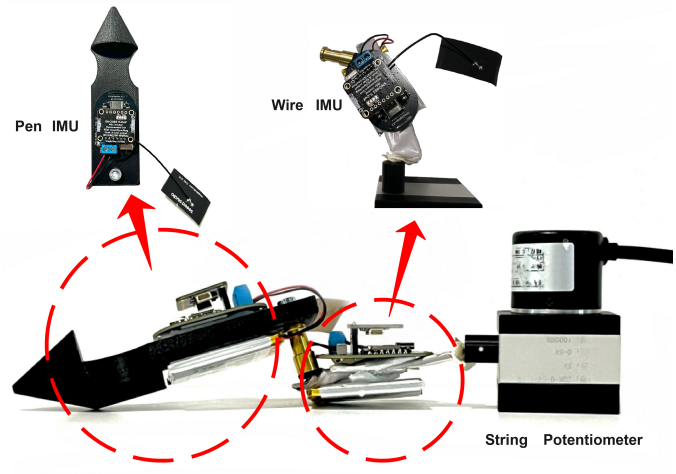


Fig. 1: Illustration of the three key components of the 6-DoF input device.

D. Relative Rotation of the Pen

To determine the rotation of the pen relative to its calibrated orientation, the initial and current quaternions of the pen IMU are denoted as $\mathbf{q}_{\text{pen}}^{\text{init}}$ and $\mathbf{q}_{\text{pen}}^{\text{now}}$, respectively. The relative quaternion is:

$$\mathbf{q}_{\text{rel}} = (\mathbf{q}_{\text{pen}}^{\text{init}})^{-1} \otimes \mathbf{q}_{\text{pen}}^{\text{now}}, \tag{5}$$

and the corresponding rotation matrix is $R_{\text{rel}} = R(\mathbf{q}_{\text{rel}}) \in SO(3)$.

E. Transforming the Pen Tip Vector

Let $L_2 \in \mathbb{R}$ be the physical length from the pen IMU to its tip. Define the local offset vector in the pen's body frame as $\mathbf{v}_0 = [0, L_2, 0]^T \in \mathbb{R}^3$. The current vector from the IMU to the tip in the world frame is:

$$\mathbf{v}_{\text{pen}}^{\text{now}} = R_{\text{rel}} \left(R(\mathbf{q}_{\text{pen}}^{\text{init}})\, \mathbf{v}_0 \right). \tag{6}$$

The inner rotation aligns the vector with the initial world orientation, and the outer applies the relative motion.

F. Final Position and Orientation

The estimated position of the pen tip in the world frame is the sum of the cable endpoint and the rotated offset:

$$\mathbf{p}_{\text{final}} = \mathbf{p}_{\text{wire}} + \mathbf{v}_{\text{pen}}^{\text{now}}. \tag{7}$$

To compute the full orientation, the global quaternion $\mathbf{q}_{\text{total}}$, which represents the estimated orientation of the pen tip in the world coordinate system, can be constructed as:

$$\mathbf{q}_{\text{total}} = \text{quat}\left(R(\mathbf{q}_{\text{wire}}^{\text{now}})\, R\left((\mathbf{q}_{\text{wire}}^{\text{init}})^{-1} \right) \right) \otimes \mathbf{q}_{\text{rel}}, \tag{8}$$

where quat$(\cdot)$ denotes the conversion from a rotation matrix to a unit quaternion.

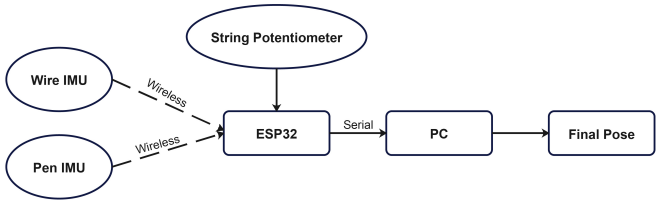


Fig. 2: System-level signal flow.



Fig. 3: Operational demonstration of the input device.

III. Design of 6-DoF Pose Measurement System

The proposed 6-DoF pose measurement system integrates a string potentiometer with dual inertial measurement units (IMUs) to enable real-time pose estimation with minimal hardware complexity and power consumption. This hybrid sensing strategy leverages the high repeatability of mechanical displacement sensing and the orientation awareness of IMUs.

A. String Potentiometer Integration

As shown in Fig. 1, a commercial string potentiometer (model: ZQK-0-5V-1.5M) is installed at the base of the device to measure the extension of a retractable cable. The sensor outputs a voltage linearly proportional to cable length, which is directly sampled by a 12-bit analog-to-digital converter (ADC) on the microcontroller. Some key specifications include:

- Voltage output: 0 - 5 V
- Effective stroke length: 1.5 m

- Repeatability: 0.01%
- Measuring wheel circumference: 1000 mm
- Maximum cable velocity: 600 mm/s
- Tensile load capacity: up to 5 N
- Operating temperature: -25°C to 85°C

The cable is routed to a lightweight 3D-printed pen-shaped end-effector, which users can hold and move freely in space.

B. Dual IMU Configuration

To achieve six-dimensional pose measurement, two BNO085 IMUs are placed at key locations of the device:

- **Base IMU (Wire IMU):** Fixed near the cable outlet, this sensor measures the orientation quaternion $\mathbf{q}_w$ of the extended cable direction in the global frame.
- **Tip IMU (Pen IMU):** Mounted at the distal end of the end-effector, this IMU captures the local orientation $\mathbf{q}_p$ of the pen interface.

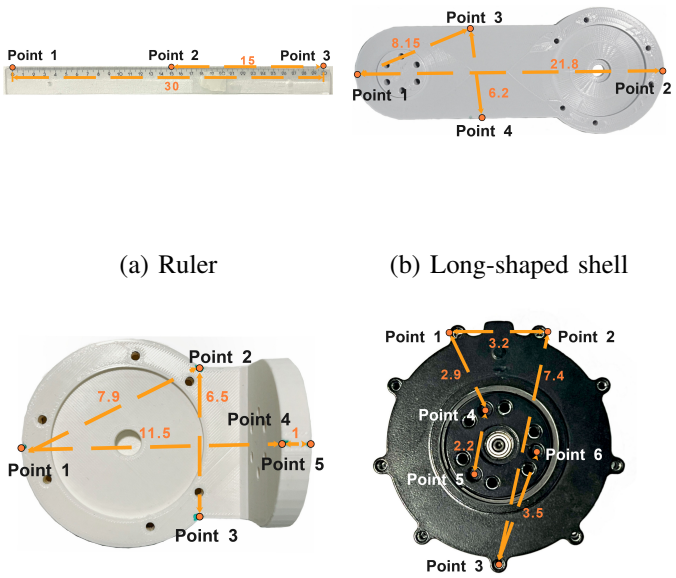
This dual-IMU setup enables reconstruction of both position and orientation without reliance on external tracking systems. By comparing the orientation readings from the two sensors, rotational drift is minimized, and consistent spatial feedback is achieved. The design prioritizes modularity, low cost, and ease of deployment, supporting intuitive single-handed operation.

C. Embedded Signal Path and Communication Architecture

The system's data flow is outlined in Fig. 2. An ESP32 microcontroller performs synchronized sampling of the string potentiometer and IMUs. The analog voltage signal is digitized at 100 Hz, and IMU data, consisting of orientation quaternions, are acquired concurrently via Wifi interfaces. In addition, all raw data, including cable length and dual IMU outputs, are timestamped and transmitted as packets over serial port to a host computer. On the PC side, these packets are processed to compute the full 6-DoF pose. Finally, the resulting position and orientation data can be used for real-time visualization, motion logging, or control applications.

IV. Verification and Discussions

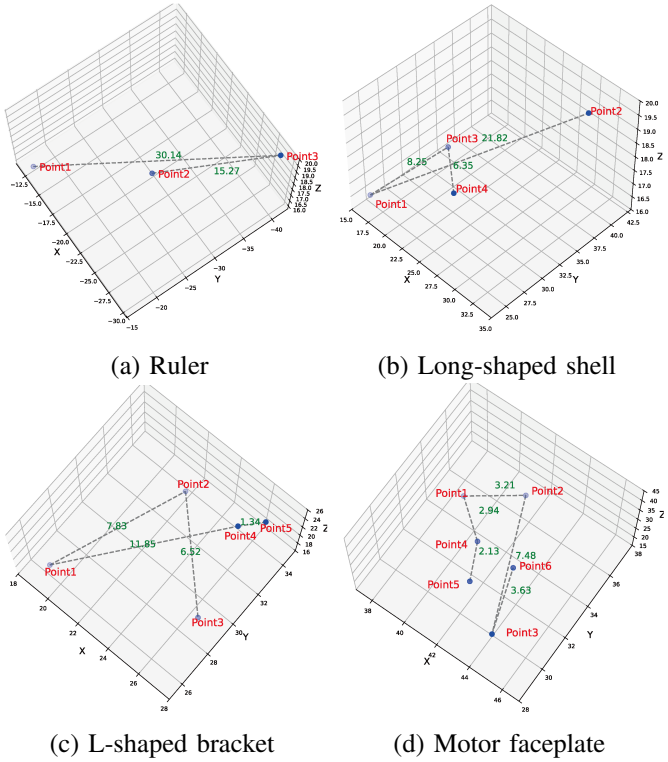
The proposed 6-DoF measurement system was evaluated through a series of structured experiments involving real-world objects. As illustrated in Fig. 3, the user manually probes designated surface points using a 3D-printed handheld pen. The system operates without external tracking infrastructure, fiducial markers, or controlled lighting, and performs reliably under standard indoor conditions. Calibration only requires an initial orientation alignment and cable length reset, and it can operate without specifying a coordinate system. The only operational



(a) Ruler (b) Long-shaped shell

(c) L-shaped bracket (d) Motor faceplate

Fig. 4: Key structural dimensions of the mechanical components (unit: cm).



(a) Ruler (b) Long-shaped shell

(c) L-shaped bracket (d) Motor faceplate

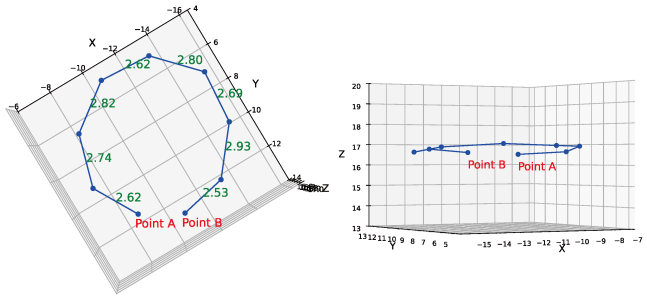
Fig. 5: Measured 3D coordinates and inter-point distances of key component surfaces (unit: cm).

TABLE II: Repeatability statistics from 10 repetitions for four shapes (unit: cm).

Ruler					Long-shape shell				
pair	**Mean**	**Std**	**RMSE**	**95% CI (±)**	**pair**	**Mean**	**Std**	**RMSE**	**95% CI (±)**
Point 1–2	15.140	0.279	0.265	0.200	Point 1–2	21.799	0.304	0.289	0.218
Point 1–3	29.897	0.325	0.308	0.232	Point 1–3	8.472	0.271	0.257	0.194
Point 2–3	14.782	0.183	0.173	0.131	Point 3–4	6.246	0.102	0.097	0.073
L-shaped bracket					**Motor faceplate**				
pair	**Mean**	**Std**	**RMSE**	**95% CI (±)**	**pair**	**Mean**	**Std**	**RMSE**	**95% CI (±)**
Point 1–2	8.373	0.276	0.262	0.197	Point 1–2	3.607	0.320	0.304	0.229
Point 2–3	6.386	0.424	0.402	0.303	Point 1–4	2.591	0.404	0.383	0.289
Point 1–4	11.326	0.237	0.225	0.170	Point 3–4	4.900	0.307	0.291	0.220
Point 4–5	1.137	0.160	0.152	0.114	Point 2–3	7.327	0.168	0.159	0.120
					Point 3–6	3.287	0.246	0.233	0.176
					Point 4–5	2.166	0.272	0.258	0.195

constraint is to keep the pen approximately vertical to the surface, to minimize orientation-induced error. To assess the system's versatility, four objects with representative geometric features were selected (see Fig. 4). These span a variety of spatial structures, including linear alignment, angular transitions, and circular or densely featured layouts. Each object contains multiple manually identified keypoints for assessing point-to-point distances in 3D space. Notably, the motor part and L-shaped bracket were chosen to test the system's ability to handle curved surfaces and tightly packed configurations. This diversity ensures that both position and orientation estimation are evaluated under varying spatial constraints.

The measured 3D coordinates were compared against real values derived from either manufacturer specifications or direct physical measurements. As shown in Fig. 5, the captured keypoint layouts closely match the expected geometries. Among the test objects, the ruler provides the most precise benchmark due to its uniformly spaced marks. Across all evaluated objects, the maximum absolute error remained within 4 mm, confirming that the system preserves high geometric fidelity over diverse shapes and scales. All pose estimates were computed from the fused 6-DoF sensor data rather than any visual or pixel-based features, demonstrating that the achieved precision arises purely from the geometric fusion mechanism. Furthermore, 10 repeated measurements were performed for each configuration to assess repeatability and temporal stability, and the resulting statistics, including Mean, Sandard deviation (Std), RMSE, and 95% Confidence Interval (CI) half-width, are presented in Table II. To specifically consider the effect of drift, the sensor system was calibrated only once at the beginning of each object's measurement



(a) Top view (b) Side view

Fig. 6: Reconstructed outer contour of the motor faceplate from (a) top and (b) side perspectives, showing sequentially measured points and distances

sequence, and all ten repetitions were conducted continuously without reinitialization. Across all four shapes, the standard deviations remain below 0.45 cm, while the 95% CI half-width stay almost within ± 0.30 cm, reflecting highly consistent distance estimation.

In addition to discrete keypoint measurements, the entire outer contour of the motor faceplate was also reconstructed to assess the system's capability in capturing continuous geometric features. As shown in Fig.6, the closed-loop path of the faceplate was obtained by sequentially probing multiple points along its perimeter. The pairwise distances between adjacent points were found to be approximately equal, reflecting the uniformity of the sampling process and the geometric consistency of the reconstruction. The deviations of all measured segment lengths from their nominal values ranged from 0.7 mm to 3.3 mm, further demonstrating millimeter-level accuracy across the contour.

Overall, the experimental results indicate that the proposed system can reliably capture spatial point re-

lationships with millimeter-level accuracy across a variety of object shapes and sizes. The device maintains stable performance in both long-range and fine-detail configurations, confirming its robustness under different operating conditions. These results highlight the system's potential for real-time, infrastructure-free 6-DoF pose measurement in scenarios where simplicity, usability, and reliability are critical. The remaining measurement errors mainly arise from IMU drift, cable nonlinearity, and manual operation variability; however, the dual-IMU geometric fusion effectively mitigates orientation drift and enhances overall spatial consistency. Furthermore, the integration of smart actuators, embedded inverse kinematics control, and 3D-printed modular structures demonstrates a practical, low-cost, and high-performance robotic platform. The proposed system offers a reproducible and accessible solution for research and education, and shows strong potential for lightweight automation and teleoperation applications requiring both real-time responsiveness and portability.

V. Conclusions

Accurate 6-DoF pose measurement remains a fundamental challenge in spatial metrology, especially under constraints of cost, infrastructure, and environmental variability. This work was motivated by the need for a portable and sustainable alternative to conventional optical or electromagnetic tracking systems, which often demand high power, precise calibration, and controlled environments.

The proposed system combines a single string potentiometer with dual IMUs to achieve real-time 6-DoF pose estimation through geometric reconstruction. The approach was implemented in hardware and validated on objects with diverse geometries, showing consistent and robust measurements across different spatial configurations. The results indicate that the system offers an accessible, low-power, and markerless solution suitable for field applications where simplicity and reliability are essential.

Although the statistical experiments confirm good repeatability of the proposed system, IMU drift remains a key limitation, especially under magnetic interference. In addition, human operation factors, such as unintentional IMU misalignment or slight sensor skew during manual handling, can also introduce measurement variations. Future work will focus on developing adaptive calibration and compensation algorithms to suppress drift and human-induced perturbations, thereby improving the system's long-term stability and overall measurement robustness.

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Measuring the Environmental Impact of ICT Products and Systems: An initial overview

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***Abstract*—This paper provides an initial overview of the measurement of the environmental impact of Information and Communication Technologies (ICTs), focusing on the importance of sustainable approaches in their design, development, and deployment. It explores the dual role of ICTs in environmental sustainability, both as enablers of resource optimization and as contributors to global warming due to their energy consumption and e-waste generation. In light of this, the paper describes a novel methodology that combines Life-Cycle Assessment (LCA) principles with the Guide to the Expression of Uncertainty in Measurement (GUM) guidelines, allowing a reliable measure of the environmental impact. The application of the methodology is shown on three case studies: Measuring Systems, Artificial Intelligence (AI) pipelines, and complex ICT infrastructures. These case studies demonstrate how the methodology can be used to estimate the Carbon Footprint while evaluating the associated uncertainty, providing actionable insights into enhancing the sustainability of various ICT systems.**

***Index Terms*—Agenda 2030, Carbon Footprint, Energy Consumption, Environmental Impact, Information and Communication Technologies, Life-cycle Assessment, Measurement, Sustainability, Uncertainty**

I. Introduction

The *2030 Agenda* for Sustainable Development, established by the United Nations, outlines 17 goals that focus on social, political, cultural, and environmental aspects [1]. One of the primary goals is to take *Climate Action* by addressing global warming and climate change challenges. This underscores the need for a more sustainable approach to consumption, production, and natural resource management to meet present and future needs. In this context, Information and Communication Technologies (ICTs) influence environmental sustainability in two dimensions. On one hand, ICTs catalyze this change, fostering advancements in social behavior and facilitating the responsible management of natural resources. These advancements, often referred to as *green by ICT* [2], relate to the ability of ICTs to reduce the impacts of human activities. On the other hand, ICTs themselves have an impact on the environment, thus contributing to global warming. This is mainly due to their high energy consumption. These considerations highlight the need for a thorough examination of the environmental sustainability of ICT products and services, known as *green of ICT* [3].

To estimate the environmental impact of ICT systems, Life-Cycle Assessment (LCA) principles are widely applied. The framework has been regulated by the International Organization for Standardization (ISO), through the ISO 14040 series of standards [4], as well as by the International Telecommunication Union (ITU) [5]. LCA assesses greenhouse gas (GHG) emissions in all stages of the life cycle of an ICT system, from production and transportation to use and end-of-life management. These emissions, primarily carbon dioxide (CO_2), are often expressed as the *Carbon Footprint*, measured in kg $CO_{2,eq}$ [6].

Since LCA typically provides point estimates with limited statistical significance, the resulting assessments may lack robustness for decision-making. To increase their reliability, LCA can be enhanced by representing outcomes not as single values but as probability density functions (PDFs) that describe the range of values reasonably attributable to the system under study. In this context, the proposed methodology integrates LCA with the principles of the Guide to the Expression of Uncertainty in Measurement (GUM) [7], specifically Supplement I [8], in order to provide a proper measure of environmental impacts.

This methodology enables (i) the identification of the most impactful components of the ICT system under consideration, (ii) the evaluation of trade-offs between system performance and environmental impact, and (iii) the balancing of impacts avoided through the use of the ICT system against those generated by the system itself, with the ultimate aim of assessing its actual environmental sustainability.

II. Method

The general methodology, outlined in Figure 1, consists of four fundamental steps that serve as the basis for properly measuring the environmental impact of various ICT systems. While the core framework remains consistent, it is adapted and tailored to the specific context of each case study. This approach ensures that the methodology is both reliable for measuring the Carbon Footprint of different types of ICT systems and flexible enough to accommodate the unique characteristics and requirements of each context, thereby enhancing the robustness and applicability of the results.

The four key steps of the methodology are outlined below:

1) *Checklist:* The first step involves creating a comprehensive checklist of all components that make up the ICT system under analysis, which may include hardware, software, consumables, site infrastructure, and any movements of goods and people, depending on the specific context. This checklist ensures that all relevant elements are accounted for in the environmental impact assessment.
2) *PDFs assignment:* For each component listed in the checklist, the Carbon Footprint is estimated, and a PDF is assigned to represent the uncertainty in the estimate. These PDFs are derived from existing literature, technical reports, or specific LCA software tools. It is important to outline the difference between *embodied* and *operational* impacts when assigning PDFs. Embodied impacts refer to the environmental footprint associated with the production, transportation, and disposal of the components, and are typically calculated based on *life-cycle analysis tools*. Operational impacts, on the other hand, are associated with the energy consumption and operational usage of the system in a certain time period. These impacts are often modeled using *conversion factors*, which vary depending on the region of interest.
3) *PDFs propagation:* Once the PDFs are assigned, they are propagated using the Monte Carlo Method (MCM), following the principles of the Supplement I to the GUM [8]. This involves conducting a finite number of extractions for each input variable in order to aggregate the individual PDFs into a single distribution that represents the overall Carbon Footprint of the system or process.
4) *Coverage Interval:* The final step involves determining the coverage interval from the output PDF representing the Carbon Footprint of the entire system. The coverage interval corresponds to a specific coverage level and reflects the range of possible values for the environmental impact.

These steps help identify the key components of the system under analysis that have the greatest environmental impact, facilitating targeted interventions to improve sustainability without compromising performance. The adaptation of the methodology to various ICT systems allows for a rigorous assessment of the Carbon Footprint, accounting for both environmental impacts and the associated uncertainties. This approach provides valuable insights into integrating sustainability into the design, operation, and evaluation of ICT systems, ultimately aiding in the reduction of their environmental footprint.

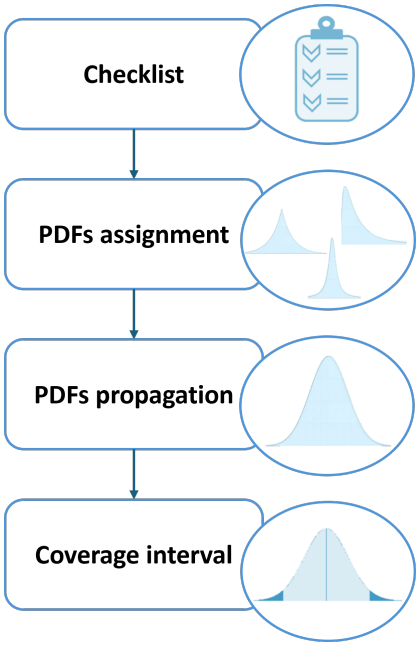


Fig. 1. Illustration of the four main steps in the proposed methodology.

III. Case Studies

The proposed methodology was applied to different case studies within the ICT domain, including Measuring Systems [9], Artificial Intelligence (AI) pipelines [10], and complex ICT infrastructures [11].

A. Measuring Systems

The aim of this case study was to develop a more comprehensive evaluation framework that incorporates environmental impact as a key performance parameter for measuring systems. In this context, the study [9] compared the Carbon Footprint of three resistance measuring systems across different scenarios. The three systems analyzed were the *Wheatstone Bridge*, the *Voltamperometric Method*, and the *Two-wire Method*, each selected for its common use in resistance measurement. Through a simulated experiment, three different laboratories, each employing a distinct method for the measurement, were considered. Specifically, *Laboratory #1* used the Wheatstone Bridge, *Laboratory #2* applied the Voltamperometric Method, and *Laboratory #3* adopted the Two-wire Method. The study evaluated these systems across three scenarios:

- *Simulated Scenario #1*, in which each laboratory employed different measurement instruments, with variations in both brands and models, to develop the measurement methods.
- *Simulated Scenario #2*, in which all laboratories used the same brands and models of instruments; however, since

the measurement methods differed, each method could require a different number or type of instruments.
- *Experimental Scenario*, where commercially available instruments were used in each laboratory, with similar site infrastructure across all configurations.

Despite the simplicity of the case study, the results still yield meaningful insights for supporting informed decisions when selecting a measurement system that effectively balances sustainability and performance criteria. With particular reference to the *Experimental Scenario*, the checklist of instrumentation considered for the measurements included:

- A multimeter, used as voltmeter, ammeter, and for two-wire direct resistance measurements;
- A signal generator;
- Two carbon film resistors, nominal value 100 Ω with a tolerance of 1 %;
- A variable resistor with a resolution of 1 Ω and a tolerance of 1 %;
- An off-the-shelf laptop weighing approximately 1.5 kg.

The analysis also considered additional elements such as site infrastructure (room, air conditioning, lighting) and supplementary items (internet equipment, pen drive). The corresponding assessments were carried out for the different cases; however, for conciseness, these details are not reported here.

The Carbon Footprint for this scenario was estimated by combining both operational and embodied impacts for each item. Embodied impacts were assessed using the life cycle analysis tool OpenLCA [12], which integrates various databases to model the life cycle of different devices and services. These embodied impacts were provided on an annual basis, and for each item, a corresponding PDF was assigned, accounting for variations across the available databases. Operational impacts were assessed based on the hourly energy consumption of the devices and then converted into carbon-based values using appropriate conversion factors. These operational impacts were annualized to allow for their summation with the embodied impacts, yielding the final Carbon Footprint for the selected scenario. Finally, Monte Carlo simulations were performed for both embodied and operational impacts, with 10^6 extractions carried out for each impact type. The resulting PDFs were propagated to obtain the final values for both impacts. The total Carbon Footprint was then calculated by summing these final embodied and operational impacts, as shown in Figure 2. This figure presents a scatter plot of the Carbon Footprint, including its associated uncertainty at the 99 % coverage level, for the three measuring systems considered in the Experimental Scenario. The visual representation enables a direct comparison of the systems, clearly illustrating the trade-offs between performance and sustainability.

B. Artificial Intelligence Pipelines

This case study assessed the environmental impact of an AI pipeline from the user's perspective. The primary objective was to identify the key stages contributing to the environmental impact and explore strategies for optimizing the trade-off

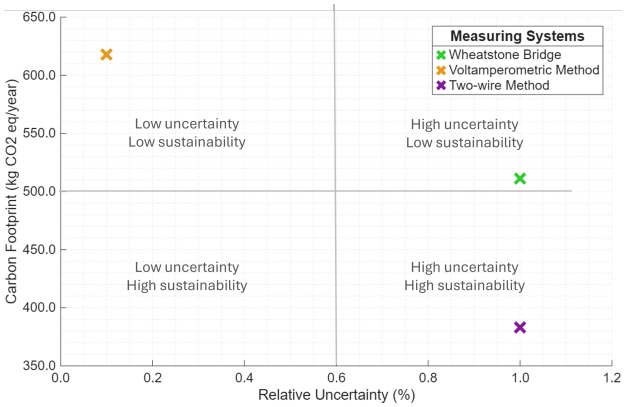


Fig. 2. Scatter plot of the Carbon Footprint and the relative uncertainty for the three resistance measuring systems (Experimental Scenario) [9].

between model performance and environmental sustainability. The methodology was preliminarily applied in [10] to a Brain-Computer Interface (BCI) application, focusing specifically on the classification of EEG signals for the recognition of steady-state visually evoked potentials (SSVEPs).

The algorithm used in this study was the Filter-Bank Canonical Correlation Analysis (FBCCA), a time-domain-based method that represents the state of the art in SSVEPs classification [13]. The FBCCA method involves preprocessing the EEG signal using a filter bank to extract specific frequency sub-bands corresponding to the SSVEP. Canonical Correlation Analysis (CCA) is then performed between the extracted SSVEP subbands and predefined reference signals to identify the correlation patterns. Finally, the signal is classified based on these correlation results. The optimal selection of parameters for each stage is typically achieved through a *grid search*, where a wide range of possible parameter values are tested, and the best performing combination is identified using cross-validation or other suitable validation strategies.

To investigate how different training strategies impact the environmental footprint, three distinct grid configurations were adopted to explore the trade-offs between model performance and sustainability:

- *Grid #1*: The most expansive configuration, encompassing the largest number of parameter combinations, resulting in a total of 2160 possible combinations.
- *Grid #2*: A reduced subset, comprising 50 % of the combinations from Grid #1, selected randomly.
- *Grid #3*: The most compact grid, including only 10 % of the possible combinations, also chosen randomly.

For each grid search, the Leave-One-Subject-Out Cross Validation (LOSO CV) method was applied to account for the variability in EEG signals across different subjects.

In terms of sustainability assessment, it is important to note that the benchmark dataset used in this analysis is sourced from [14]. Consequently, the impact assessment did not include the hardware and software used for data collection. Instead, the evaluation focused on the components directly involved in the application of the AI pipeline, as outlined below,

along with the methodology for assessing their environmental impact:

- *Laptop:* The energy consumption for each grid search was estimated based on the processing time, measured in kWh. This value was then converted into kilograms of $CO_{2,eq}$ using a conversion factor for Italy, where each kWh of energy corresponds to approximately 0.3 kg of $CO_{2,eq}$ [10].
- *Software:* No direct operational impact was attributed to the software itself, as its environmental impact is considered to be included within the operational impact of the hardware.

The embodied impact, as assessed in [10], was not included in this overview since it remains constant across all grid search configurations. Instead, the focus was placed on the operational impact, which corresponds to the energy consumption of the system during both the training and inference phases. This operational impact was quantified for each grid search configuration. Table I presents the total operational Carbon Footprint of the system for each configuration, reporting the 99 % coverage interval.

TABLE I
OPERATIONAL CARBON FOOTPRINT MEASURED FOR THE THREE DIFFERENT GRID SEARCHES (99 % COVERAGE INTERVAL)

Grid	**Carbon Footprint (kg $CO_{2,eq}$)**
#1	[3.6 ÷ 4.2]
#2	[1.5 ÷ 1.8]
#3	[0.0 ÷ 0.1]

Once the environmental impact for each configuration was estimated, the classification accuracy was evaluated to assess the trade-offs between model performance and sustainability. As shown in Figure 3, the results highlight that configurations with similar classification performance can exhibit substantial differences in terms of their environmental footprint. For example, Grid #1, which includes the largest number of combinations, achieved the highest classification accuracy but also incurred the highest Carbon Footprint. In contrast, Grid #2, a more compact configuration, delivered nearly identical performance while significantly reducing the environmental cost.

These findings highlight the potential to optimize AI model training by strategically balancing computational resources with the goal of minimizing environmental impact. Future work will expand the environmental assessment to include the entire AI pipeline, considering not only the training phase, but also the sustainability efforts associated with dataset creation. This will involve accounting for embodied impacts, particularly those related to the inclusion of additional devices, further enhancing the overall environmental evaluation of the AI pipeline.

C. Dynamic Fourth Lane of the A4 Italian Highway

The third case study investigated the environmental sustainability of complex ICT infrastructures, as explored in [15]

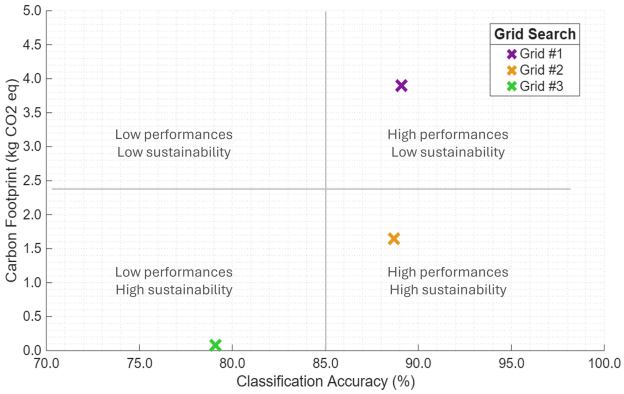


Fig. 3. Scatter plot of the results in terms of environmental sustainability and performance for the three grids [10].

with the *dynamic fourth lane* of the A4 Italian highway, developed by *Movyon S.p.A.*, a company of the *Autostrade per l'Italia* group. This infrastructure is designed to enhance traffic flow and road safety by converting the emergency lane into an active lane during periods of high traffic, using real-time traffic monitoring. The dynamic lane system integrates multiple technologies, including sensors, actuators, and Internet of Things (IoT) components, which are grouped into six main categories: monitoring systems, camera systems, weather stations, signposting devices, power supply and control, and data management. The primary aim of the study was to evaluate the *Sustainability Balance*, defined as the difference between emissions saved through the implementation of the infrastructure and the emissions generated by its operation.

The environmental impact of the infrastructure was assessed by calculating both embodied and operational emissions for each component:

- *Embodied emissions* refer to the *fixed impacts* associated with the infrastructure's life cycle. These emissions are considered fixed because they are incurred during the production and eventual dismantling of the infrastructure, rather than during its ongoing operation. The embodied emissions were calculated using OpenLCA, modeling the impacts of each component throughout its life cycle. A PDF was assigned to each embodied impact to account for the market variability of the components and the uncertainties inherent in the models created through OpenLCA.
- *Operational emissions* are considered *variable impacts* and depend on the actual usage of the infrastructure. These emissions were calculated by first considering the power consumption of all equipment involved, followed by determining the energy usage based on the operating time. The resulting energy was then converted into Carbon Footprint using appropriate conversion factors, specifically from the Electricity Maps platform [16], taking into account Italian values for 2024. A PDF was assigned to each operational impact, reflecting variability in power consumption ranges and fluctuations in the

conversion factor for electricity in Italy, which changes month-to-month.

After the impacts assessment, Monte Carlo simulations with 10^6 extractions were performed to propagate the PDFs and obtain the final distribution of embodied and operational impacts. The resulting PDFs are shown in Figure 4.

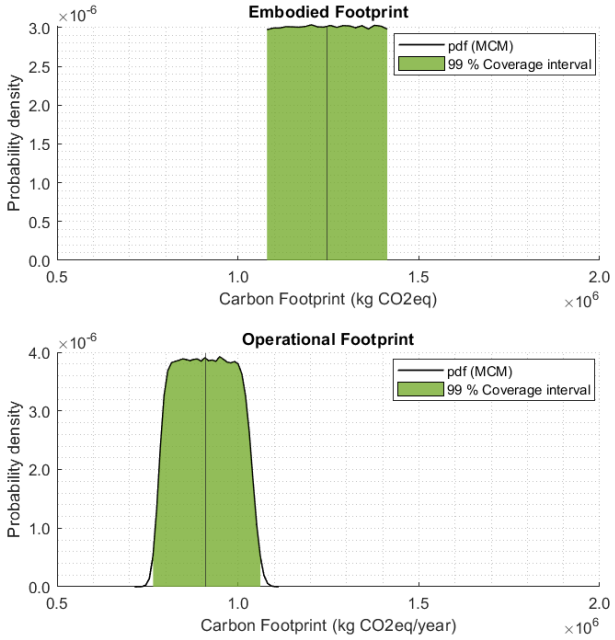


Fig. 4. Embodied and Operational Carbon Footprint of the dynamic fourth lane considering the combined contribution of all its components [15].

The estimation of the environmental impacts of the infrastructure was used to perform a *Sustainability Balance*, which also took into account the emissions saved due to the implementation of the infrastructure. This analysis involved comparing the current infrastructure to the pre-existing system, considering key factors such as vehicle speed and congestion levels. A study conducted over two sample weeks revealed a significant increase in average vehicle speed, from approximately 77 km/h to 100 km/h when the dynamic fourth lane was in operation. This improvement in traffic flow led to a marked reduction in emissions, driven by fewer congestion events and tailbacks.

The Sustainability Balance was then assessed by comparing the emissions saved (*Emission Savings*) to the emissions generated (*Total impact*) over the same time period. The results, presented in Table II, clearly show that the kg $CO2, eq$ saved in one year far exceed the kg $CO2, eq$ emitted during the same period. In conclusion, the dynamic fourth lane leads to a significant reduction in emissions, with the savings far outweighing the emissions generated. The application of the methodology helps to demonstrate that ICT-based infrastructures can provide substantial sustainability benefits.

TABLE II
GENERATED AND AVOIDED EMISSIONS OF THE DYNAMIC FOURTH LANE AT 99% COVERAGE LEVEL.

Impact Category	**kg $CO_{2,eq}$**
Embodied Impact (Fixed)	[1073819 ÷ 1419869]
Operational Impact (Annual)	[765893 ÷ 1059419]
Total Impact (Year 1)	[1839712 ÷ 2479288]
Emission Savings (Annual)	[7140996 ÷ 9077390]
Sustainability Balance (Year 1)	[5301284 ÷ 6598102]

IV. CONCLUSION

This study provided an overview of the environmental impact measurements of ICTs, emphasizing their dual role in sustainability. While ICTs have the potential to optimize resource use and contribute positively to environmental goals, they also play a significant part in global warming, driven by high energy consumption and e-waste generation. A novel methodology that integrates the LCA framework with the GUM principles was described. This combined approach strengthens environmental impact assessments by accounting for both the Carbon Footprint and the associated uncertainties. Currently, the methodology is applied across three case studies: Measuring Systems, AI pipelines, and complex ICT infrastructures, demonstrating its flexibility and effectiveness in evaluating environmental impacts. The case studies revealed that this methodology can identify key components of ICT systems that significantly influence their ecological footprint, enabling targeted sustainability improvements.

However, it is important to acknowledge certain limitations of the current methodology. The quality and consistency of the data used in the LCA can introduce uncertainties. For embodied impacts, various tools and databases provide valuable insights, but they often rely on different data sources, methodologies, and assumptions. As a result, discrepancies can arise even when assessing the same devices or services. Similarly, the variability in operational impact data stems from the use of conversion factors, for which multiple data sources exist. These factors are influenced by the energy mix of different countries, and inconsistencies often emerge due to variations in energy mix data across sources, further contributing to uncertainty in the final assessment.

Further research should focus on enhancing the quality of data sources and developing methods to standardize data across various geographical regions and time periods. Additionally, the methodology could be applied to other ICT domains, offering valuable insights into uncertainty management and supporting the creation of more sustainable ICT systems.

ACKNOWLEDGMENT

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Robotics in Sustainability: Opportunities and Challenges for a Holistic Environmental Assessment

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***Abstract*—Robotics offers significant potential for advancing sustainability across various sectors, including environmental monitoring, precision agriculture, and manufacturing. By improving efficiency and enabling more precise interventions, robots can help meet critical global challenges, including those outlined by the Sustainable Development Goals (SDGs) of the United Nations. However, the environmental benefits of robotics must be balanced against the challenges they introduce, such as high energy consumption, material waste, and the depletion of resources, particularly in the case of multi-robot systems.**

This paper examines the dual impact of robotics on sustainability, focusing on both the positive contributions of robotics and the environmental issues that arise from their production, use, and disposal. The paper aims to lay the groundwork for overcoming the current fragmented research, which often addresses robotic subsystems in isolation rather than considering the integrated systems as a whole. For a comprehensive framework that evaluates the full environmental impact of robotic technologies, the paper draws attention to the need for an integrated, holistic approach to sustainability in robotics, ensuring that technological advancements align with environmental goals.

***Index Terms*—Robotics, sustainability, multi-robot network, environmental monitoring, measurements**

I. Introduction

In recent years, advancements in robotics, encompassing automation, artificial intelligence (AI), and mobility, have positioned this technology as a transformative technology capable of addressing a wide range of global challenges [1]. Among the numerous applications of robotics, such as automating complex tasks and improving efficiency and precision, many are specifically targeted at achieving the Sustainable Development Goals (SDGs) of the United Nations [2]. These are a set of 17 global objectives adopted by the United Nations, aiming to provide a framework for collective action [3]. The application of robotics to promote sustainability in alignment with SDGs becomes crucial [4]. However, while robotics can drive innovations that improve efficiency and contribute to cleaner energy solutions, the production and disposal of robotic systems themselves impose significant environmental costs [5]. Challenges include high energy consumption, material waste, reliance on scarce resources, and potential workforce displacement, which may limit or counteract the benefits of robotic interventions.

As robots are increasingly employed across various industries, their integration into sustainability initiatives must be carefully managed [6], and their dual impact on sustainability requires careful consideration. The challenge, therefore, is to balance the benefits of robotics in promoting sustainable development while mitigating its environmental and social drawbacks [7]. Despite the significant contributions in current literature, much research develops fragmented approaches that focus on specific robotics subsystems or aspects, failing to fully capture the interconnected nature of robotic systems. This paper aims to draw attention to this gap, stressing the need for a more robust and integrated approach to assess the true environmental costs of robotics.

The paper highlights the dual impact of robotics on sustainability to stimulate the development of a comprehensive framework that can provide a clearer understanding of how robotics can contribute to sustainable development. With this

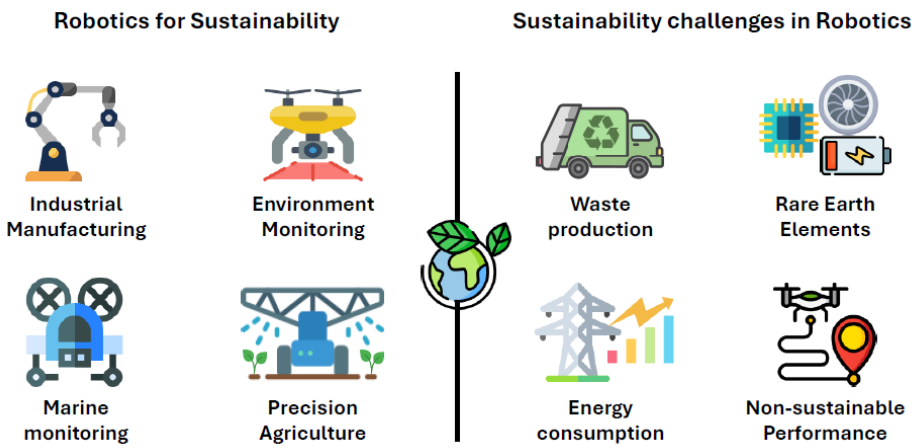


Fig. 1. Examples of fields in which robotics is an opportunity for sustainability and the challenges that need to be addressed in order to reduce its impact.

aim, the paper critically reviews the role of robotics, presenting a balanced analysis that incorporates insights from current research. By addressing the balance between benefits and drawbacks of robotics, this paper aims to provide preliminary guidance for the future development of methods to evaluate the its environmental impact. The complex and dual role of robotics, which acts both as a solution for sustainability and as a source of environmental challenges, is summarized in Fig. 1.

The paper is organized as follows. Section II provides an overview of the deployment of robotic system as an enabler of sustainable goals. Section III presents the challenges of the robotic ecosystem to align with sustainability. Finally, in Section IV, a comprehensive perspective on the distinction between single and multi-robot systems is presented to identify a critical methodological gap in the literature.

II. Robotics for Sustainability

Robotics for sustainability refers to the design, development, and deployment of robotic systems aimed at supporting the preservation, restoration, and sustainable management of natural ecosystems. It embodies the convergence of robotics with environmental science and sustainable principles, using robotic systems to contribute directly to environmental monitoring, biodiversity preservation, and resource resilience, aligning with the objectives of SDGs [8]. Governmental and institutional initiatives reinforce this perspective, identifying robotics as a critical infrastructure technology for promoting climate resilience and sustainable industrial transformation.

A. Precision Agriculture and Sustainable Manufacturing

Precision agriculture refers to management approaches based on advanced technology to collect and analyze data with the aim of improving crop production [9]. Its adoption has been one of the most significant developments in the field of sustainable farming [10]. In this framework, robotics tools can be used to accurately perform selective weeding, enabling targeted interventions that reduce the need for excessive water, fertilizer, and pesticide use, which not only lowers the cost of farming but also reduces the environmental impact of agricultural practices [11].

In manufacturing, industrial robots are being used to automate production processes, playing a critical role in reducing energy consumption and material waste, improving production efficiency [12]. For instance, the use of robots in recycling operations has improved the efficiency of material sorting, while simultaneously reducing human exposure to hazardous materials [13]. In the context of recycling, robots are being employed to sort waste materials more efficiently. These robots are equipped with machine vision systems that enable them to distinguish between different types of materials, such as metals, plastics, and paper, thus improving the recycling process and reducing waste sent to landfills [14].

B. Environmental Monitoring

In addition to agriculture and manufacturing, robotics plays a crucial role in environmental monitoring, which refers to the use of technologies to collect data on environmental parameters, such as air and water quality, with the aim of assessing the health of ecosystems and responding to environmental threats [15].

One important system involved in environmental monitoring are the unmanned aerial vehicles (UAVs), i.e., remote-controlled drones with no pilot on board [16], By integrating lightweight and low-cost environmental sensors to measure key atmospheric parameters, such as particulate matter (PM) and carbon dioxide (CO_2) [17], UAVs can map pollutant concentrations across different altitudes and locations. In comparison with conventional fixed reference stations, which are limited in spatial coverage, or with satellite observations, which suffer from high operational costs, UAV-based systems provide a flexible and cost-effective platform for collecting three-dimensional high-resolution data over large and complex areas [18]. Building upon the capabilities of robotics in air-quality monitoring, recent developments have further expanded the role of UAVs in atmospheric monitoring to quantify greenhouse gases (GHGs), particulate matter, and

other airborne pollutants across densely populated urban areas [19].

Robotic systems have also become pivotal in observing and protecting marine and aquatic environments [20], supporting or replacing traditional manual methods. Robots deployed for monitoring the ocean environment, including underwater vehicles, play an essential role in addressing climate change and carbon cycling by collecting data related to ocean temperature, chemical composition, and marine biodiversity [21]. Such data are fundamental for understanding the contribution of oceans to global climate regulation and for assessing their capacity to absorb and mitigate greenhouse gases. The localization and mapping capabilities of cooperative multi-robot systems offer scalable and adaptive solutions for tracking pollutants, allowing for a more precise understanding of their movement and impact in real-time, which in turn enhances situational awareness and enables more effective environmental protection strategies [22]. These systems also play a transformative role in ecosystem restoration, assisting in monitoring reef health and deploying restoration materials [23].

III. Sustainability Challenges in Robotics

The concept of sustainable robotics extends beyond what robots can do for sustainability, to include how the robotic ecosystem itself can evolve in alignment with environmental and ethical responsibility [24]. Although robotics holds significant promise for advancing environmental sustainability, as robotic deployment scales across industries, the footprint of these systems on the environment becomes increasingly relevant to their overall sustainability assessment [25]. The design, manufacturing, and operation of robots demand substantial material and energy resources, often relying on rare-earth elements, high-carbon production processes, and non-recyclable electronic components [26].

A. Energy Consumption and Environmental Impact

As the number of robotic systems deployed increases, the amount of energy consumed increases [27], making it essential to reduce their reliance on conventional power grids and decrease overall carbon emissions. This consumption is expected to rise as automation expands beyond manufacturing into logistics, healthcare, and domestic sectors. Energy use stems primarily from actuators and motors that drive mechanical motion, but also from continuous sensor operation, data transmission, and onboard computation, all of which require constant power input [28]. Furthermore, in regions where electricity generation relies on fossil fuels, this energy consumption has a substantial impact. With this aim, recent literature explores energy-efficient robots and the integration of renewable energy sources to power them [29].

Beyond hardware and energy infrastructure, software design choices play a critical role in determining the environmental footprint of robotic systems. Efficient algorithms for perception, motion planning, and control can substantially reduce computational and energy demands, particularly in resource-constrained or mobile platforms [30]. In large-scale deployments, such software-driven optimizations contribute not only to lower energy consumption but also to reduced wear on hardware components, indirectly extending system longevity and supporting broader sustainability goals [31].

In planning and scheduling, algorithms that explicitly account for actuator effort, sensing energy, and battery state generally reduce the overall environmental burden, even when they require longer computation times or exhibit slightly lower peak performance [32]. Optimizing computational efficiency while ensuring task effectiveness is a key strategy for enhancing sustainability in robotic systems. By intentionally reducing resource consumption, significant gains in operational efficiency can be achieved.

B. Circular Economy Principles in Robotic Design

The lifecycle of robotic systems is often challenged by the manufacturing process of the robot itself, which involves the mining of rare earth materials that are required for robotic components, such as sensors and batteries, contributing to resource depletion and environmental degradation [33]. To mitigate the environmental impact of robotics, there is an increasing emphasis on incorporating circular economy principles in robot design. These principles are particularly important in the robotics industry, where the longevity of robots and their components must be maximized [34].

Sustainable design practices must include the use of recyclable and renewable materials to mitigate these effects [35]. Additionally, the use of biodegradable and recyclable materials in robot manufacturing can significantly reduce the environmental footprint of these technologies. Furthermore, sustainable actuators and self-healing materials [36] are emerging as important innovations in robot design. Sustainable actuators, which consume less energy and use environmentally friendly components, can reduce the environmental impact during the operation phase. Meanwhile, self-healing materials offer the potential to extend the lifespan of robotic components by autonomously repairing damage, thus reducing the need for frequent replacements and lowering material consumption.

IV. Toward a Holistic Assessment of Robotics in Sustainability

Understanding the overall role robotics can play in fostering sustainable development is essential for delving into the complexities of the technology's environmental and systemic impacts. Current research addressing the environmental impact of robotics tends to focus on individual subsystems or components, such as batteries, sensors, materials, or optimization algorithms, rather than evaluating the robot as a whole [37], [38]. Thus far, this paper has primarily focused on robotic systems in general terms, without delving into the key distinction between single robots and multi-robot systems. Understanding this difference is crucial when evaluating their respective roles in sustainability applications.

A. Single robots and multi-robot systems

Robotic systems can be broadly classified into individual robots and multi-robot systems according to their operational

TABLE I
COMPARISON OF EXTENSIVE AND INTENSIVE SUSTAINABILITY METRICS IN ROBOTICS.

Metrics	Extensive	Intensive
Definition	Scale-dependent	Scale-independent
Measure	Total magnitude	Normalized efficiency
Value	It changes with the size of the system and duration of its use	It is normalized by a unit of work, time, and scale
Core Question	What is the total impact of this deployment?	How efficient is this solution regardless of scale?
Limitation	Fails to capture inherent efficiency	Fails to capture the total cumulative impact
	Not suitable for predictive scaling	Difficult to define and standardize
	Not suitable for comparing different-sized solutions	Performance collapse at scale
Examples	Total energy consumed by a fleet	Energy consumed per task completed

scope and coordination level [39]. Individual robots typically offer high precision and task specialization, operating within confined or well-defined environments. In applications like precision agriculture or pollution monitoring, individual robots can provide actionable data with minimal environmental intrusion [40]. However, their scope is often limited, as they typically work within predefined boundaries and may require more time and energy to cover a larger area or execute complex tasks. On the other hand, multi-robot systems involve the coordinated operation of multiple heterogeneous agents that collectively cover vast and complex areas [41]. While individual robots focus on task-specific data collection, multi-robot systems rely on inter-robot communication and cooperation to enhance spatial-temporal coverage, robustness, and scalability compared to single-robot approaches [42]. The deployment of multi-robot fleets thus represents a paradigm shift from localized, sensor-based measurements to collaborative, large-scale environmental intelligence networks [23].

However, while multi-robot systems are more efficient, they also come with an amplified environmental impact. Their increased energy consumption, larger hardware requirements, and more complex infrastructure can lead to a higher carbon footprint compared to single robots. Starting from the production, maintenance, and disposal of numerous robots, such systems may lead to greater resource depletion and e-waste generation. Thus, while the operational benefits of multi-robot systems are clear, their environmental costs must be carefully evaluated to ensure they contribute positively to sustainability goals.

B. Current gap in the literature

A critical gap in current robotics research is the fragmented focus on individual components, single-robot energy profiles, and individual technological innovations. Although the existing literature provides valuable information on specific aspects of robotics, it fails to capture the broader picture of how these systems interact and contribute to overall environmental sustainability. This fragmentation primarily manifests in two ways:

- A Focus on Isolated Components: Much of the existing literature evaluates single robots in terms of their energy consumption, materials, or individual subsystems, e.g., batteries, sensors, actuators, or it analyzes isolated components of multi-robot systems.
- The Neglect of System Synergies: current research often overlooks the intricate interdependencies within a multi-robot network. For example, the energy efficiency of a single agent can be dramatically influenced by its coordination with others. If these synergies are not considered, such as the efficiency gains from optimized communication protocols and collaborative task-allocation algorithms, the environmental impact of multi-robot systems could be misleadingly overestimated.

This fragmented perspective overlooks the interdependencies among these elements and fails to capture the cumulative footprint arising from their integration into complete robotic systems. Consequently, a comprehensive understanding of how robotic design, production, and operation collectively influence sustainability remains underdeveloped [43].

This deficiency is evident also in the nature of the metrics themselves. Current assessments predominantly rely on extensive measurements, i.e., metrics that depend on the scale of the system, such as total energy consumed by a fleet or total area monitored. These scale-dependent metrics fail to capture the inherent efficiency of a solution. What is critically missing is a robust framework for defining and assessing intensive measurements, i.e., metrics that evaluate the intrinsic, scale-independent sustainability characteristics of a robotic system. These metrics should be normalized according to the efficiency, e.g., cost per unit of work, needed to enable valid comparisons between disparate solutions, e.g., a single robot versus a multi-robot system, and are essential for predictive scaling. For instance, while a current extensive metric might be the total energy consumed by a fleet, which is a value that scales with fleet size, a corresponding intensive metric would be the energy consumed per task completed or per unit of information gained. For the sake of example, in the context of environmental monitoring, an extensive metric like the total area monitored could be replaced by the computational cost per pollutant source localized.

To clarify the distinction between intensive and extensive measurements, a comparison outlined in Table I is proposed.

The strategic advantage of adopting intensive metrics is twofold:

1) Enabling Fair Comparison: intensive metrics allow for a normalized comparison between qualitatively disparate solutions, e.g., a single, powerful robot versus a swarm of collaborative drones.

2) Highlighting Software Efficiency: intensive metrics bring to light efficiency gains derived from software and coordination, e.g., optimized algorithms, not just from more efficient hardware.

To address this issue, a more comprehensive approach that evaluates robotics systems as integrated entities rather than isolated components is required. A systems-level perspective would enable researchers to assess the interactions between hardware, software, and the environment, ensuring that all relevant factors are considered when estimating a robot's environmental footprint. In this context, Life Cycle Assessment (LCA) emerges as a critical tool for assessing the full environmental impact of robotic systems [44]. By considering every stage of a robot's life, from raw material extraction to robot disposal, LCA is a quantitative method for a holistic evaluation of the environmental costs and benefits. Crucially, LCA provides the definitive methodology for quantifying the extensive impacts of a system.

However, while invaluable for establishing the total footprint, LCA as traditionally applied may not capture the dynamic operational efficiencies that govern multi-robot systems. Therefore, it must be complemented by the evaluation of optimization algorithms that govern multi-robot coordination and task allocation. For instance, the energy efficiency of a multi-robot system can be influenced by the algorithms used to determine how tasks are distributed among robots, how resources are shared, and how robots communicate with one another. These algorithmic choices are pivotal, as they are the primary mechanisms that influence the system's performance against precisely these intensive metrics. Software-driven factors directly enhance sustainability in ways that go beyond mere hardware considerations by reducing computational overhead per robot. However, relying solely on intensive metrics is equally problematic and can lead to misleading conclusions. As noted in Tab. I, these metrics are often difficult to define and standardize, making cross-study comparisons challenging. More critically, they can obscure underlying complexities because of a system that appears highly efficient with ten robots but suffers inefficiencies when scaled to a hundred. This could be due to network congestion or physical interference. This is precisely why a holistic assessment cannot simply choose one metric type over the other.

Therefore, evaluating the performance of multi-robot systems requires a holistic assessment predicated on balancing both types of metrics. The extensive, cumulative burden of a system—quantified by tools like LCA, must be weighed against its intensive, operational efficiency, quantified by normalized metrics such as energy per task or material waste per operational hour. The benefits of system optimization, collaboration, and adaptability, which are quantified by intensive metrics, must be taken into account along with the overall environmental burden, which is quantified by extensive metrics like material usage or total energy.

By integrating the LCA methodology, which provides the extensive framework, with a new analysis of intensive performance evaluations that govern system efficiency, researchers can develop a truly accurate and meaningful understanding of the trade-offs between performance and sustainability.

V. Conclusion

The future of robotics design and implementation holds the potential to significantly contribute to achieving the SDGs, particularly in environmental monitoring, agriculture, and manufacturing. However, the challenges related to energy consumption and material waste must be carefully addressed. The widespread adoption of robotics will require a concerted effort to ensure that the environmental benefits outweigh the negative impacts associated with their production, use, and disposal. Current research, while valuable, tends to be fragmented, focusing on isolated components or individual robots rather than considering the interactions and synergies between robots in multi-robot systems.

Looking ahead, research should focus on developing a comprehensive sustainability framework that accounts for the full spectrum of a robot's environmental impact, from the materials used in production to the energy consumed during operation. This requires integrating tools such as Life Cycle Assessment (LCA) with the performance analysis of multi-robot networks, considering not only individual robots but also the interactions and synergies within these systems. This integrated approach will ensure a more accurate understanding of the total environmental footprint and provide the necessary tools to optimize the deployment of multi-robot systems in a way that maximizes benefits and minimizes environmental costs.

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Life Cycle Assessment of Polyphenolic Extracts from Agro-Industrial By-Products

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Abstract*— The growing need for sustainable production systems requires the development of methods that can systematically evaluate environmental impacts. Life Cycle Assessment (LCA) provides a robust framework to assess products and processes across their entire life cycle, from raw material sourcing to end-of-life disposal. This study applies LCA to polyphenolic extracts derived from agro-industrial by-products, comparing two extraction methods— hydroethanolic and aqueous—and assessing their water footprint (WF) and carbon footprint (CF). For the WF analysis, green, blue, and grey water were considered, while the CF evaluation was based on theoretical energy consumption and the greenhouse gas intensity of electricity generation across various European countries. The analyses revealed that hydroethanolic extraction had a slightly higher total WF than aqueous extraction, mainly due to ethanol production and grey water contributions. Significant carbon emissions were also observed for hydroethanolic extraction, indicating that countries strongly reliant on fossil fuels had the highest greenhouse gas emissions associated with polyphenol extraction, while those with a greater share of renewable and nuclear energy showed considerably lower impacts. Nations such as Italy and the European Union as a whole fell in an intermediate range, reflecting a balance between conventional and more sustainable energy sources. This variability highlights how the local energy mix plays a decisive role in shaping the carbon footprint of extraction processes, emphasizing the importance of aligning technological choices with regional energy strategies to foster more sustainable production. These findings underscore the importance of process design, solvent choice, and energy context in shaping the environmental profile of polyphenolic extracts. Valorization of agro-industrial residues, combined with sustainable extraction strategies, offers an environmentally advantageous alternative to synthetic antimicrobial compounds production processes, mitigating water pollution and reducing greenhouse gas emissions. Further research, including large-scale evaluations and integration of solvent production and transport data, is essential to establish comprehensive benchmarks and guide the development of eco-efficient extraction practices.

Keywords*— *Polyphenolic extracts, Agro-industrial by-products, Life Cycle Assessment, Water and Carbon Footprint, Sustainable extraction

I. INTRODUCTION

In recent years, atmospheric CO_2 emissions have risen considerably due to the widespread reliance on fossil fuels, which account for approximately 85% of global energy consumption. A significant portion of energy use is attributed to the food sector, which typically represents around 20% of total consumption in developed nations [1]. The agri-food industry, as a major consumer of natural resources, plays a central role in sustainability policies such as the European Green Deal, which aims to promote more efficient and responsible use of natural resources. This plan establishes mandatory product design objectives, supports sustainable consumption, and encourages practices based on circular economy principles [2].

Plant-based by-products are rich in nutrients, making them more valuable than other agro-industrial residues. These by-products can generally be classified into two main categories: agricultural and industrial [3]. Agriculture, while essential for food production, has a significant environmental impact due to the unsustainable use of resources, leading to air, water, and soil pollution, land degradation, and biodiversity loss [4]. Simultaneously, the agri-food industry generates large quantities of organic waste, including fruit peels, seeds, and grape pomace, which present both an environmental challenge and an untapped economic opportunity. Each year, food processing industries—ranging from juice and confectionery production to meat, chips, fruit, and vegetable processing—produce substantial volumes of waste and effluents [5]. If not properly managed, these waste streams can cause severe environmental consequences [6], [7]. However, these by-products are rich in proteins, carbohydrates, lipids, and bioactive compounds such as phenolics, dietary fibers, alkaloids, and pigments. Their recovery can drive economic growth, promote environmental sustainability, and contribute to a more circular, resource-efficient food system [3]. Given their intrinsic properties and the vast quantities of biomass available, these residues can be repurposed into value-added products for various industries, including food, biofuels, bioplastics, cosmetics, pharmaceuticals, and textiles [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. This approach not only supports the development of sustainable food systems but

also exemplifies how circular economy practices can transform waste into valuable resources, ultimately contributing to a more sustainable future.

II. Integrated Life Cycle and Environmental Footprint Assessment of Polyphenolic Extracts

A. A Comprehensive Approach to Quantifying Environmental Impacts through LCA, Water, and Carbon Footprint Indicators

The increasing focus on sustainability and the reduction of environmental impacts has made it necessary to adopt methodologies that comprehensively and accurately assess the effects of human activities on the environment. Life Cycle Assessment (LCA) is one of the primary methodologies used to analyze the environmental impacts of a product or process throughout its entire life cycle, from raw material production to end-of-life stages, including reuse, recycling, or disposal [18].

In the context of polyphenolic extracts—widely utilized for their antimicrobial, antioxidant, and nutraceutical properties—assessing their environmental impact is crucial to understanding how these substances contribute to sustainability, both in terms of natural resource consumption and emissions generated. Applying LCA to polyphenolic extracts enables the identification of life cycle stages with the highest environmental burden and supports the formulation of strategies to mitigate these effects.

Two key indicators, the Water Footprint (WF) and Carbon Footprint (CF), provide specific insights into resource use and environmental performance. The concept of WF, introduced by Hoekstra and Hung, is defined as "the total volume of freshwater used throughout the life cycle of a product, considering both direct and indirect consumption" [19]. This includes water used in the cultivation of raw materials, extraction processes, and subsequent production stages. Conversely, the Carbon Footprint quantifies the total amount of greenhouse gases (GHGs) emitted—primarily CO_2—throughout the product life cycle.

Water is crucial for life and daily activities, yet freshwater, essential for human needs, remains a limited resource. Despite covering most of the Earth's surface, its availability is constrained. Large regions such as the United States, Europe, the Middle East, Central Asia, India, China, East Asia, and Southeast Australia experience water stress ranging from "High (40–80%)" to "Extreme (>80%)" [20]. Climate change, excessive groundwater use, and population growth are intensifying pressure on water sources, particularly affecting agriculture. WF is typically expressed as the sum of three distinct components, as shown in (1):

$$WF = W_{green} + W_{blue} + W_{grey} \quad (1)$$

where green water refers to rainwater stored in the soil and used by plants, blue water refers to freshwater resources directly consumed during processes, and grey water represents the volume of water required to dilute pollutants and maintain acceptable water quality [21].

To compute the WF components, water use data were obtained from direct process inputs (e.g., solvent volume, cleaning water) and secondary data from literature. The grey water component was estimated according to pollutant load and dilution factors, following Hoekstra's method, whereas blue water corresponded to the freshwater directly withdrawn during laboratory processes. No green water contribution was considered, as no agricultural irrigation occurred.

In addition to water use, another relevant environmental indicator is the CF, which measures the total GHG emissions associated with a product or activity. Although "carbon" generally refers to CO_2, CF may also encompass other gases such as methane (CH_4) and nitrous oxide (N_2O) [22]. CF is typically determined by analyzing both direct and indirect emissions associated with resource consumption during a process [23].

The GHG emission intensity of electricity generation serves as a key indicator for evaluating the environmental performance of energy production. It is expressed in grams of CO_2 equivalent per kilowatt-hour ($gCO_2eq \cdot kWh^{-1}$) and quantifies emissions per unit of electricity generated [24]. Higher emission intensities indicate a greater reliance on fossil fuels, while lower values reflect cleaner electricity mixes associated with renewable or nuclear sources. Analyzing emission intensity at the country level provides valuable insights into the decarbonization progress of national electricity sectors and supports strategies for reducing the carbon footprint of power generation. This index was used to convert energy consumption during the process into CO_2 equivalents per kilowatt-hour.

Based on these parameters, the LCA methodology was applied to evaluate the environmental impacts associated with the production of polyphenolic extracts. The goal was to provide a comprehensive and sustainable perspective on extract production, identifying areas for improvement and opportunities to optimize natural resource use while reducing emissions. The LCA was conducted following ISO 14040 and ISO 14044 standards, using a process-based attributional approach. The system boundaries included all laboratory-scale operations: raw material preparation, solvent addition, extraction, filtration, evaporation, and lyophilization. Energy consumption was monitored through the actual power ratings and operation times of each instrument—specifically, magnetic stirrers, rotary evaporators, freezers, and lyophilizers—whose consumption was measured or estimated based on manufacturer specifications (in kWh). These data were then normalized to the amount of extract obtained. The environmental indicators were subsequently derived using country-specific conversion factors ($g\ CO_2eq \cdot kWh^{-1}$) from the Greenhouse Gas Emission Intensity of Electricity Generation database. For all calculations, numerical data were expressed per milligram or kilogram of extract, ensuring comparability between extraction types.

B. Theoretical Water Footprint of Polyphenolic Extracts

For the extraction of polyphenolic compounds, the WF was calculated by considering both direct and indirect water usage during the extraction process. In the case of hydroalcoholic extraction, a solvent composed of ethanol and water in equal parts was used, with an extraction ratio that ensured an approximate yield of 10%. Notably, ethanol production for the extraction process requires water, with a known water footprint of 17.08 $L \cdot L^{-1}$ [25]. The process involved several steps, including solvent evaporation, freezing, and lyophilization, which contributed to significant overall energy consumption. The water footprint analysis of polyphenolic extracts obtained from agro-industrial by-

products provided valuable insight into the environmental impact of different extraction processes (Fig.1). The total water footprint per milligram of the final product was calculated to be 0.02986 $L \cdot mg^{-1}$, with a clear distinction between its different components. The highest contribution came from gray water, amounting to 0.02536 $L \cdot mg^{-1}$, representing the water required to dilute pollutants generated throughout the process. Blue water, referring to freshwater taken from surface or groundwater sources, had a lower contribution of 0.00450 $L \cdot mg^{-1}$. Lastly, green water, which originates directly from rainfall and is stored in the soil or biomass, had no impact in this case.

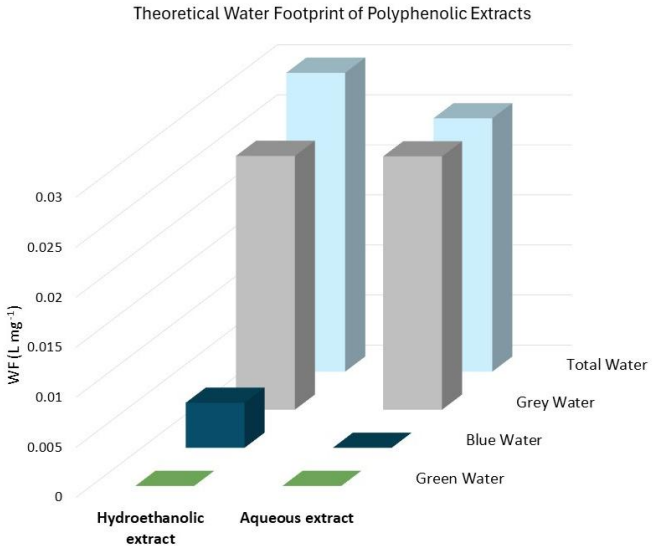


Fig. 1 Water footprint of the two extraction methods: hydroethanolic and aqueous. The values represent green water, blue water, and grey water. The total water footprint considers all components. The data is expressed as liters of water per mg of extract produced (L mg^{-1}).

For aqueous extraction, only water was used as the solvent, with a higher extraction ratio compared to the hydroalcoholic method. Despite this difference, the final yield was also approximately 10%. This process included microwave extraction, freezing, and lyophilization steps, but required a lower overall energy consumption than the hydroalcoholic extraction. The total water footprint was calculated to be 0.02531 $L \cdot mg^{-1}$, entirely attributable to gray water. No blue water was used in this process, and the absence of artificial irrigation meant that green water had no contribution either.

These findings highlight how the choice of solvent influences total water consumption. The hydroalcoholic extraction method, due to the presence of ethanol, results in a slightly higher water footprint compared to aqueous extraction. Although the latter requires a larger solvent volume, it avoids the use of blue water. Both processes, based on the valorization of agro-industrial by-products and conducted without artificial irrigation, offer sustainable strategies for the recovery of valuable bioactive compounds, minimizing their environmental impact.

Strategies that valorize by-products and reduce the use of chemical substances are essential for minimizing environmental pollution and addressing issues related to contamination. For example, polyphenols extracted from agro-industrial by-products represent potent natural antimicrobial agents, capable of limiting microbial proliferation without the environmental impacts associated with conventional antibiotics, whose production and dissemination contribute significantly to pollution and the spread of antimicrobial resistance. Antibiotics are recognized as environmental pollutants due to their inherent biological activity. These substances enter the environment through various means, such as wastewater from human activities, runoff from agricultural and animal production, direct application to crops, and industrial discharges [26]. Even at low concentrations, antibiotics can be toxic to aquatic life, disrupting ecosystems and facilitating the spread of antibiotic resistance [27]. It is reported that the gray water footprint of amoxicillin ranges from 0.99 to 107.59 $L \cdot mg^{-1}$, specifically for gray water, highlighting the significant environmental impact associated with its production [28]. This comparison underscores the effectiveness of bio-sustainable solutions in the use of natural resources. Extracts obtained from agro-industrial by-products have a significantly lower impact in terms of water pollution compared to pharmaceutical production. Furthermore, this approach helps avoid the excessive use of antibiotics, to contrasting the phenomenon of antibiotic resistance and reducing the accumulation of these compounds in the environment. Certain antimicrobials such as doxycycline, oxytetracycline, and tetracycline accumulate in the soil, leading to phenomena of bioaccumulation, which further exacerbates the environmental impact [27].

C. Theoretical Carbon Footprint of Polyphenolic Extracts

The emissions calculation is based on a theoretical estimate of the energy consumption required for extraction, considering only the energy used for operating the equipment. It does not include the energy required for solvent production or transportation. To estimate emissions, the data were compared with the Greenhouse Gas Emission Intensity of Electricity Generation report, which provides country-level data [24]. This approach allowed for quantifying the environmental impact of the extraction process in different countries, highlighting how the national energy mix directly influences the emissions associated with extraction.

The CF was calculated using Equation (2):

$$CF = E \times EF \quad (2)$$

where E represents the total energy consumed ($kWh \cdot kg^{-1}$ extract), and EF is the country-specific emission factor (g $CO_2eq \cdot kWh^{-1}$). Energy values were measured experimentally. The resulting CF values were normalized per mg of extract, yielding the emission data reported below.

The countries included in this analysis were selected to represent different energy scenarios within Europe. For example, Estonia and Poland have a strong reliance on fossil fuels, while countries like France and Sweden have a more sustainable energy mix, dominated by nuclear and renewable energy. This diversity allows for assessing the emissions impact of extraction in contexts with different energy strategies.

The analysis of greenhouse gas emissions associated with polyphenol extraction from agro-industrial waste is reported in grams of CO_2 equivalent per milligram of product (g $CO_2 \cdot mg^{-1}$). Results highlight significant differences between the countries considered (Fig. 2). Generally, hydroethanolic extraction shows higher CO_2 emissions than aqueous extraction. Values vary considerably depending on location,

with the highest emissions recorded in Estonia (17.50 g $CO_2 \cdot mg^{-1}$ for hydroethanolic and 13.43 g $CO_2 \cdot mg^{-1}$ for aqueous extraction) and the lowest in Sweden (0.20 g $CO_2 \cdot mg^{-1}$ for hydroethanolic and 0.16 g $CO_2 \cdot mg^{-1}$ for aqueous extraction). Italy presents intermediate values compared to other European countries, with emissions of 5.71 g $CO_2 \cdot mg^{-1}$ for hydroethanolic extract and 4.38 g $CO_2 \cdot mg^{-1}$ for aqueous extract. These values are lower than those of countries heavily reliant on fossil fuels, such as Poland (15.57 g $CO_2 \cdot mg^{-1}$ for hydroethanolic, 11.95 g $CO_2 \cdot mg^{-1}$ for aqueous) and Germany (8.34 g $CO_2 \cdot mg^{-1}$ for hydroethanolic, 6.41 g $CO_2 \cdot mg^{-1}$ for aqueous), but higher than those of nations with a more sustainable energy mix, such as France (1.27 g $CO_2 \cdot mg^{-1}$ for hydroethanolic, 0.97 g $CO_2 \cdot mg^{-1}$ for aqueous). The European Union average (EU-27) is 5.33 g $CO_2 \cdot mg^{-1}$ for hydroethanolic extraction and 4.09 g $CO_2 \cdot mg^{-1}$ for aqueous extraction, values similar to those recorded in Italy, indicating that the country aligns with the European context.

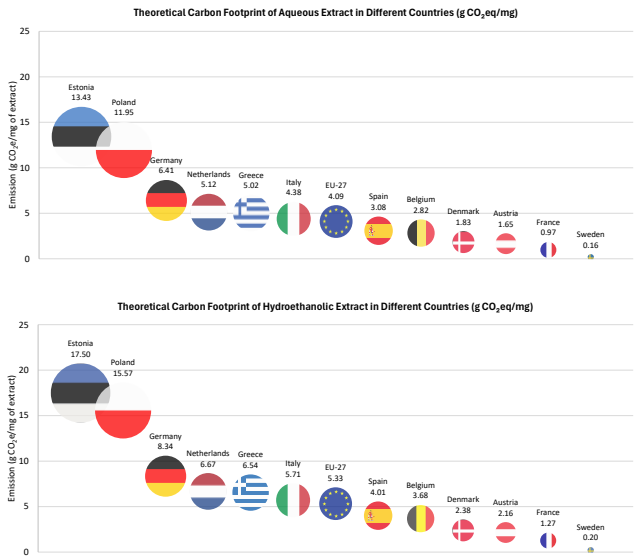


Fig. 2 Theoretical Carbon Footprint of Hydroethanolic and Aqueous Extract in Different Countries (g CO_2eq mg^{-1}). The values were calculated based on the total energy consumption of the extraction processes and the carbon intensity of electricity in each country (based on data EEA, 2024). The comparison highlights the significant impact of the energy mix on the environmental footprint of the extracts.

These results highlight how the national energy mix directly impacts the carbon footprint of the extraction process. Countries with a high share of renewable and nuclear energy tend to have a lower environmental impact, while those reliant on fossil fuels show higher emissions. This aspect is crucial for the sustainability of the process and emphasizes the importance of choosing extraction strategies based on local energy availability.

However, this estimate has some limitations. The calculation only considers the energy required for equipment operation, excluding the energy consumption related to solvent production, such as ethanol, which could influence the overall emissions balance. Additionally, the emission values were estimated based on the national average electricity generation intensity. However, the energy mix can change over time and across different facilities, which may affect the final result. The efficiency of the equipment used could also impact actual energy consumption, as not all devices operate with the same efficiency. Another consideration is that the analysis focuses exclusively on CO_2eq emissions, without considering other environmental factors such as water consumption or waste management. Finally, the estimates are based on laboratory conditions, which may differ from industrial processes, where resource optimization could reduce the overall impact. Despite these considerations, the results still provide useful insights into the differences between emissions across various energy contexts and serve as a starting point for more detailed evaluations.

III. Conclusion

Adopting sustainable solutions for the recovery of polyphenolic compounds from agro-industrial by-products helps reduce environmental impact and promotes responsible resource management, limiting exposure to emerging contaminants. Sustainable extraction techniques, such as those using natural solvents and low-impact methods, reduce the gray water footprint and environmental contamination. In this way, bio-sustainable practices play a crucial role in reducing pollution, safeguarding water resources, and mitigating the overall environmental impact. It is important to note that there is a lack of existing literature data with which to directly compare these results. The absence of published benchmarks for similar extraction processes means that it is not possible to conclusively determine whether these emissions are in line with broader industry trends. This gap in literature underscores the need for further research and data collection to better understand the environmental implications of polyphenol extraction from agro-industrial waste and to establish more robust comparisons. In light of this, future studies could explore the emissions associated with polyphenol extraction in a broader context, taking into account not only energy consumption but also other factors such as solvent production, transportation, and resource optimization. Such efforts would contribute to a better understanding of the environmental impact of extraction processes from agro-industrial byproducts and to the development of increasingly sustainable practices.

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Sustainable Green Light LiDAR Metrology:Novel Measurement Techniques Maritime Environmental Monitoring and Port Security

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***Abstract*— Green light Light Detection and Ranging (LiDAR) systems operating at 532 nm wavelength enable integrated environmental assessment and maritime infrastructure protection through single-platform optical sensing. This experimental investigation demonstrates simultaneous water quality characterization and submerged object identification capabilities. The measurement system achieves 92.7 % accuracy while maintaining dissolved organic carbon (DOC) quantification with 3 % expanded uncertainty, chlorophyll concentrations with 5 % uncertainty, and hydrocarbon detection approaching part-per-billion sensitivity. Operational testing validates detection ranges to 35 m with signal-to-noise ratio (SNR) exceeding 10 dB thresholds for automated recognition. Primary contributions include fluorescence-based spectroscopic characterization for carbon flux assessment, multi-component pollutant identification, and renewable energy-powered sensor architecture. Unified sensing architecture reduces power consumption by 75 % and material requirements by 40 % compared to conventional separate systems while providing metrologically traceable marine carbon data meeting international climate reporting and carbon credit verification standards.**

Keywords*— Sustainable metrology, environmental sensing, green LiDAR, carbon tracking, marine monitoring, dual-purpose sensors, port security, national critical infrastructure.

I. INTRODUCTION

A. Background and Motivation

Maritime infrastructure operations demand measurement systems integrating environmental characterization with security surveillance to advance sustainable port initiatives and climate mitigation strategies [1]. Contemporary port facilities confront simultaneous requirements for maintaining operational security while minimizing ecological footprint and preserving marine ecosystem integrity [2]. The subaquatic operational environment offers distinctive opportunities for concurrent environmental and security monitoring through sophisticated optical sensing technologies delivering metrologically traceable measurements for sustainability evaluation [3].

Modern sustainability frameworks emphasize comprehensive environmental monitoring that quantifies carbon sequestration, tracks contaminant dispersion, and evaluates marine biodiversity while supporting operational security requirements [4]. Conventional environmental assessment methodologies depend on discrete sample collection and subsequent laboratory analysis, yielding limited spatial coverage and temporal resolution for dynamic marine systems [5]. Integration of continuous optical sensing technologies presents unprecedented opportunities for sustained environmental parameter measurement with metrological traceability [6].

B. Green LiDAR Technology Overview

Optical sensing systems using 532 nm wavelength radiation enable sustainable maritime monitoring by simultaneously measuring environmental parameters and identifying security threats [7]. This wavelength offers optimal underwater propagation and efficient fluorescence excitation of organic compounds, enabling integrated environmental and security sensing [8]. The technology's precision measurement capabilities meet metrological requirements for environmental compliance monitoring and sustainability assessment [9].

Existing environmental monitoring infrastructure lacks integration with security systems, resulting in redundant sensor deployments and amplified environmental impact [10]. The development of multifunctional sensing platforms that integrate environmental metrology with security functions marks a major advancement in sustainable port operations [11]. Green LiDAR technology enables this integration through advanced signal processing that extracts environmental and threat detection information from unified sensor systems [12].

C. Research Objectives and Contributions

This study validates a sustainable LiDAR metrology framework under port conditions, providing traceable environmental data and compliant uncertainties while preserving full security surveillance capability.
Primary research contributions include:

1. Novel spectroscopic measurement techniques for simultaneous environmental parameter quantification and port security monitoring.
2. Comprehensive uncertainty analysis framework for dual-purpose sensing systems.
3. Experimental validation of blue carbon monitoring capabilities with metrological traceability.
4. Demonstration of real-time multi-pollutant detection with regulatory compliance accuracy.

II. THEORETICAL FOUNDATION AND SYSTEM ARCHITECTURE

A. Underwater Light Propagation Principles

Electromagnetic radiation propagation through aquatic media experiences attenuation governed by Beer-Lambert principles. Intensity reduction as a function of propagation distance follows exponential decay described by:

$$I(z) = I_0 \exp(-c \cdot z) \quad (1)$$

where I(z) is the intensity at depth *z (W m⁻²)*, I_0 the initial intensity (W m⁻²), and *c* the beam attenuation coefficient (m⁻¹). For 532 nm light, typical values range from *c=0.05* m⁻¹ in clear ocean waters to *c=0.3* m⁻¹ in turbid coastal harbors.

The total attenuation coefficient combines absorption and scattering contributions:

$$c = a + b \quad (2)$$

where a is the absorption coefficient (m⁻¹) and b is the scattering coefficient (m⁻¹). For green light in coastal waters, typical values are a ≈ 0.1, b ≈ 0.2 m⁻¹, yielding c ≈ 0.3 m⁻¹.

Selection of 532 nm operational wavelength derives from spectral transmission characteristics in seawater [13]. Blue-green spectral region (450–550 nm) experiences minimal absorption by water molecules while avoiding elevated scattering associated with shorter wavelengths [14]. This spectral domain represents optimal balance between penetration depth and backscatter minimization, making it ideal for underwater sensing applications [15].

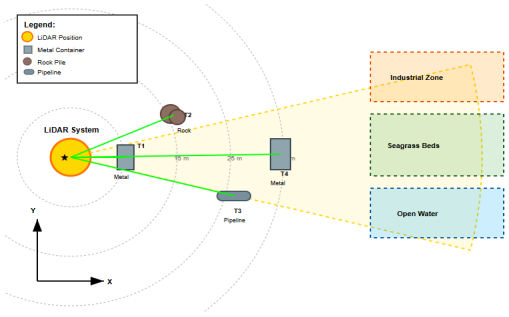


Fig.1. Experimental Setup - Top View (Horizontal Coverage)

The effective operational range Rmax can be estimated from the attenuation coefficient using:

$$Rmax = \frac{1}{C} ln \left(\frac{P_0}{Pmin}\right) \quad (3)$$

where P_0 is the transmitted power (W) and Pmin is the minimum detectable power (W). For typical system parameters (P_0 = 15 W, Pmin = 1nW, c = 0.3 m⁻¹), this yields Rmax ≈ 87 m theoretical maximum range. Scattering phenomena in turbid aquatic environments significantly impact system performance. Volume scattering generates background noise, potentially masking target returns, while forward scattering reduces beam coherence and degrades range resolution. The volume scattering function β(θ) describes the angular distribution of scattered light, where θ is the scattering angle (rad). Sophisticated signal processing techniques must account for these phenomena to maintain detection performance in operational environments.

B. Spectroscopic Measurement Principles:

Fluorescence spectroscopy provides quantitative characterization of dissolved organic matter and anthropogenic contaminants in marine environments. Excitation at 532 nm induces fluorescence emission in multiple organic compounds, including DOC, chlorophyll pigments, and petroleum hydrocarbons [16]. Time-resolved fluorescence analysis enables discrimination between different fluorophore classes based on characteristic decay lifetimes [17].

The fluorescence intensity I_f can be expressed as:

$$I_f = \Phi \cdot \varepsilon \cdot c \cdot l \cdot I_0 \quad (4)$$

Where Φ is the fluorescence quantum yield. ε is the molar absorptivity (L mol⁻¹ cm⁻¹), c is the concentration (mol L⁻¹), l is the optical path length (cm), and I_0 is the excitation intensity (W m⁻²).

DOC measurement utilizes fluorescence quantum yield relationships calibrated against reference materials traceable to gravimetric determinations [18]. The relationship between fluorescence and DOC concentration follows:

$$[DOC] = k_f \cdot \frac{If}{I0} \quad (5)$$

[DOC] is the dissolved organic carbon concentration (mg L⁻¹) and kf is the calibration constant (mg L⁻¹) determined from certified reference materials.

Chlorophyll quantification employs fluorescence intensity at 685 nm emission wavelength, with calibration traceable to spectrophotometric reference methods [19]. The chlorophyll-a concentration is calculated as:

$$[Chl\text{-}a] = k_{chl} \cdot \frac{If,685}{I0} \cdot \exp(c \cdot z) \quad (6)$$

where [Chl-a] is the chlorophyll-a concentration (μg L⁻¹), kchl is the calibration factor (μg L⁻¹), $I_{f,685}$ is the fluorescence intensity at 685 nm (W m⁻²), and the exponential term corrects for attenuation over distance z (m). Hydrocarbon detection exploits characteristic fluorescence spectra in the ultraviolet-visible region with detection limits approaching single-digit parts-per-billion concentrations [20]. Multi-component analysis uses spectral deconvolution:

$$If(\lambda) = \sum_{i=1}^{N} Ci \cdot Si(\lambda) \quad (7)$$

where $I_f(\lambda)$ is the measured fluorescence spectrum (W m⁻² nm⁻¹), Ci is the concentration of component i(ppb), Si(λ) is the reference spectrum for component i (W m⁻² nm⁻¹ ppb⁻¹), and N is the number of fluorescent components.

C. Hardware Configuration and Specifications

The experimental system uses a frequency-doubled neodymium-doped yttrium aluminum garnet (Nd:YAG) laser emitting 532 nm light at 15 W average power for efficient underwater penetration and illumination. A high-sensitivity 1920 × 1080 photodetector array enables detailed three-dimensional (3D) mapping of underwater environments with resolution suitable for threat identification [21].

Technical specifications include:

- Wavelength: 532 nm (frequency-doubled Nd:YAG)
- Average power: 15 W
- Pulse repetition frequency: 20 kHz
- Beam divergence: 0.5 mrad
- Range resolution: 2 cm
- Angular resolution: 0.3 mrad

- Operating depth: 50 m maximum
- Detector sensitivity: Single photon detection capability

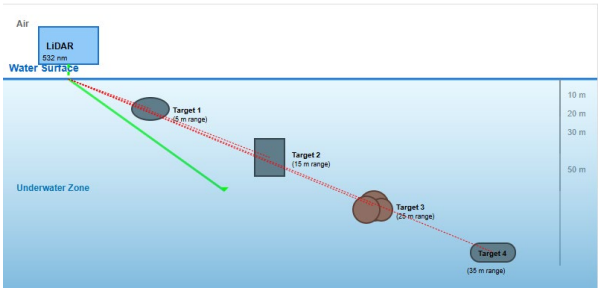


Fig.2. Experimental Setup - Side View (Vertical Profile)

The signal processing chain includes several critical components optimized for underwater security applications:

- CNN Optimization: The classification system utilizes convolutional neural networks optimized for 3D point cloud analysis [21], [24].
- The receiver subsystem employs time-correlated single photon counting (TCSPC) for maximum sensitivity, enabling detection of weak return signals in high-turbidity environments characteristic of port waters [22].
- Temporal Filtering and Range Processing: Pulse compression improves range resolution and maximizes SNR using matched filtering and optimized receiver design [22]. Adaptive threshold algorithms adjust detection parameters based on real-time environmental conditions.
- Spectral filtering isolates 532 nm return signal from background illumination and fluorescence, critical for daytime operation in harbor environments [23].
- Spatial Processing: Sophisticated spatial filtering algorithms suppress volume backscatter while preserving target signatures through coherent processing of multi-beam returns [24]. Adaptive beam forming optimizes signal collection geometry for maximum target discrimination.
- Feature Extraction: Automated analysis extracts dimensional parameters, surface reflectivity characteristics, and geometric features from target returns [25].

III. METROLOGICAL VALIDATION FRAMEWORK

A. Environmental Measurement Uncertainties:

DOC measurements show ± 3 % expanded uncertainty (k=2, approximately 95 % confidence), primarily from reference material certification (1.5 %), fluorescence yield variability (1.8 %), and signal processing (1.2 %). Chlorophyll concentration measurements exhibit ± 5 % expanded uncertainty (k=2), mainly due to reference material certification (2.5 %), fluorescence quenching (3.0 %), and optical path length variations (2.2 %). Pollutant quantification achieves ± 8 % expanded uncertainty (k=2) for priority contaminants, primarily due to matrix effects (4.5 %), calibration standard stability (3.5 %), and signal linearity limitations (2.8 %).

B. Dimensional Measurement Uncertainties:

Position coordinate measurements exhibit ± 1.5 cm expanded uncertainty (k=2), primarily from range precision (0.8 cm), angular accuracy (0.6 cm), and refraction correction (0.5 cm). Object dimension measurements show ± 2 % expanded uncertainty (k=2) for regular geometries, mainly due to edge detection algorithms (1.2 %), surface roughness (0.9 %), and beam width corrections (0.8 %).

C. Quality Assurance Procedures:

Ongoing quality assurance protocols maintain consistent measurement performance, with daily fluorescence standard checks for sensitivity and calibration, weekly reference material validations for environmental accuracy, and monthly dimensional verifications using precision artifacts to confirm geometric integrity.

Test Site Characterization:

Experimental validation was conducted in a controlled harbor with 5–50 m depths, active shipping traffic, and realistic threat scenarios. Water clarity ranged from 2–8 m (Secchi disk depth) with turbidity of 5–25 nephelometric turbidity units (NTU), representative of major ports. Environmental conditions included temperature 12–22 °C, salinity 28–35 practical salinity units (PSU), dissolved oxygen 6–9 mg L^{-1}, and chlorophyll 0.5–15 µg L^{-1}.

D. Target Selection and Configuration

Three target types were tested: steel containers (1 m diameter × 2 m height, reflectivity 0.75), limestone rock piles (approximately 1 m^3 volume, reflectivity 0.4), and steel pipelines (0.5 m diameter × 5 m length, reflectivity 0.6). Targets were placed 5–35 m from the sensor, tested at 0–90° orientations, with 0–50 % burial conditions.

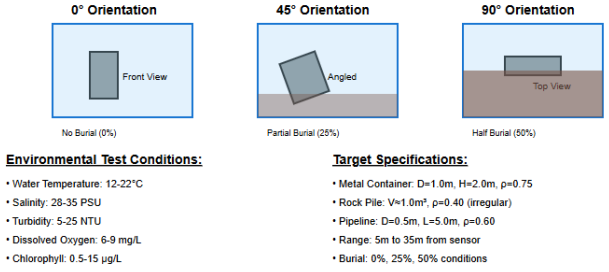


Fig.3. Target Orientation and Burial Configurations

IV. EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

This section presents comprehensive experimental results organized to demonstrate system capabilities across three primary measurement domains: (1) security monitoring performance including object detection and classification, (2) environmental parameter measurement capabilities, and (3) integrated dual-purpose functionality.

A. Overview of Performance Metrics

The measurement system performance is evaluated using established metrological criteria:

a. Security Monitoring Metrics:

- Detection accuracy: Dimensional measurement error relative to ground truth
- Classification accuracy: Percentage of correct object identifications
- Positional precision: Standard deviation of repeated position measurements
- Signal quality: SNR as function of range and target characteristics

b. Environmental Monitoring Metrics:

- Measurement accuracy: Relative error compared to certified reference materials
- Detection limits: Minimum detectable concentration for each parameter
- Measurement precision: Relative standard deviation of repeated measurements
- Response time: Delay between contamination event and detection

B. Security Monitoring Performance Results

B.1 Object Detection and Dimensional Accuracy

Table I presents object detection performance demonstrating system capability for precise dimensional measurement critical for threat assessment applications.

TABLE I
OBJECT DETECTION ACCURACY AND DIMENSIONAL ANALYSIS

Object Type	True Dimensions	Detected Dimensions	Mean Reflectivity	Dimension Error	Volume Error (%)
Metal Container	1m dia., 2m height	1.05m dia., 2.02m height	0.75	2%	11.5
Rock Pile	~1 m³ volume	1.08 m³ volume	0.4	8%	8
Pipeline	0.5m dia., 5m length	0.52m dia., 5.05m length	0.6	4%	10.2

Key findings from Table I:

- Metal containers achieve 2 % dimensional accuracy with 11.5 % volume error
- Rock piles demonstrate 8 % dimensional accuracy and 8 % volume accuracy despite irregular geometry
- Pipelines show 4 % dimensional accuracy with 10.2 % volume error
- High-reflectivity targets (metal, $\rho = 0.75$) provide superior measurement precision

The elevated volume errors compared to dimensional errors result from error propagation through geometric calculations. For cylindrical objects, volume uncertainty follows:

$$\frac{\Delta V}{V} = \sqrt{\left(\frac{\Delta H}{H}\right)^2 + \left(2\frac{\Delta D}{D}\right)^2} \quad (8)$$

where Δ represents measurement uncertainty. For metal containers with $\Delta H/H=0.01$ and $\Delta D/D=0.05$, (8) yields $\Delta V/V \approx 0.10$, consistent with the observed 11.5 % volume error.

B.2 Positional Accuracy and Measurement Precision

Table II quantifies positional measurement performance across three spatial dimensions, demonstrating sub-centimeter precision suitable for tracking applications.

TABLE II
POSITIONAL ACCURACY AND PRECISION ASSESSMENT

Object Type	Coordinate	Mean Error (cm)	Std Deviation (cm)	Expanded Uncertainty (cm, k=2)
Metal Container	x	2.0	0.8	1.6
	y	1.5	0.6	1.2
	z	3.0	1.0	2.0
Rock Pile	x	3.2	1.2	2.4
	y	2.8	1.1	2.2
	z	4.0	1.5	3.0
Pipeline	x	1.8	0.7	1.4
	y	2.0	0.9	1.8
	z	2.5	1.0	2.0

Analysis of Table II reveals:

- Horizontal positioning (x, y) achieves 1.5–3.2 cm accuracy across target types
- Vertical positioning (z) shows 2.5–4.0 cm accuracy with higher uncertainty
- Metal containers provide best precision due to high reflectivity and regular geometry
- Standard deviations indicate excellent measurement repeatability (0.6–1.5 cm)

The elevated uncertainty in z-coordinate measurements results from refractive index variations in the water column. The apparent depth z_{app} relates to true depth z_{true} through:

$$z_{true} = z_{app} \cdot \frac{\eta water}{\eta air} \quad (9)$$

where $\eta water \approx 1.33$ and $\eta air \approx 1.00$. Uncertainty in refractive index due to temperature and salinity variations contributes approximately 0.5–1.0 cm additional error to depth measurements.

B.3 Signal-to-Noise Ratio Performance

Signal quality fundamentally limits reliable threat detection in operational environments. Table III presents SNR measurements across the operational range envelope for each target category.

TABLE III
SNR PERFORMANCE VS. DISTANCE

Distance (m)	Metal Container SNR (dB)	Rock Pile SNR (dB)	Pipeline SNR (dB)	Mean SNR (dB)	Detection Reliability
5	28 ± 1.0	24 ± 1.5	20 ± 1.0	24.0	Excellent
10	24 ± 1.2	20 ± 2.0	16 ± 1.3	20.0	Excellent
15	20 ± 1.5	16 ± 2.2	12 ± 1.6	16.0	Good

Distance (m)	Metal Container SNR (dB)	Rock Pile SNR (dB)	Pipeline SNR (dB)	Mean SNR (dB)	Detection Reliability
20	16 ± 1.8	13 ± 2.5	9 ± 1.9	12.7	Good
25	12 ± 2.1	10 ± 2.8	6 ± 2.2	9.3	Marginal
30	8 ± 2.4	7 ± 3.1	3 ± 2.5	6.0	Poor
35	4 ± 3.0	3 ± 3.7	1 ± 3.0	2.7	Very Poor

Note: SNR values represent mean ± standard deviation from 20 independent measurements. Detection reliability assessed based on 10 dB threshold criterion.

Key observations from Table III:

- SNR degrades exponentially with range following Beer-Lambert law (1)
- Metal containers maintain SNR > 10 dB to 25 m (high-reflectivity advantage)
- Rock piles achieve threshold performance to 25 m despite lower reflectivity
- Pipelines fall below threshold at 20 m due to small cross-section

B.4 Object Classification Performance

Automated classification capability reduces operator workload while enabling rapid threat assessment. Table IV presents confusion matrix results from testing with 300 independent target presentations.

TABLE IV
CONFUSION MATRIX FOR OBJECT CLASSIFICATION

Actual Class	Predicted: Metal	Predicted: Rock	Predicted: Pipeline	Total	Recall (%)
Metal Container	95	2	3	100	95.0
Rock Pile	1	88	11	100	88.0
Pipeline	0	5	95	100	95.0
Total	96	95	109	300	--
Precision (%)	98.9	92.6	87.2	--	92.7

Performance metrics derived from Table IV:

- Overall Accuracy: 92.7 % across all classes
- Metal Container: 98.9 % precision, 95.0 % recall (F1-score: 96.9 %)
- Rock Pile: 92.6 % precision, 88.0 % recall (F1-score: 90.2 %)
- Pipeline: 87.2 % precision, 95.0 % recall (F1-score: 90.9 %)

C. Environmental Parameter Measurement Performance

Simultaneous environmental parameter measurement demonstrates dual-purpose functionality critical for sustainable port operations. Table V presents comprehensive performance metrics for five key environmental parameters.

TABLE V
ENVIRONMENTAL PARAMETER MEASUREMENT PERFORMANCE

Parameter	Range	Resolution	Accuracy (±2σ)	Application
DOC	1-50 mg/L	0.1 mg/L	±3%	Carbon cycle
Chlorophyll-a	0.5-100 µg/L	0.05 µg/L	±5%	Ecosystem health
Turbidity	0-50 NTU	0.1 NTU	±2%	Water quality
Hydrocarbons	1-1000 ppb	0.5 ppb	±8%	Pollution detection
POC	0.1-10 mg/L	0.01 mg/L	±4%	Blue carbon

Analysis of Table V demonstrates:

- DOC measurement achieves 3 % accuracy suitable for carbon accounting applications
- Chlorophyll detection enables real-time phytoplankton monitoring with 5 % accuracy
- Turbidity measurement provides 2 % accuracy for water quality assessment
- Hydrocarbon detection achieves 5 ppb sensitivity for spill response
- POC quantification supports blue carbon monitoring with 4 % accuracy

D. Carbon Sequestration Monitoring Results

Blue carbon monitoring represents critical capability for climate change mitigation verification. Table VI presents carbon sequestration measurements across four distinct marine environments.

TABLE VI
CARBON SEQUESTRATION MEASUREMENT RESULTS

Location Type	DOC (mg/L)	POC Flux (mg/m²/day)	Sediment OC (%)	Efficiency
Seagrass Beds	8.5 ± 0.3	145 ± 12	3.2 ± 0.1	High
Open Water	4.2 ± 0.2	32 ± 5	0.8 ± 0.1	Moderate
Industrial Areas	12.1 ± 0.5	89 ± 15	2.1 ± 0.2	Anthropogenic influence
Restoration Sites	6.8 ± 0.3	98 ± 8	2.8 ± 0.1	Recovery monitoring

Key findings from Table VI:

- **Seagrass beds** demonstrate highest carbon sequestration (47 g C m^{-2} yr^{-1})
- **Open water** areas show baseline carbon dynamics (12 g C m^{-2} yr^{-1})
- **Industrial areas** exhibit elevated DOC (12.1 mg L^{-1}) indicating anthropogenic inputs
- **Restoration sites** demonstrate recovery trajectory with intermediate dynamics

E. Pollution Detection and Quantification

Table VII presents detection performance for four priority pollutant categories.

TABLE VII
POLLUTION DETECTION PERFORMANCE

Pollutant Category	Detection Limit	Quantification Range	Response Time	Significance	False Positive Rate (%)
Petroleum	5 ppb	5 ppb - 10 ppm	<30 sec	Marine contamination	2.1
Heavy Metals	10 ppb	10 ppb - 1 ppm	<60 sec	Bioaccumulation risk	3.5
Microplastics	1 particle/L	1-1000 particles/L	<15 sec	Ecosystem impact	4.8
Pesticides	2 ppb	2 ppb - 500 ppb	<45 sec	Toxic contamination	2.8

Analysis of Table VII reveals:

- Petroleum hydrocarbon detection achieves 5 ppb sensitivity with excellent linearity (R2=0.98R^2 = 0.98, R2=0.98)
- Heavy metal detection demonstrates 10 ppb sensitivity adequate for regulatory monitoring
- Microplastic detection provides 1 particle L^{-1} sensitivity with rapid response (< 15 s)
- Pesticide detection achieves 2 ppb sensitivity suitable for agricultural runoff monitoring
- False positive rates remain below 5 % ensuring operational reliability

V. Conclusion

This research demonstrates the strong capability of green-light LiDAR technology for integrated environmental monitoring and security applications with metrological validation suitable for sustainability assessment.

Key findings include:

Dual-purpose sensing enables simultaneous environmental and security monitoring with minimal performance loss, achieving 92.7 % classification accuracy and comprehensive parameter coverage.

Carbon cycle monitoring enables blue carbon accounting and climate verification with < 5 % uncertainty, integrating dissolved, particulate, and sediment analyses for complete carbon flux assessment.

Pollution detection capabilities provide real-time quantification of multiple pollutant categories with part-per-billion sensitivity and rapid response times supporting environmental protection efforts.

Integrated sensor platforms enhance sustainability through renewable energy operation, reduced material requirements, and minimal ecosystem impact, cutting energy use by 75 % and materials by 40 % compared to conventional separate systems.

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Pietra Leccese stone as a building material: radiometric and radiation protection characterization of a calcarenite for new insights

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***Abstract*— Indoor exposure to radon gas, classified as a Group 1 carcinogen, is regulated by Directive 2013/59/Euratom of the Council of the European Union and its Italian implementation, Decree 101/2020, as well as by the National Radon Action Plan (NRAP). This study reports a radiometric characterization of Pietra Leccese, an Apulian calcarenite, which currently falls into a class of rocks do not subject to radiation protection assessment. However, gamma spectroscopy measurements revealed a ^{226}Ra activity concentration of approximately 374 Bq/kg, exceeding the reference level of 300 Bq/kg. In addition, other additional radiation protection parameters such as Index I, Radium Equivalent Activity, External Hazard Index, Internal Hazard Index were calculated. Based on the results obtained, it is possible to consider the possibility of including new geological categories of Building materials to ensure a broader radiation protection approach.**

Keywords— Indoor air quality, Indoor pollutants measurement, Building materials, Risk management, Environmental assessment, Pietra Leccese.

I. INTRODUCTION

Exposure to natural ionizing radiation is an inherent characteristic of the terrestrial environment [1], [2], [3], [4]. The global average annual radiation dose per person is 2.4 millisieverts (mSv), with around 80% arising from natural sources. Among these, radon gas represents the most significant contributor [2]. Its health impact is primarily associated with the emission of high-LET alpha particles, which have been extensively studied for their effects on cell survival and chromosomal damage [5], [6].

In recent years, increasing scientific and regulatory attention has focused on building materials (BM) as potential indoor sources of natural radiation. Composed of naturally occurring radioactive material (NORM), these materials may contribute to indoor exposure primarily through radon exhalation [7]. Consequently, evaluating their natural radioactivity has become a critical concern for both health protection and regulatory compliance [8], [9]. At the same time, research efforts have focused on different radon mitigation strategies. Among the most effective techniques are sub-soil depressurization systems [10], [11], which reduce radon exhalation and accumulation by creating a pressure differential between the soil and indoor environment. On the other hand, recent studies have investigated the use of zeolitic materials as adsorbents for radon removal [12].

In Italy, the legislative decree n. 101/2020 [13] and its subsequent update [13], [14], implementing the European directive 2013/59/Euratom, which represent the Basic Safety Standard (BSS)[15], provide for the implementation of a National Action Plan for Radon (NRAP) [16],. Among its key actions, the NRAP aims to identify high-risk areas and to promote the radiological characterization of BM [17].

The case study focuses on Pietra Leccese, a marly calcarenite extensively used in construction across Lecce and the Apulia region in southern Italy [18]. Despite its widespread engineering and commercial applications, Pietra Leccese is currently not included in the BSS framework, which primarily targets materials of volcanic or igneous origin. Preliminary investigations indicate that this material may require further scrutiny [19], [20].

This study therefore aims to assess the radiological relevance of a regionally prevalent BM that may require future regulatory attention.

II. Materials and Methods

A. Study Area and Sampling

In the Apulia region of southern Italy, as illustrated in Figure 1 numerous open-pit quarries are active in the extraction of calcarenite, a type of carbonate sedimentary rock. These rocks are primarily composed of bioclastic material and exhibit low degrees of cementation, indicative of deposition in shallow marine environments such as coastal zones, temperate seas, and Apulian calcarenites [18].

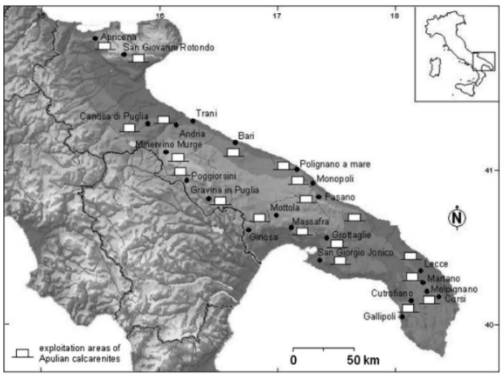


Figure 1 Geographic location of the main extraction areas of the Apulian calcarenities [18]

Limestone represents the predominant lithological component of the Salento Peninsula, extensively used as a BM. It is extracted from multiple sites and originates from various geological epochs, thereby displaying a wide spectrum of chemical and physical properties [21], [22]. This study focuses on a specific variety of limestone known as Pietra Leccese.

Pietra Leccese is a fine-grained, light yellow to white limestone [19], [20].

For this study, 3 samples were collected from open-cast quarries located in the municipality of Corigliano d'Otranto, within the central-southern sector of the Salento region. [23].

B. Preparation of samples

Sample preparation was carried out in accordance with ISO 18589–2:2015 [24]. Samples were pulverized using a PM 100 planetary ball mill. To ensure uniform grain size, the milled material underwent a sieving process, limiting the particle diameter to a maximum of 1 mm. Moisture removal was achieved by placing the samples in a Digitronic Selecta 2005141 oven and subjecting them to thermal treatment at 105 °C for a duration of 2 hours. The powdered materials were weighed and sealed in Marinelli beakers for a period of 4 weeks. This storage duration allowed for secular equilibrium to be established between ^{226}Ra and its radon progeny.

C. Gamma spectroscopy

High-resolution gamma-ray spectrometry was performed using a coaxial High-Purity Germanium (HPGe) detector (ORTEC® AMETEK, Oak Ridge, TN, USA; model GMX-45P4ST). The system is equipped with a beryllium window, which ensures good sensitivity to low-energy photons (<100 keV). The detector exhibits a relative efficiency of 48% and an energy resolution - expressed as full width at half maximum (FWHM) - of 2.16 keV at 1.33 MeV. Energy and efficiency calibrations were carried out using a mixed radionuclide reference source (Eckert & Ziegler Nuclitec GmbH, Germany) with an activity of 49 kBq, a density of 1 g/cm³, and an emission energy range from 60 to 1836 keV. The calibration geometry was established for a 1 L Marinelli beaker, consistent with the geometry used for the samples. The sample masses ranged from 800 to 1200 g. Self-attenuation and density corrections were applied to account for photon absorption within the samples and for differences between sample matrices and the calibration standard. To minimize background radiation, the detector was enclosed within a circular 10 cm-thick lead shield. Gamma spectra were acquired using an ORTEC® DSPEC-LF digital signal processor coupled with MCA Emulator software and subsequently analyzed using GammaVision Spectrum Analysis Software. Background spectra were also recorded under identical conditions and subtracted from the sample spectra to eliminate extraneous contributions.

The statistical reliability of the data was ensured by applying acquisition times of approximately 172,800 s (48 h) for sample measurements and 259,200 s (72 h) for background recordings. The analysis focused on characteristic gamma transitions associated with the decay chains of ^{238}U and ^{232}Th, as well as the gamma emission from ^{40}K.

The standard uncertainty associated with the activity measurements was evaluated in accordance with the UNI EN ISO 18589-2:2015 protocol [24]. The main contributions considered in the uncertainty budget included counting statistics, detector efficiency calibration, peak fitting, sample mass, and self-attenuation correction. Individual uncertainties were propagated using the law of quadratic summation, resulting in a total combined relative uncertainty typically ranging between 5% and 7%, depending on the radionuclide and activity level. The minimum detectable activity (MDA) was estimated following the 95% confidence level methodology proposed by [25]. The main factors influencing the MDA include detector resolution, background count rate, calibration geometry, and radionuclide characteristics.

D. Radiation protection indices

For a radiation protection analysis, the radiometric characterization included the calculation of radiation protection indices not specified by the current regulatory decree [13], [15]. Radiation protection indices are tools used to assess and manage the risk associated with exposure to ionizing radiation. They provide an estimate of the received exposure, support risk evaluation, and guide the implementation of effective protective measures. The main radiological protection indices used in this study are listed below:

- The Index I, as outlined in current regulations, serves as an effective screening tool to evaluate the suitability of a material for commercialization, ensuring adequate radiological protection for the general population [8], [13], [15]. This index estimates the excess gamma radiation dose within a building constructed using a specific material, relative to typical outdoor exposure levels. A value of I equal to 1 corresponds to a BM that may result in an effective dose of 1 mSv/year. It is calculated according to Equation (1):

$$I = \frac{C_{Ra-226}}{300Bq \cdot kg^{-1}} + \frac{C_{Th-232}}{200Bq \cdot kg^{-1}} + \frac{C_{K-40}}{3000Bq \cdot kg^{-1}} \quad (1)$$

Where:

C_{Ra-226}: Activity concentration of ^{226}Ra expressed in Bq/kg
C_{Th-232}: Activity concentration of ^{232}Th expressed in Bq/kg
C_{K-40}: Activity concentration of ^{40}K expressed in Bq/kg.
According to Annex II of Legislative Decree 101/2020, if I < 1, no further assessments are required, and the material can be placed on the market.
Conversely, if I ≥ 1, the decree requires that an assessment of the effective doses be carried out within 6 months by a qualified Radiation Protection Expert (level II or III, depending on the intended use of the material). If the resulting dose values fall below the exemption thresholds (1 mSv/year), the material may enter the production cycle, and the measurements must be repeated every 3 years. However, if the evaluation indicates dose levels exceeding the reference limits, the material cannot be used as a structural building component for residential or high-occupancy buildings. The risk management procedure follows the flow chart presented in Figure 2 [26].

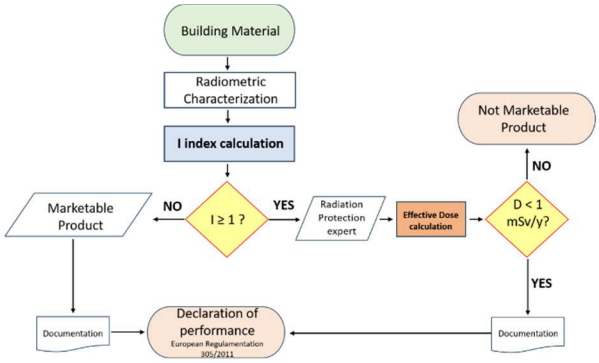


Figure 2 Risk management in Radiation Protection for BM [26].

- The Index I_α is a screening tool used to assess the activity concentration of alpha-emitting radionuclides in BM [27]. It is defined by the Equation (2):

$$I_\alpha = \frac{C_{Ra-226}}{300Bq \cdot kg^{-1}} \quad (2)$$

The threshold value to consider is 1: if I_α < 1, the associated dose remains within acceptable limits, and the material can be used. Conversely, if $I_\alpha \geq 1$, the materials may pose a radiological risk.

- The Radium Equivalent Activity Ra_{eq} is defined by the Equation (3) [1], [28]:

$$Ra_{eq} = 370\left(\frac{C_{Ra-226}}{370Bq \cdot kg^{-1}} + \frac{C_{Th-232}}{259Bq \cdot kg^{-1}} + \frac{C_{K-40}}{4810Bq \cdot kg^{-1}}\right) \quad (3)$$

The threshold value to consider is 370 Bq/kg.

- External Hazard Index H_{ex} is a parameter used to assess the radiological risk associated with external exposure to gamma radiation emitted by BM containing naturally occurring radionuclides. It is defined by the Equation (4) [29]:

$$H_{ex} = \frac{C_{Ra-226}}{370Bq \cdot kg^{-1}} + \frac{C_{Th-232}}{259Bq \cdot kg^{-1}} + \frac{C_{K-40}}{4810Bq \cdot kg^{-1}} \quad (4)$$

The threshold value to consider is 1.

- Internal Hazard Index H_{in} is a parameter used to evaluate the internal radiological risk associated with the inhalation of radon and its decay products. It is defined by the following equation (5) [30]:

$$H_{in} = \frac{C_{Ra-226}}{185 \cdot kg^{-1}} + \frac{C_{Th-232}}{259Bq \cdot kg^{-1}} + \frac{C_{K-40}}{4810Bq \cdot kg^{-1}} \quad (5)$$

The threshold value to consider is 1.

III. Results

A. Results of Gamma Spectroscopy

A total of 3 different samples were prepared and analyzed by means of gamma spectroscopy: the average activity concentration results for ^{226}Ra and ^{232}Th are illustrated in Table 1, with the associated uncertainties corresponding to one standard deviation of the measured data. For ^{40}K, in all 3 samples the measured activity concentration was below the minimum detectable activity (MDA, 1.16 Bq/kg).

Table 1 Average activity concentration for ^{226}Ra, ^{232}Th and ^{40}K for 5 different samples of Pietra Leccese obtained through gamma spectroscopy.

	Average activity concentration of Pietra Leccese *in this study*
^{226}Ra [Bq/kg]	374 ± 28
^{232}Th [Bq/kg]	9 ± 4
^{40}K [Bq/kg]	<1.16

Comparative activity concentration with data already available in the literature for the same material [19], [20] are shown in Table 2.

Table 2 Comparison between the activity concentration values obtained in this study and those reported in the literature for Pietra Leccese.

	Pietra Leccese *in this study*	**Pietra Leccese in** [19]	**Pietra Leccese in** [20]
^{226}Ra [Bq/kg]	374 ± 28	274 ± 34	349 ± 19
^{232}Th [Bq/kg]	9 ± 4	2 ± 1	3 ± 1
^{40}K [Bq/kg]	<1.16	31 ± 5	25 ± 3

B. Results of Radiation protection indices

Based on the results obtained from gamma spectroscopy, the radiation protection indices I, I_α, Ra_{eq}, H_{ex} and H_{in} were calculated and are presented in Table 3.

Table 3 Calculated values of the radiation protection indices I, I_α, Ra_{eq}, H_{ex} and H_{in}.

	Pietra Leccese *in this study*	**Reference Values**
I	1.3	<1
I_α	1.2	<1
$R_{\alpha eq}$ [Bq/kg]	386	<370
H_{ex}	1	<1
H_{in}	2	<1

Comparative radiation protection indices with data already available in the literature for the same material [19], [20] are shown in Table 4.

Table 4 Comparison between the radiation protection indices obtained in this study and those reported in the literature for Pietra Leccese.

	Pietra Leccese *in this study*	**Pietra Leccese in** [19]	**Pietra Leccese in** [20]
I	1.3	0.9	1.2
I_α	1.2	0.9	1.2
$R_{\alpha eq}$	386	280	355
H_{ex}	1	1	1

IV. Discussion and conclusions

The results obtained from the gamma spectrometric analysis of the Pietra Leccese samples (Table 1) highlight specific radiological concerns. In particular, the activity concentration of ^{226}Ra is significantly elevated (374 Bq/kg), while the concentrations of ^{232}Th and ^{40}K are relatively low, measuring 9 Bq/kg and below 1.16 Bq/kg, respectively.

The comparative analysis (Table 2) reveals that the activity concentration of the radionuclide ^{226}Ra measured in this study (374 Bq/kg) exceeds both the value reported in [19] (274 Bq/kg) and that in [20] (349 Bq/kg). This finding confirms that ^{226}Ra is the primary radiological contributor in Pietra Leccese, while some variability in the activity concentrations of ^{40}K (1 Bq/kg) and ^{232}Th (9 Bq/kg) is observed compared to literature values [19], [20]. These differences are plausibly attributable to the specific geological origin or stratigraphic characteristics of the Pietra Leccese sample analyzed, which may influence the presence of certain radionuclides, such as potassium-bearing minerals.

Concerning the findings on the radiation protection indices (Table 3), The index I, which serves as a key screening parameter for the commercialization of BM, was found to be 1.3, exceeding the legal limit of 1. This indicates the need for a detailed assessment of effective doses to be carried out by a radiation protection expert (second or third level), in accordance with current regulatory requirements. Similarly, the index I_α was found to be 1.2, also exceeding the threshold value of 1. This result suggests a non-negligible risk of radon emission and its progeny, with potential implications for the internal exposure of building occupants. The calculated Ra_{eq} is 386 Bq/kg, exceeding the recommended limit of 370 Bq/kg, above which the radiological risk associated with the use of BM increases. Additionally, the H_{ex} is exactly 1, indicating a borderline situation regarding external gamma radiation exposure. The most critical H_{in} result , which was found to be 2-twice the threshold value of 1. This indicates a high risk of internal exposure, primarily due to radon inhalation, which is particularly relevant in enclosed environments.

The comparative analysis (Table 4) reveals that The Index I is 1.3, exceeding the values reported in [19] (0.9) and [20] (1.2), indicating a higher radiological concern for the analysed sample. The Iα Index (1.2) is consistent with the value reported in [19] (1.2), but higher than that in [19] (0.9). The calculated Raeq (386 Bq/kg) is greater than the value reported in [19] (280 Bq/kg) and slightly higher than that in [20] (355 Bq/kg), further suggesting an increased potential radiological risk. The external Hex are equal to 1 in all considered studies, indicating that under normal conditions, external exposure remains at the acceptable limit in all cases. The Hin has a value of 2 both in the present study and in [20], whereas in [19] it is 1. This confirms that internal exposure (radon and its progeny) represents the primary risk factor associated with the use of Pietra Leccese in construction. In summary, the comparison with literature data confirms the tendency of Pietra Leccese to exhibit significantly higher 226Ra concentrations compared to 232Th and 40K, resulting in a notable concern primarily related to internal radon exposure.

The deviations observed between the present results and previously published data may arise from both geological and methodological factors. From a geological standpoint, Pietra Leccese deposits are known to exhibit variable degrees of marly and phosphatic components depending on the stratigraphic horizon and depositional environment. Layers richer in phosphates or clay minerals tend to accumulate higher concentrations of uranium and its decay products, particularly 226Ra. Furthermore, differences in the porosity and grain size distribution can influence the retention and exhalation of radon, thus affecting apparent activity concentrations. From an analytical perspective, slight discrepancies may also reflect variations in sample preparation (grain size, moisture removal). Overall, these factors jointly explain the moderate deviations observed with respect to literature data.

In contrast to previous investigations on Pietra Leccese [19], [20] which provided preliminary radiometric data mainly aimed at classifying regional natural stones, the present work introduces several novel aspects. First, it reports a refined gamma-spectrometric characterization with improved counting statistics, lower detection limits, and extended measurement times, ensuring a higher reliability of the obtained activity concentrations. Second, the study includes the full set of radiation protection indices (I, Iα, Raeq, Hex, Hin), allowing a more comprehensive assessment of both internal and external exposure risks. Third, a comparative interpretation is provided to explain the observed deviations from literature values in terms of geological and mineralogical variability within the calcarenitic formation.

This radiometric investigation highlighted a crucial issue: Lecce Stone, being a sedimentary rock, is not currently regulated; however, it meets all the requirements to be classified as a BM of radiation protection interest.

The results obtained further support the need to expand the regulatory scope to adequately include natural BM.

The use of Lecce Stone, without adequate mitigation measures, may pose a significant radiological risk, both from external exposure and, to an even greater extent, from internal exposure. In particular, the application of this material in confined and highly frequented environments should be carefully evaluated and, if necessary, limited or subordinated to the implementation of exposure reduction strategies (e.g., surface treatments, increased ventilation, or limiting use to the exterior of buildings).

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Modified Gellan Gum Gels with Nanodiamonds, tert-butylammonium borane and calcium propionate for the Cleaning Cultural Heritage Artifacts

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***Abstract* — The preservation of paper-based cultural heritage objects, especially those degraded by oxidation and acidity, demands cleaning systems that are both effective and minimally invasive. Gellan gum hydrogels have emerged as promising tools for localized, controlled cleaning with reduced wetting. In this study, we formulated and evaluated modified gellan gum gels enhanced with functional additives to improve their performance. Nanodiamonds (NDs) were introduced at various concentrations, with 0.1% identified as optimal for effective cleaning without leaving residues. Further modifications included calcium propionate for antifungal protection and tert-butylammonium borane as a reducing agent. These additives were tested individually and in combination to assess potential synergistic effects. The gels were applied to oxidized paper supports and assessed for cleaning efficiency, material safety, and residue absence, confirming their potential for sustainable and non-invasive conservation treatments.**

Keywords— Gellan gum hydrogels, Cultural heritage conservation, Nanodiamonds, Paper cleaning, Non-invasive restoration

I. INTRODUCTION

The conservation of paper-based cultural heritage artifacts, such as manuscripts, archival documents, and photographic albums, requires restoration strategies that are both effective and non-invasive. While traditional aqueous cleaning can reduce acidity and remove degradation byproducts, it may also cause over-wetting, ink bleeding, and fiber weakening [1],[2]. Gel-based systems offer a safer alternative by allowing controlled delivery of cleaning agents and moisture [3], [4]. Among these, gellan gum hydrogels, stand out for their localized moisture release and minimal capillary action, making them well-suited for fragile papers [5]. Recent developments include gellan microgels, which enhance surface interaction and penetration while preserving structural integrity [6]. Functionalization of gellan gels has further expanded their potential. For example, formulations enriched with EDTA, nano-calcium carbonate, and sodium dithionite have shown improved cleaning and pH stabilization [7], while other studies confirm the low invasiveness and versatility of gel-based methods [4], [8]. In this study, we investigate gellan gum gels modified with nanodiamonds (NDs), tert-butylammonium borane (TBAB), and calcium propionate, tested both individually and in combination. NDs offer high surface area, good water dispersibility, mechanical polishing capacity, and mild deacidification properties, making them useful in both wet and dry cleaning [9], [10]. Though initially developed for biomedical and electronic use, NDs have shown promise in heritage science, including applications on parchment [11] and in slowing biodeterioration in cellulose materials [12]. Their antimicrobial and water-retention properties can also stabilize gel systems and reduce tidemarks [13–15], [3]. After preliminary tests on papers with varying oxidation levels, we selected 0.1 wt% ND, based on both literature and experimental screening [11–13], [3]. The gels were further enhanced with TBAB, a selective reducing agent known for bleaching oxidized cellulose without affecting molecular integrity [16–18], leaving minimal residues and ensuring long-term chemical stability. Additionally, calcium propionate (CaP) was included as a dual-function additive, acting both as a deacidifying agent and antifungal compound [7], [19], [20]. Calcium ions buffer paper acidity, while the propionate anion helps inhibit mold growth, especially under humid conditions [20].

We prepared eight gel formulations and tested them on an album from the Guido Calvi collection, housed at the Museo Nazionale Preistorico ed Etnografico Luigi Pigorini, donated by the Istituto Italiano per il Medio ed Estremo Oriente (I.M.E.O.) in 1939 and incorporated into the Museo delle Civiltà in 2017.

By combining these active components, this study proposes a new generation of cleaning gels that address both aesthetic restoration and long-term preservation. The effectiveness of each formulation was assessed through optical microscopy, FTIR-ATR spectroscopy, and colorimetric analysis, offering a multimodal evaluation aligned with sustainable, science-based conservation practices.

II. MATERIALS AND METHODS

A. Preparation of Functionalized Gels with Additives

The initial phase of the study focused on optimizing the concentration of nanodiamonds (NDs) to be incorporated into gellan gum gels for cleaning purposes. Four formulations were prepared using a fixed concentration of gellan gum, GG (LA, Kelcogel) at 3% (w/v), while varying the ND content (from 0% to 0.05%, 0.1% and 0.5%):
Before gel preparation, NDs were dispersed in deionized water via ultrasonic bath (30 min), followed by probe sonication (20 min). GG was then added to the ND dispersion, and the mixture was heated until boiling using a microwave. The resulting gel was poured into flat-bottom molds and left to cool at room temperature for full gelation. Based on the cleaning tests that will be shown in the discussion section, the 0.1% ND formulation was selected as optimal, offering effective cleaning without leaving residues or discoloration.

Following ND optimization, eight GG gel formulations were developed using 3% of GG, with the addition of selected active agents: 0.1% NDs, 0.5% calcium propionate (CaP), and 0.5% tert-butylammonium borane (TBAB) and pictures of the gels are reported in **Fig.1**.

The general procedure involved dispersing the additives in deionized water prior to gelation. When CaP was included, it was always added before the GG to assist mixing and improve gel consistency. When TBAB was used, it was added to the solution after microwave heating during the boiling phase, as its stability is enhanced in hot aqueous media. ND dispersions were always pre-sonicated before gel preparation.

The tested Gel Formulations have the following composition:

#1. 3% GG (unmodified)
#2. 3% GG + 0.1% ND
#3. 3% GG + 0.5% CaP
#4. 3% GG + 0.1% ND + 0.5% CaP
#5. 3% GG + 0.5% TBAB
#6. 3% GG + 0.1% ND + 0.5% TBAB
#7. 3% GG + 0.5% TBAB + 0.5% CaP
#8. 3% GG + 0.1% ND + 0.5% TBAB + 0.5% CaP

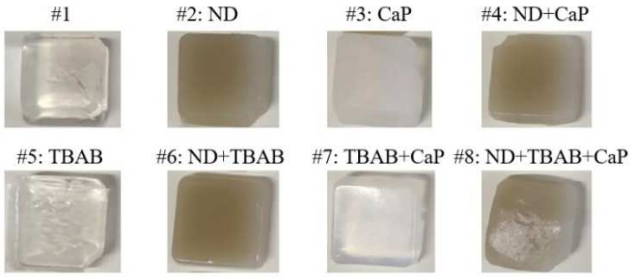


Fig. 1. *Picture of the 8 types of modified gellan-gums used in this work.*

B. Gels' rheological and thermal characterization

The rheological properties of the GG composites were evaluated using a rheometer (HR20 from TA instruments, Waters, US) with parallel-plate geometry (PP20, gap of 1 mm). The analysis was carried out at 25 °C, a dynamic frequency sweep in the range of 0.1–100 1/s at a fixed strain amplitude ($\lambda = 5.0\%$) within a linear viscoelastic region.
The thermal characterization of the GG composites was performed to evaluate the water retention over time. It was carried out using a TGA55 from TA instruments, Waters, US. The samples are conditioned at 25°C, the heated up to 200°C with a ramp of 5°C/min.

C. Paper samples characterization

The performance of the gels was evaluated through visual inspection, optical microscopy, and Fourier-transform infrared spectroscopy (FTIR). Optical observations were conducted using a NIKON Eclipse TS100 microscope. FTIR spectra were acquired using a single-reflection diamond ATR cell, over a wavenumber range of 4000–650 cm^{-1}, with a spectral resolution of 4 cm^{-1}. pH was measured using a using a Crison Instrument (mod. Basic-20, Crison Instrument s.a., Alella, Barcelona, Spain) and a flat tipped symmetry glass electrode (Hanna Instrument., Woonsocket, RI, USA). Colorimetric analysis was recorded using a StellarNet GREEN-Wave spectrometer equipped with a D65 illuminant for measurements in the 350–1150 nm range. The instrument is optically coupled via fiber to a cube containing an internal integrating sphere capable of measuring an area with a diameter of 1 cm^2. System calibration was performed using a reference target with certified reflectance >97% across the 300–1700 nm range.

III. RESULTS AND DISCUSSION

A. Preliminary investigation to determine nanodiamond optimal concentration

A preliminary investigation was carried out to identify the optimal nanodiamond (ND) concentration in gellan gum (GG) gels. Tests were performed on a series of selected samples, shown in **Fig.2a–f**, including: oxidized paper (a); paper with adhesive tape stains (b); paper affected by microbial contamination (purple mold, c); 18th-century paper with iron gall ink and tide marks (d); paper with ink stains (e); and paper with vinyl adhesive residues (f).
Initial visual assessment revealed that the most promising results were achieved on oxidized papers treated with gels containing 0.05% and 0.1% ND, which exhibited noticeable brightening and reduced wetting, evident from diminished tide mark formation.



Fig. 2. *Photographs of paper samples treated with gellan gum gels containing varying concentrations of nanodiamonds (ND): 0%, 0.01%, 0.1%, and 0.5%. The increasing ND concentration is visually distinguishable by the progressively darker color of the gels. (a) Oxidized paper; (b) paper with adhesive tape stains; (c) paper affected by microbial growth; (d) 18th-century paper with iron gall ink and tide marks; (e) paper with ink stains; (f) paper with vinyl adhesive residues. (g–h) Samples a-b after 15 minutes of treatment; (i–j) samples a-b after 30 minutes of treatment.*

These tests were repeated on additional oxidized papers, both modern and historical ones, by recording the gel weight before and after application. Photographic documentation was collected every 15 minutes to monitor gel behavior on the paper surfaces. **Fig. 2g–j** displays a selection of representative images from the study, captured after 15 minutes (g,h) and 30 minutes (i,j) of treatment, supporting the selection of 0.1% ND as the optimal concentration.
The choice was further validated through optical microscopy analysis, as shown in **Fig. 3**. No tide marks were observed, and the gels effectively removed surface soiling.



Fig. 3. *Microscope images of two papers at two different oxidation stages before and after cleaning treatment with 0.1% ND gels (magnification: 20X).*

B. Evaluation of the stability of the Gellan-gum

In this study, we tested several modified gellan gum formulations (gellan gum with nanodiamonds, TBAB, and calcium propionate). However, only the results for pristine gellan gum and gellan gum modified with nanodiamonds (GG–ND) are reported here, as these were the most significant and representative systems. The oscillatory frequency sweep performed at 5% strain, in the 0.01–100 Hz range, showed the typical viscoelastic behavior of gellan gels, with G′>G″ over the entire frequency domain, confirming the predominance of the elastic component, and both moduli show only a weak dependence on frequency, confirming the formation of elastic, solid-like gels. This behaviour is consistent with the widely accepted mechanism of gellan gelation, whereby on cooling aqueous solutions the polymer chains undergo a coil-to-helix transition, followed by aggregation of (double) helices into junction zones that are stabilized by cation bridging of the carboxylate groups; the density and connectivity of these junction zones govern the plateau modulus of the gel.
Although the qualitative viscoelastic response is similar, GG–ND gel consistently exhibits lower G’ values than the unmodified gellan gum. This result is somewhat unexpected, because particulate fillers are often associated with an increase in stiffness of the hosting matrix. In agreement with this common picture, previous work on nanodiamond–cellulose systems reported an increase in viscosity and G’ upon ND addition, despite an overall improvement in flowability of the dispersions [13, 21]. Similarly, the addition of clay particles to agar/gellan matrices has been shown to enhance gel stability and rigidity [22].
In the present case, however, as can be observed in **Fig. 4**, both G’ and G’’ exhibit a modest but reproducible decrease for GG–ND. This trend is also reported in other studies [23–25]. The formation of gellan gum gels is strongly dependent on the ability of gellan chains to interact and form a continuous crosslinked network [26, 27]. The presence of solid particles can interfere with this process by disrupting chain–chain interactions, thereby reducing the effective crosslink density. Moreover, the functional groups on the ND surface may interact with gellan gum chains and interfere with their association, thereby hindering the formation of a fully crosslinked network. Only at sufficiently high filler loadings does particle–particle contact begin to dominate, leading to an overall stiffening of the gel. At the lower nanodiamond concentrations used in this work, the disruption effect appears to prevail, resulting in a modest softening of the network. Despite this slight reduction in stiffness, the GG–ND composite gels remain mechanically robust, easy to handle, and fully suitable for conservation treatments.

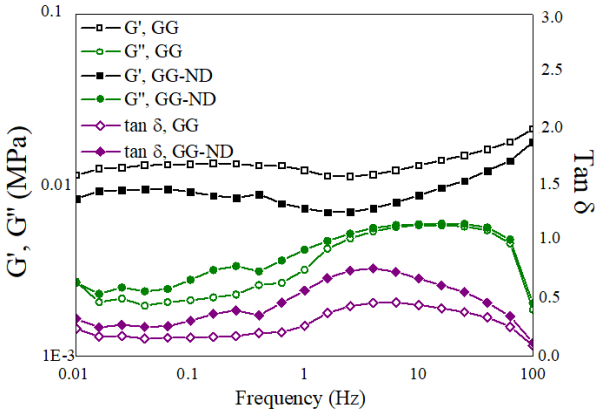


Fig. 4. *Oscillatory frequency sweep (0.01–100 Hz, 5% strain) of pristine gellan gum (GG) and gellan gum modified with nanodiamonds (GG–ND).*

Thermogravimetric analysis was used to monitor the water loss of the gels, as the amount and binding state of water are crucial parameters for assessing how much moisture can be transferred to the paper substrate during restoration. For both formulations, the first weight-loss step, ending around 150 °C and clearly visible in the DTG curves, is attributed to the evaporation of free and weakly bound water, whereas the main degradation of the polysaccharide network occurs at higher temperatures. To evaluate the temporal evolution of the gels, TGA measurements were carried out 2 h after preparation, on the following day, and after three days. For neat gellan gum, the temperature of the DTG peak associated with water loss varies markedly with time: it is initially lower (around 80°C), then progressively shifts to higher temperatures, reaching about 143 °C by the third day. This behaviour suggests a progressive reorganization of water within the gel, where loosely bound or more mobile water is progressively lost in the first days of storage, leaving a fraction of water that is more strongly associated with the polymer network and therefore requires higher temperatures to be removed.
In the GG–ND gels, the temporal changes in the position of the water-loss DTG peak are still present but significantly reduced, and the curves reach a quasi-stable profile earlier, with smaller shifts in temperature (From around 120°C to 145°C). This indicates that the presence of nanodiamonds moderates the rearrangement of water in the gel, likely by providing additional interaction sites and contributing to a more stable microstructure and distribution of water domains. From a conservation perspective, these results imply that pure gellan gum gels undergo a more pronounced evolution of their hydration state over the first days after preparation, whereas GG–ND formulations exhibit a more reproducible and stable water-release profile, which is advantageous for controlled and repeatable application on paper substrates.

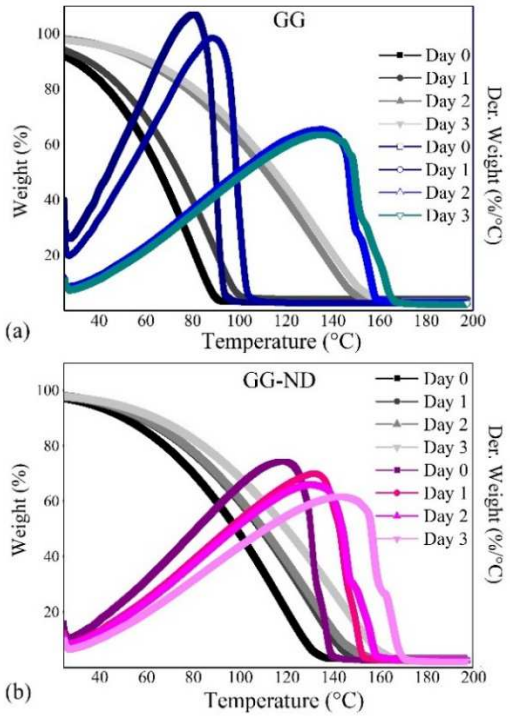


Fig. 5 *TGA-DTG curves from 25 to 200°C for (a) GG and (b) GG-ND. The TGA curves are reported in grey scale for both GG and GG-ND. The DTG are reported in blue scale for GG and pink scale for GG-ND. The shift in the peak of the DTG curve is far more evident for GG than GG-ND.*

C. Application of Gels Modified with nanodiamond, Calcium Propionate and Tert-Butylammonium Borane

Preliminary visual assessment of the Guido Calvi collection revealed evident signs of acidity and oxidation affecting the secondary cardboard supports of the albumen prints. These observations were confirmed by pH measurements, which indicated highly acidic conditions. Values recorded at three different points on two separate cardboard samples averaged pH 2.5 ± 0.6**,** prompting the development of a targeted treatment to restore the pH balance and recover the original appearance and stability of the supports.

Since the restoration project did not allow for detaching the photographs from their mounts, treatments were applied only to the reverse side, ensuring no contact with the photographic emulsions and preserving their integrity.

Various gellan gum gels, enhanced with deacidifying and reducing agents, were used to perform controlled humid treatments. These gels form rigid, moisture-releasing sheets that clean effectively while minimizing water exposure and structural risk. The application of these eight gels is reported in **Fig. 6**.



Fig. 6 *application of modified gellan gums (from 1 to 8) on the cardboards supports of the albumen prints of the Guido Calvi's collection album.*

Results were evaluated through colorimetry, optical microscopy, and FTIR spectroscopy, confirming both visual improvement and the preservation of the paper's chemical structure.

Colorimetric measurements were conducted to quantitatively assess color changes induced by the treatments. The analysis was based on the CIELAB 1976 color space. In this system, each color is defined by three coordinates**:** L* (lightness), where higher values indicate increased brightness; a*, representing the green–red axis (positive values toward red, negative toward green); and b*, representing the blue–yellow axis (positive toward yellow, negative toward blue). This model enables the detection of subtle variations in hue, saturation, and brightness, thereby allowing objective evaluation of cleaning efficacy and visual impact on paper substrates.

The color difference is expressed as the chromatic distance between two points in the CIELAB 1976 color space, using the ΔE* parameter, calculated as follows:

$$\Delta E^* = \sqrt{(L_f - L_i)^2 + (a_f - a_i)^2 + (b_f - b_i)^2}$$

Color variations are conventionally considered perceptible when ΔE* ≥ 2. Table 1 reports the CIELAB 1976 values measured before and after treatment, along with the corresponding ΔE * values calculated using this equation.

TABLE I. COLORIMETRIC DATA BEFORE AND AFTER TREATMENT

Gellan type	Before treatment			After treatment			
	L*	a*	b*	L*	a*	b*	ΔE
#1	67.3	8.8	11.9	68.6	5.6	18.3	7.3
#2	66.8	8.8	11.9	68.3	5.2	18.2	7.4
#3	67.0	8.8	11.3	68.2	5.5	18.1	7.7
#4	66.9	8.7	11.7	68.4	5.3	18.0	7.3
#5	67.1	8.6	11.9	71.6	4.4	19.0	9.4
#6	66.5	9.0	11.2	73.1	4.5	17.2	10.0
#7	67.0	8.9	11.3	71.2	5.1	16.7	7.8
#8	66.5	9.0	11.3	71.2	4.9	16.9	8.4

The data in **Table 1** show a significant color difference (ΔE* > 7) for all treatments. Notably, the most pronounced brightening was observed in the areas treated with GG, TBAB and NDs,

Microscope images of the eight treated area are reported in **Fig. 7**. Consistent with the results of the colorimetric analysis, these images reveal a more pronounced lightening effect in areas treated with tert-butylammonium borane. The brightest area overall, when compared to the untreated region, is observed in the sample treated with both nanodiamonds and tert-butylammonium borane (gels #5 and #6).

The pH of the samples was measured after treatment with the modified gels. All samples exhibited an increase in pH, as reported in **Table 2**. Given that the untreated paper was highly acidic, this shift indicates a partial neutralization effect. The most pronounced deacidifying action was observed in the gels containing calcium propionate and/or nanodiamonds.

TABLE II. PH VALUES BEFORE AND AFTER TREATMENT

pH before	Gellan type	pH after
2.5 ± 0.6	#1	3.7 ± 1.0
	#2	4.2 ± 0.7
	#3	4.1 ± 0.6
	#4	4.3 ± 1.0
	#5	4.0 ± 1.2
	#6	4.1 ± 0.8
	#7	4.2 ± 0.5
	#8	4.3 ±0.4

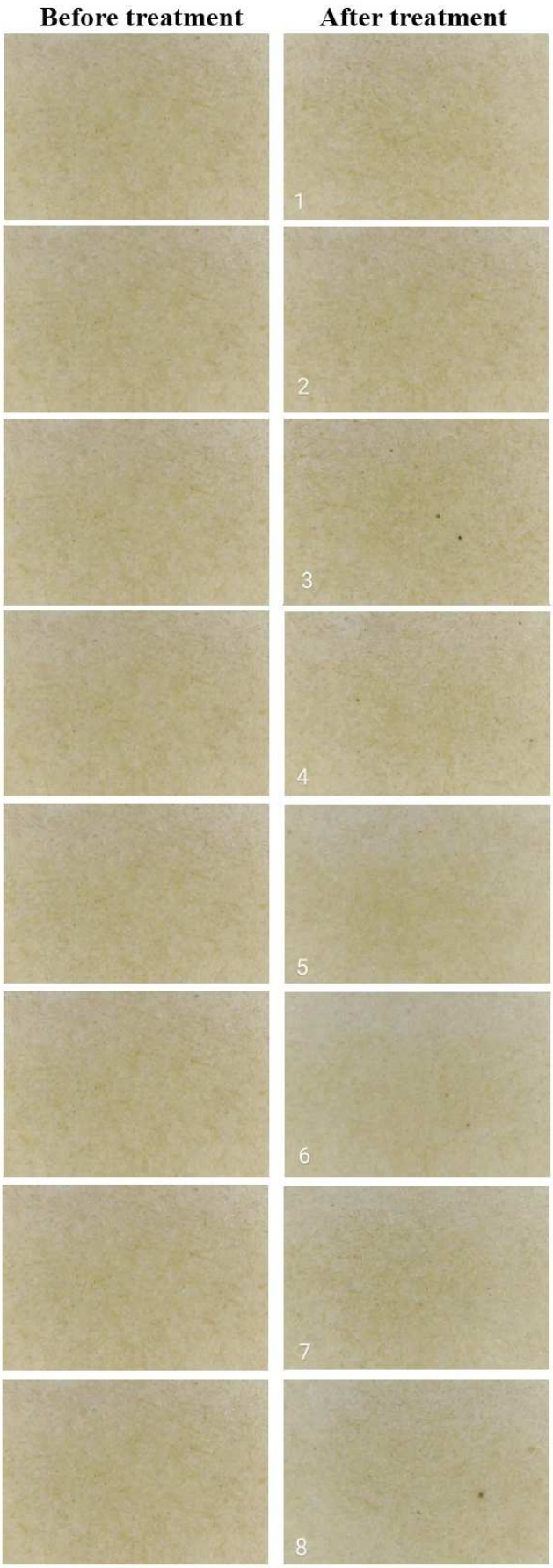


Fig. 7. *Microscope images of paper treated with the eight types of Gellan gum gels.*

The infrared (IR) spectroscopy analysis was conducted to evaluate the chemical changes induced by the application of the modified gellan gum gels on paper substrates.

This approach enabled the detection of any residual materials, alterations to the cellulose structure, and potential interactions between the additives and the paper matrix.

FTIR analyses were performed at eight selected points corresponding to the areas treated with different gel formulations. Spectra were recorded before, during, and after treatment to monitor chemical changes related to the application and removal of the gels.

The acquired spectra (**Fig. 8**) show no significant differences among the samples; however, subtle variations can be observed upon closer examination. From the spectral region around 900 cm^{-1}, characteristic absorption bands associated with cellulose are observed. These correspond to stretching vibrations of CO, CC, and bending of OCH, HCH and CCH groups. The spectra from the treated paper supports exhibit a consistent, slight reduction in intensity between 900 and 970 cm^{-1} when compared to the untreated sample. This suggests an improvement in the paper's structural integrity, as the 900 cm^{-1} band is particularly sensitive to the presence of amorphous cellulose, its broadening reflects higher levels of disordered structure [28-30].

Between 970 and 1100 cm^{-1} (**Fig. 8c**), a region typically associated with the crystalline domains of cellulose, all spectra remain aligned. This indicates that the treatments did not alter or damage the crystalline cellulose structure.

Finally, the band at 1700 cm^{-1}, associated with oxidation products of cellulose, shows decreased intensity across all treated samples compared to the untreated one. This reduction further supports the efficacy of the cleaning treatments in mitigating oxidative degradation [31, 32].

Importantly, no additional bands are observed; it can be concluded that none of the treatments damaged the support or left detectable residues.

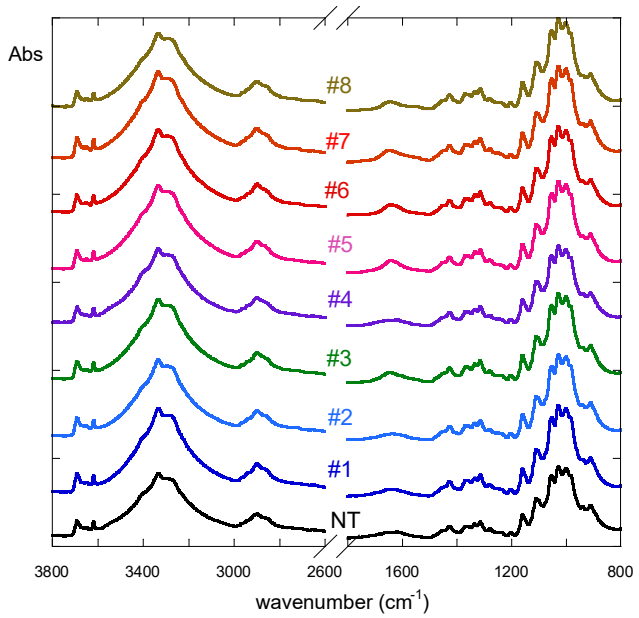


Fig. 8. *FTIR-ATR spectra of the untreated paper support (NT) compared with treated samples (#1 to #8). The spectral region between 800 and 1200 cm^{-1} highlights vibrations associated with cellulose structure. The spectral region from 1100 to 1800 cm^{-1} includes signals related to oxidation products and gypsum. The high-wavenumber region between 2700 and 3600 cm^{-1} corresponds to OH and CH stretching vibrations.*

IV. Conclusion

This study demonstrated the effectiveness of modified gellan gum hydrogels for the cleaning and preservation of oxidized paper-based cultural heritage artifacts. By optimizing the concentration of nanodiamonds (0.1 wt%) and incorporating functional additives such as calcium propionate and tert-

butylammonium borane, we developed gels that enhanced surface cleaning while also providing deacidifying, antifungal, and reducing functionalities. Although the pH remains below neutrality, the treatment is very promising. Future optimization in GG composition or contact time may allow the system to reach the preferred pH range for paper stability (≈7–8) while avoiding over-alkalinization (>9), which can negatively affect cellulose and media. Colorimetric analysis confirmed a significant removal of surface dirt, and FTIR spectroscopy revealed not only the absence of chemical damage or residual deposition but also a marked decrease in the intensity of the cellulose oxidation band around 1700 cm^{-1}. This spectral change supports the chemical effectiveness of the treatments in reducing oxidation products. Overall, the proposed gel formulations offer a non-invasive, multifunctional, and sustainable method for the conservation of fragile and degraded paper materials.

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An Electrodermal Activity-Based Approach for the Assessment of Cognitive Stress

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***Abstract*—Cognitive stress refers to the mental tension resulting from complex or demanding cognitive tasks. It is linked to physiological signals, such as variations in skin conductance and brain activity, as the human body responds to stress with measurable changes in these parameters. The purpose of this work was to measure cognitive stress using commercially available and low-cost wearable devices. To this end, an experimental protocol of 1200 seconds was implemented, consisting of both relaxation and stress phases, during which the electrodermal activity (EDA) signal was acquired. The stress-inducing stimulus was represented as a computerised version of the Stroop Colour-Word Test implemented in PsychoPy, in which participants were also required to name the ink colour of words that could denote incongruent colours, thereby engaging inhibitory control and cognitive flexibility. This task was administered together with an additional quiz task. Thirty-two subjects participated in the test, aged between 23 and 37 years. EDA features were extracted within a 90-second window. Statistical analysis showed significant variations in all EDA features, except latency. Analyses based on the Cognitive Interference Index (IG) calculated according to Golden's method and on perceived stress distinguished participants as stressed or non-stressed, showing significant differences in some EDA features. These results provide evidence supporting the effectiveness of the proposed protocol and wearable devices for assessing cognitive stress, and suggest promising directions for engineering applications in continuous health monitoring and m-health.**

***Index Terms*—Wearable Stress monitoring, mobile health, stress, Stroop Test, EDA.**

I. Introduction

Stress is defined as the psychophysical response to tasks, even very diverse ones, of emotional, cognitive, or social nature, which the person perceives as excessive [1]. The General Adaptation Syndrome (G.A.S.), coined by Selye [2], is a fundamental concept in modern stress research. It describes the biological mechanism through which the body copes with difficulties and attempts to restore homeostasis, divided into three phases: alarm reaction, resistance, and exhaustion. Stress in humans is a complex phenomenon that extends beyond natural responses to danger, encompassing everyday life events as well. Cognitive stress [3], in particular, manifests through mental pressures often stemming from fast-paced work environments and high demands. This type of stress can lead to psychological disorders such as stress itself, anxiety, and panic. Prolonged exposure to such stress can culminate in burnout [4], a serious condition requiring targeted psychological interventions to redirect thinking and effectively manage interpersonal relationships. Cognitive styles and interpersonal relationships also play a role in vulnerability to stress, with sociotropy and autonomy influencing the risk of depression [5]. According to Ioannis Kyrou and Constantine Tsigos [6], the nervous, endocrine, and immune systems coordinate the stress response via hormones such as ACTH, cortisol, growth hormone (GH), prolactin, and catecholamines. Evidence also indicates sex-related differences in stress reactivity: men and women differ both psychologically and biologically [7]. In particular, estrogens modulate the hypothalamic–pituitary–adrenal (HPA) axis in women, contributing to observed disparities in acute responses [7]. Recognising these differences may inform more effective prevention and intervention strategies. A study reports that men, on average, show higher acute physiological responses than women [7]. Assessment methods range from subjective reports to objective physiological measurements. Reliance on self-reported symptoms introduces subjectivity. To increase objectivity, research focuses on stress-induced physiological alterations driven largely by sympathetic hyperactivation and parasympathetic inhibition, with prominent cardiac effects. Invasive (or minimally invasive) methodologies are often employed to directly quantify validated stress biomarkers, such as cortisol, adrenaline, and noradrenaline, in blood or saliva [8], [9]. These biomarkers provide quantitative indices of the stress response and are widely considered the gold standard. Complementary information is obtained from non-invasive

physiological signals, including the electrocardiogram (ECG), electromyogram (EMG), blood pressure, electrodermal activity (EDA), skin temperature, blood volume pulse (BVP), and electroencephalogram (EEG). EDA can be decomposed into a slowly varying tonic component, the skin conductance level (SCL), and a fast, event-related phasic component, the skin conductance response (SCR) [10], [11]. The tonic SCL reflects the baseline/background conductance that drifts over tens of seconds to minutes and is modulated by global sympathetic arousal and contextual factors (e.g., thermoregulation) [12]. The phasic component consists of transient SCRs with rapid rise and slower recovery, time-locked to stimuli or occurring spontaneously, reflecting bursts of sudomotor sympathetic activity. Because closely spaced SCRs superimpose on the tonic background, many studies apply model-based deconvolution to separate tonic and phasic activity prior to feature extraction [13]. Recent advances in wearable and ambient sensing now enable real-time monitoring and analysis of EDA, supporting proactive and personalised stress management. This approach aligns with the growing field of mobile health (m-health), which integrates wearable and smartphone-based technologies to monitor and promote wellbeing [14]. Within this context, EDA stands out as a key marker. First linked to psychological processes by Vigouroux (France, 1879), EDA reflects autonomic sympathetic activity associated with emotional arousal, although electrical changes alone do not identify the specific emotion elicited [15]. Sympathetic-driven changes in sweating (and blood flow) underlie EDA, from which measures are derived. Using wearable sensors, researchers can monitor participants' stress-related physiological activity in real time during daily life [16] thereby minimising biases due to memory and self-awareness. Thus, EDA can be recorded while administering stress-inducing tasks such as the Stroop colour–word test (SCWT) [17] or mental arithmetic, enabling controlled investigation of stress responses. or mental arithmetic tasks. This approach allows for a more accurate and objective evaluation of the factors influencing stress and effective management strategies. Additionally, their use allows for the collection of a large amount of data on a wide sample of participants, promoting more robust and in-depth statistical analyses. This can help researchers identify patterns, trends, and correlations that might not emerge with traditional research methods. Considering these innovations, the devices used for this work were chosen following a thorough analysis of various low-cost wearable devices available on the market. The decision to use low-cost wearable EEG and EDA devices was driven not only by their economic accessibility but also by their ease of use, portability, and the potential to innovate research methodologies, expand data collection, facilitate interdisciplinary collaborations, and promote education and clinical applications. Such devices support methodological innovation by allowing for the experimentation of new study designs and exploring research questions that would have been challenging to address with more expensive and complex technologies. Additionally, being noninvasive and often integrated with other technologies, such as smartphone apps and cloud computing platforms, they easily facilitate translating research into clinical and therapeutic applications. Although the preliminary analysis included both EEG, and EDA wearable devices, the scope of the present study was restricted to EDA measures. Our approach relies on a single low-cost wearable EDA device embedded in a protocol specifically designed for the assessment of cognitive stress, rather than general emotional arousal, with the aim of enabling future m-health and real-world applications. This focus reflects our interest in EDA as a reliable and noninvasive marker of stress reactivity.

II. Methods

The experiment was conducted in a meeting room located on the ground floor of the Teoresi office in Naples. This room was chosen because it lacked noisy stimuli that could distract the subject or interfere with the successful acquisition of signals, and because it maintained a temperature of approximately 23°C, optimal for measuring EDA. The experiment was conducted on 32 subjects, including 15 women and 17 men aged between 23 and 37 years. All participants took part voluntarily and without compensation. Before participation, they were informed about the purpose and procedures of the study, including how the task would be performed, and gave their informed consent. Additionally, in compliance with privacy regulations, the test was conducted completely anonymously. Participants in the test were selected based on three characteristics: age between 20 and 40 years, educational qualifications, and colour blindness, due to the inability to complete the SCWT. Muse S and EmoBit (sampling rate of 15 Hz) devices were used for collecting EEG and EDA data, respectively. In this work only the EDA signal is analyzed.

A. Experimental set up

The experimental setup was designed considering established literature [18] for the acquisition of the EDA signal. The Emobit device was placed on the middle fingers to capture EDA data.

The experimental protocol was structured utilising PsychoPy [19], into six phases, as shown in fig 1, which are respectively:

- EYES CLOSED: the subject is asked to remain silent with their eyes closed for 180 seconds;
- EYES OPEN: the subject, remaining silent, must stare at the cross that appears at the center of the screen for 180 seconds;
- STROOP COLOR WORD TEST. The test is composed of three blocks: (W) congruent word, (C) congruent colour, (CW) incongruent condition. Each block has a fixed duration of 120 seconds, totaling 360 seconds. Each stimulus appears on the screen for 1.2 seconds; if the subject responds in more time than that, the response is considered incorrect. The stimuli for each block appear on the screen one at a time in the center of the monitor, randomly presented by the program itself, and the responses are given by the subject using a keyboard. In block W, the subject is asked to use the keyboard to indicate the name of the color displayed on the screen.

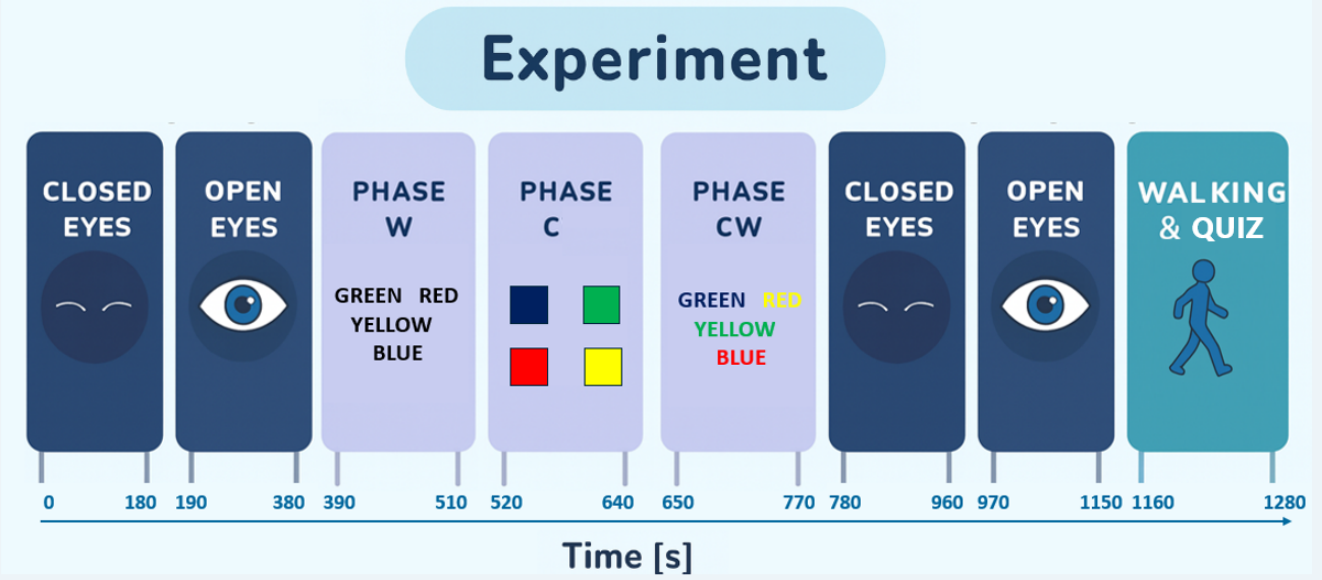


Fig. 1: Acquisition protocol.

In block C, the subject is asked to indicate the color of the square, while in block CW, the subject is required to indicate the color of the ink with which the word is written;

- EYES CLOSE for 180 seconds;
- EYES OPEN for 180 seconds;
- WALKING and ARITHMETIC TEST (WeT): the subject is asked to perform 17 mental arithmetic operations during 120 seconds of straight line walking, consisting of three questions regarding their perception of stress during the experiment.

Each phase is always separated by a 10-second pause. The SCWT [20] is a widely used neuropsychological test to assess the ability to inhibit cognitive interference, which occurs when processing a specific stimulus feature hinders simultaneous processing of another stimulus attribute, known as the Stroop effect. Various psychological mechanisms underlie the Stroop task [21], including information processing speed, working memory, semantic activation, and the ability to reinforce a response feature. The Stroop Test is considered an effective indicator of cognitive stress [22] because it requires high levels of attentive and inhibitory control, highlighting how the brain manages competition between conflicting information and measures the ability to maintain optimal cognitive performance under stress. Specifically, during the incongruent phase of the test, where participants must identify the ink colour in which words are written, there is a conflict between the word's meaning and the ink colour, forcing the brain to inhibit an automatic response (reading the word) in favour of a less automatic response (naming the colour) [20]. This inhibition process requires significant cognitive effort, and the task difficulty level can induce cognitive stress. The extent to which a person can overcome this interference without errors or with reduced response time provides an indication of their ability to manage cognitive stress [23], [24]. The Stroop Test allows for the calculation of the Interference Index (IG), measuring an individual's ability to maintain focus on a relevant task while ignoring irrelevant distractions. This concept is crucial in cognitive psychology [25], as it indicates the ability to filter out irrelevant information essential for efficient human cognitive functioning. Different scoring methods are proposed in the literature [26] to measure the Stroop effect; in this case for the study in question, the scoring method proposed by Golden [25] was considered, such that:

$$IG = CW - \frac{W \times C}{W + C}$$

.

B. Data analysis

For the analysis of EDA, from a population of 32 subjects, 2 subjects were excluded due to missing data caused by acquisition issues. A low-pass filter with a cutoff frequency below 1 Hz is implemented to remove electrical noise from the signal. Movement artifacts are removed by adding manual inspection to the low-pass filtering. Once the signal is cleaned, the EDA curve is decomposed because analysing the individual components mentioned above (especially SCR) provides richer information about the person's stress level. The Ledalab toolbox, in its version 3.4.9, was used in this study for EDA signal analysis, supporting the import of various data formats, such as MATLAB data and text data. The analysis was carried out considering an event response time of 90s focused on the five most significant EDA features calculated using the Continuous decomposition analysis (CDA) method: the number of SCRs, latency, ISCR (the area of the phasic driver equal to SCR multiplied by the response window size [µS*s]), the sum of the amplitudes of significant SCRs, and the mean tonic activity.

The data analysis was conducted:

- By phase, to provide a statistical comparison for each EDA feature across all test phases: pre-Stroop phase, Stroop W, Stroop C, Stroop CW, post-Stroop, and Walking and Test. To accomplish this, a Friedman test was conducted for each EDA feature. After determining differences between the phases using the Friedman test, we performed pairwise comparisons using the Wilcoxon test to identify which specific phases differ from each other.
- by gender: to provide a statistical comparison for each EDA feature across all test phases: pre-Stroop phase, Stroop W, Stroop C, Stroop CW, post-Stroop, and Walking and Test.
- based on median IG: to understand the behaviour of the signals by distinguishing the population into stressed and non-stressed subjects according to the ognitive Interference Index IG score. The calculation of IG, allowed for the division of the population into two categories: stressed and non-stressed. Specifically, the classification was made by considering the median value of IG for EDA. All participants with IG values higher than IG MED are considered non-stressed, while those with IG values lower than IG MED are considered stressed, in line with the literature [26], which states that low IG values indicate difficulty in inhibiting cognitive interference and therefore higher stress.
- Based on perceived stress: according to the response to question no. 3 of the final test questionnaire. At the conclusion of the experimental test, each subject was administered a questionnaire to assess the level of perceived stress. Specifically, about question Q2: "Did you feel nervousness, anxiety during the completion of the test? YES or NO", subjects were divided into two categories: stressed and non-stressed.

The statistical analyses by gender, based on median IG, and perceived stress were all conducted using the U Mann-Whitney test. In all cases, the resulting p-values are compared against a significance level of $\alpha = 0.05$.

III. Results and Discussions

Before the actual experiment, subjects were asked if they had experienced anxiety or panic attacks related to stressful situations in the past. In response to this question, only 34% of the participants stated that they had suffered from anxiety or panic attacks linked to high stress situations, while 66% of them reported never having experienced such a condition.
Regarding the EDA results by phase, the Friedman test revealed significant differences across phases for all EDA features except Latency (Table I). Although Latency did not differ significantly, its values decreased during exposure to stressful stimuli (Stroop and arithmetic tasks; Fig. 2), indicating a faster sympathetic nervous system response. Specifically, during the Stroop CW incongruent phase, the median Latency was lower than in the two preceding Stroop phases, suggesting higher stress levels. The sum of SCR amplitudes (Fig. 3, as well as ISCR tends to increase under stress, reflecting an overall

TABLE I: P-values of EDA features by phases with the Friedman test.

	N SCR	**TONIC**	**LATENCY**	**AMP SUM**	**ISCR**
p-value	< 0.001	< 0.001	0.172	< 0.001	< 0.001

TABLE II: Pairwise comparisons for the Sum of amplitude and NSCR across experimental phases.

Pairwaise comparison	**P-Value AmpSum**	**P-Value nSCR**
$PRE - CW$	0.006	<0.001
$PRE - W$	0.004	<0.001
$PRE - WeT$	<0.001	<0.001
$C - WeT$	<0.001	<0.001
$POSTS - WeT$	<0.001	<0.001
$CW - WeT$	<0.001	<0.001
$W - WeT$	<0.001	<0.001

increase in skin responses. Similarly, SCRs which represent brief increases in skin conductance caused by external stimuli, such as in the Stroop test or the walking and test phase, tend to increase in number in stressful situations, as shown in Fig. 4 because the sympathetic nervous system is more active and causes more frequent sweat gland responses. The results of the pairwise comparison across phases are shown in Table II. The increase in characteristic values during the stress phases of the test reflects the subject's stress condition compared to the initial relaxation phase, as indicated by significant differences between the baseline and stress tasks, such as the Stroop phase, the Walking phase, and the Quiz phase.

To conduct a gender-based analysis the population was divided into two groups: 17 males and 13 females. The test results indicated that only latency varied significantly between genders in the phase preceding the Stroop test, defined as PRE-STROOP. However, the other Mann-Whitney test results did not show statistically significant differences between genders for any other features during any phase of the test, suggesting that, from a statistical standpoint, gender does not influence

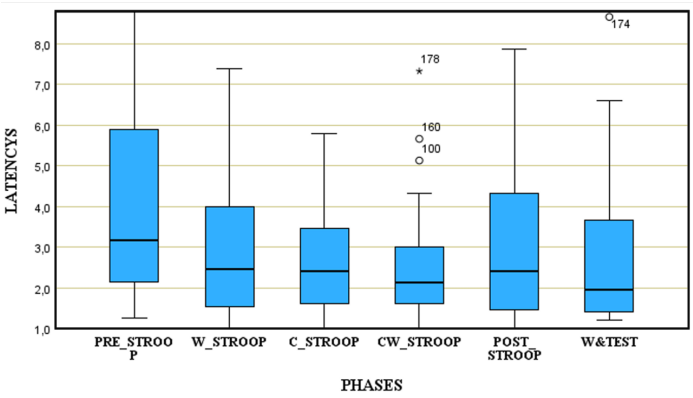


Fig. 2: Variation in the Latency across the six phases of the test

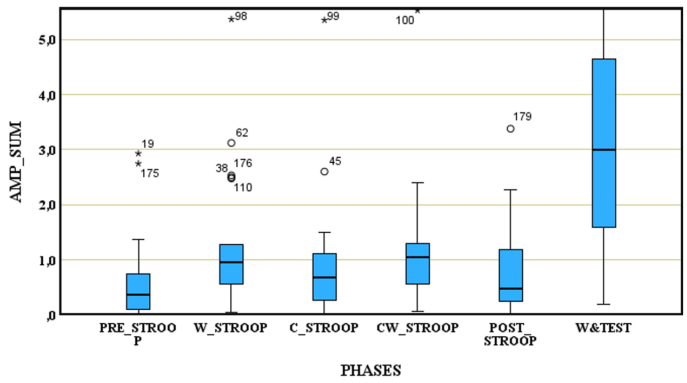


Fig. 3: Variation in the sum of Amplitudes across the six phases of the test.

these specific EDA parameters under test conditions.

For stress analysis, subjects were divided into 15 stressed and 15 non-stressed individuals, depending on whether their IG score was greater or less than the IG MED value. However, the comparison between stressed and non-stressed groups based on the IG value did not show a significant difference. Additionally, the EDA features were analysed based on the perceived stress of each subject at the end of the experiment. In this case, the population was divided into stressed and non-stressed based on their response to question Q2 in the satisfaction questionnaire, resulting in a group of 20 stressed subjects and a group of 10 non-stressed subjects. The analysis conducted showed a statistical difference between stressed and non-stressed subjects for the Tonic component in the CW phase of the Stroop test and the post-Stroop relaxation phase. Physiologically and in terms of stress, a significant difference between the two groups suggests that basal levels of sympathetic activation differ between stressed and non-stressed subjects during the Stroop task. Specifically, the significant difference may indicate that non-stressed subjects have a greater ability to regulate or recover from cognitive stress induced by the Stroop task. In contrast, stressed subjects may

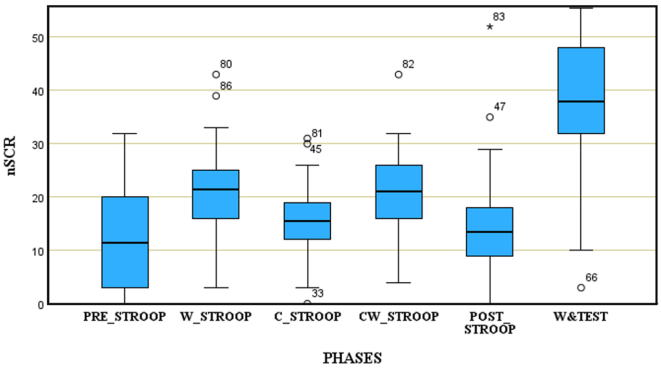


Fig. 4: Variation in the number of SCR across the six phases of the test.

exhibit a lower physiological response in the tonic component, suggesting reduced recovery ability or increased persistence of stress response.

IV. Conclusions

This study, conducted in collaboration with Teoresi S.p.A., aimed to investigate the physiological response to cognitive stress induced by the Stroop test and arithmetic tasks, measuring EDA using portable device. The experiment involved 32 subjects. The test included four main phases (pre-Stroop relaxation, Stroop test, post-Stroop relaxation, and walking and test). The Friedman test highlighted significant differences in various EDA characteristics between test phases, except for latency, showing increased values during stress phases. EDA analysis based on gender and IG score found no significance between stressed and non-stressed groups. Significant differences were observed in the tonic component in the CW phase and in the post-Stroop relaxation phase when considering perceived stress. However, the limited sample size and the lack of variety in stress-inducing stimuli suggest the need for further studies to expand the sample size and types of induced stressors, and improve subject comfort. Moreover, the results obtained in the analysis based on the cognitive interference index value necessitate future studies where the calculation of this parameter also considers response time to improve accuracy. This study lays the groundwork for future research that should integrate multimodal inputs, for example, combining EDA with other physiological and behavioural signals [27], [28] to enhance robustness and clinical utility [29]. It also supports the implementation of innovative solutions and strategies enabling the concurrent acquisition of EDA and EEG, applicable in both real-world and clinical settings. Overall, our data support the use of the Stroop test as a valid inducer of cognitive stress and indicate that low-cost wearables can detect it via physiological measures such as EDA.

Acknowledgment

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Performance Analysis of Thermoelectric Generators Coupled with Pietra di Modica for Thermal Gradient Enhancement

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***Abstract*— This study investigates the performance of thermoelectric generators (TEGs) integrated with *Pietra di Modica*, a traditional Sicilian stone, used as a passive thermal interface to induce a temperature gradient. The research focuses on three primary aspects: the relation between thermal gradient and output voltage, the thermal behavior of the system over time, and the evolution of electrical output during a controlled 60-minute heating cycle, respectively. Experimental tests were conducted under three different heating conditions, with continuous monitoring of surface temperatures on both sides of the stone to assess its thermal absorption and propagation properties. Results show that the system achieves both thermal and electrical stability within 30-40 minutes of operation. These findings demonstrate the potential of using local stone materials like *Pietra di Modica* for developing autonomous energy harvesting sensing systems, particularly in historical or architecturally significant contexts.**

Keywords—Energy Harvesting, Passive Cooling, Pietra di Modica, Temperature Gradient, Thermoelectric Generators

I. INTRODUCTION

The shift toward complex IoT systems has created strong interest in remote devices [1,2], raising challenges related to system powering and energy generation through transducers. It is worth noting that novel materials [3,4,5] and energy harvesting from surrounding environments [6,7] represent an ideal and sustainable solution to this problem. Various energy sources were considered for this process such as thermal, hydro and vibrational energies. The thermal energy conversion to electricity was discovered at the beginning of the 1820s by Thomas Seebeck [8]. Nowadays thermoelectric generators are highly demanded in the usage for powering remote devices [9].

A thermoelectric generator works based on the Seebeck effect, where a temperature difference between its hot and cold sides creates a flow of charge carriers. The device uses n-type and p-type semiconductors to convert this thermal gradient directly into electrical voltage [10].

Continuous research and development on these devices have taken different directions. Many studies worked on varying thermocouple materials as well as their size looking for an optimal output by the TEG module [11,12,13].

Other studies focused on improving the temperature gradient between two sides. A main challenge lies in cooling one side of the TEG module [14]. Several studies have worked on the design of a cooling system to improve the TEG performance whether by using an active cooling system which requires power, or passive systems [15].

The use of active cooling systems brings the problem of efficiency [16] and whether the harvested energy is more than the consumption for powering the system. A study presented in [17] indicates that achieving net power gain in a self-cooling system requires a minimum inlet airflow temperature as well as an appropriate external load resistance. In contrast, the passive cooling systems are 100% sustainable. Heat sinks, in particular, showed heat dissipation criteria and have been a great solution in increasing the system performance [15,18]. Many studies [15,19,20] have investigated different designs of heat sinks by looking at the optimal fin size and spacing between them.

The use of the thermoelectric generators expanded across various fields. Each field employs specific module size, targets particular temperature gradient, and selects appropriate heat sources. In the medical field, the authors of [21] used body temperature to harvest energy for powering a monitoring system. In the automotive industry [22,23] motor thermal energy was targeted as a source of heat for the TEG. In high temperature cities, pavements store an interesting amount of heat which was used to heat TEG modules [24]. Also, buildings [25] are strong heat holders and materials such as bricks, concrete, and rocks have good thermal properties for heat storage. In [26], the authors analyzed the thermal behavior of a historical building in Catania constructed with lava rocks. Similarly, in [27], the authors explored the potential of using thermal energy stored in volcanic rocks to heat a TEG module and power a monitoring system.

Researchers have primarily focused on using rocks and their thermal properties as a heating system for the TEG modules. No significant study has looked into using rocks as a cooling system. In this paper, we will explore the use of a local

carbonate rock cropping out in Modica, a town in south-eastern Sicily, as a cooling system for a TEG device. This stone, extensively used in the Sicilian late Baroque architecture of the Val di Noto area [28,29], is still employed today as building and decorative material.
In Section II the experimental setup is deeply explained with the identification of the different used materials. Section III presents the results of the experiment and Section IV includes the conclusion of the paper.

II. Experimental Setup

This section explains the experimental process in detail including the devices used to evaluate the voltage generated by the system. Fig 1. shows the thermoelectric module used in the experiment. The characteristics of this module [30] are as follows:

- Reference: CP2, 127, 10L
- Size (mm): 62.0 x 62.0 x 5.6
- Number of thermocouples: 127
- Seebeck Coefficient: 0.19 V/k



Fig 1. TEG used in the experiment

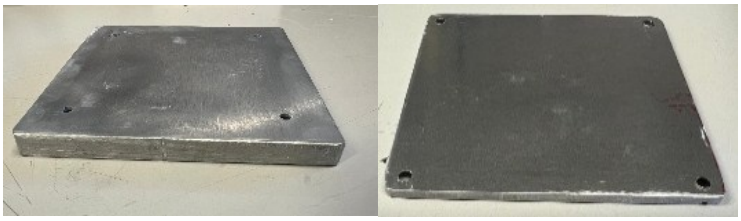


Fig 2. Aluminum plates

This TEG module was encapsulated by two different aluminum plates shown in Fig 2. The dimensions of the plates (in millimeters) are as follows:

- 75.0 x 75.0 x 3.0
- 92.0 x 92.0 x 8.2

The experiment used a commercial plate heater from Torrey Pines, as illustrated in Fig 4. An aluminum plate was positioned between the heater and the device, serving as a heat spreader to provide uniform thermal energy distribution across the device.

For data acquisition, the InfiniiVision Digital Storage Oscilloscope (DSO-X 3024A), illustrated in Fig 4, was utilized to measure the voltage generated by the TEG modules, offering an acquisition accuracy of approximately ±2% [31]. Each measurement consisted of 2000 data points recorded at a sampling rate of 100 MSa/s, which were subsequently averaged during the data processing stage to ensure reliable results. Temperature measurements were carried out using the FLIR T650sc thermal camera, shown in Fig 4, which provides a measurement accuracy of ±1 °C within the temperature range of 5 °C to 150 °C [32]. Similar instruments have been reported in previous experimental studies to ensure measurement consistency [21,33]. Furthermore, silicone-based thermal paste was applied between the components to improve thermal conductivity and minimize interfacial resistance [34].

Fig 3 shows the rock specimen used in this experiment, known as Pietra di Modica.



Fig 3. Image of the used rock 'Pietra di Modica'

The rock sample is cubic, with each side measuring 70 mm. During the experiment, the encapsulated TEG was placed on the heater. The thinner aluminum plate was placed on the hot side and the thicker one on the cold side. The rock was placed on top of the device to study its heat dissipation capability as a passive cooling material.

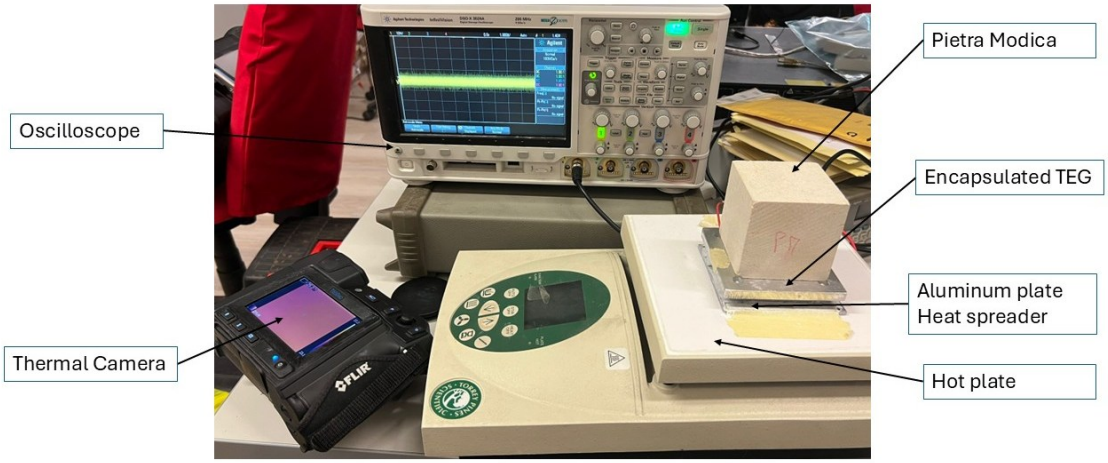


Fig 4. Experimental setup with the measurement devices

III. Results and Findings

Measurements were conducted with the hot plate set to 30 °C, 40 °C, and 50 °C. Each experiment lasted 60 minutes, during which five parameters were recorded every 10 minutes: the voltage generated by the device, the temperature of the device's cold side, the temperature of the device's hot side, the temperature of the rock surface in contact with the device, and the temperature of the opposite side of the rock. Fig 5 illustrates the positions of the temperature sensing points on the setup. The sensing point corresponding to the "in-contact side of the rock" was located at the center of the rock surface in contact with the device, similar to the sensing point on the opposite side, which was also positioned at the center of the upper surface. To verify repeatability, each experiment was repeated twice under identical conditions, and the results showed consistent trends across all measurements. Data processing was conducted using MATLAB®, which facilitated the plotting and analysis of the results presented in the following section.

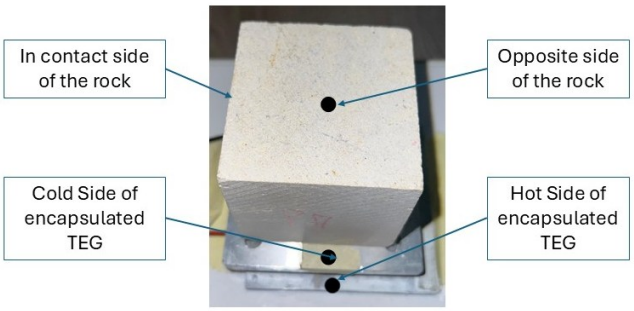


Fig 5. Temperature sensing points

The study analyzes the voltage generated by the system and evaluates the rock's effect on the cooling process. Fig 6 presents the voltage generated by each system as a function of the temperature difference by associating the measured voltage to the measured temperature gradient.

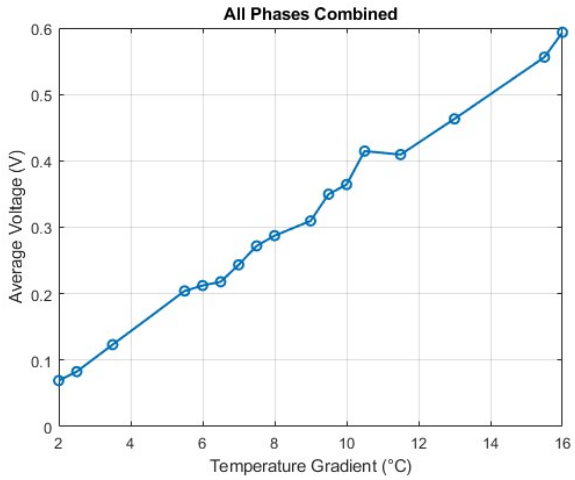


Fig 6. Voltage Generated per Gradient with Pietra Modica rock

The plot shows a quite linear evolution of the voltage generation in terms of temperature gradient on the TEG device, which aligns with the voltage equation for thermoelectric generators:

$$V = \Delta T \times S \qquad \text{(eq. 1)}$$

where ΔT is the temperature gradient and S is the Seebeck coefficient related to the module. In our case, the temperature measurement did not target the TEG module but the aluminum encapsulation. Therefore, we introduced a correction factor α to account for the temperature drop across the aluminum and TEG interfaces. It was empirically derived by comparing the measured plate temperatures with those estimated at the TEG junctions using the voltage generated and Seebeck coefficient provided in the datasheet of the module.

$$V = \Delta T \times \alpha \times S \qquad \text{(eq. 2)}$$

Fig 6 presents the fitting of the measurement results with the mathematical model in eq. 2.

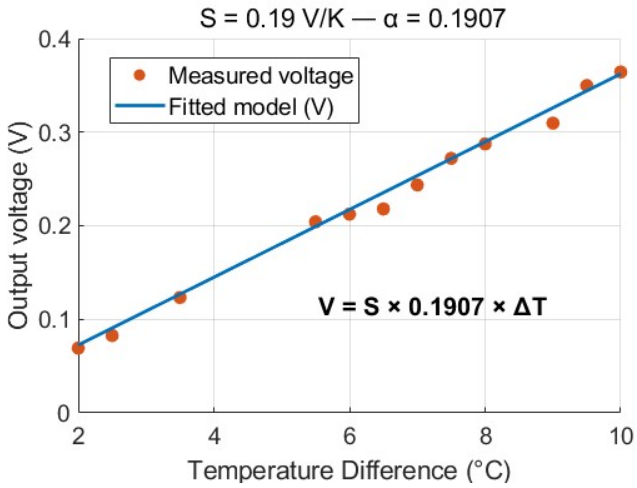


Fig 7. Mathematical model fitting for the voltage output

According to Figs. 6 and 7, it can be observed that the maximum voltage generated was approximately 600 mV for a 16 °C temperature gradient. During this experiment, the voltage and temperature evolution over time were also studied. Fig. 8 shows the evolution of the temperature gradient of the TEG device over 60 minutes.

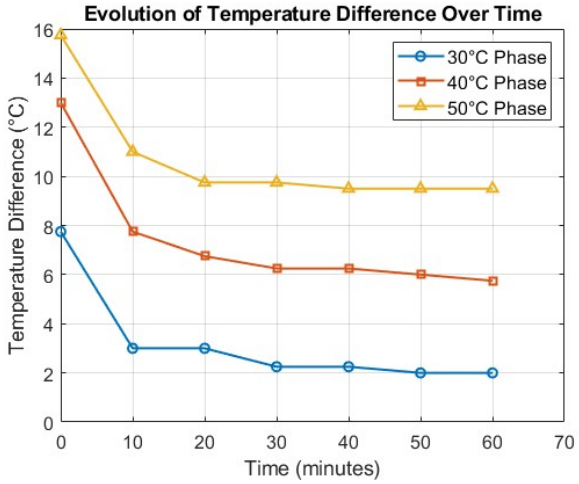


Fig 8. Thermal Gradient evolution of the TEG device over time with Pietra di Modica rock

From the three curves in Fig. 8, a consistent trend can be observed: the temperature difference stabilizes after approximately 20 minutes in all cases. This suggests that the system reaches a steady state beyond this point, where the thermal energy transferred from the hot plate to the device is nearly balanced by the energy dissipated through the rock.

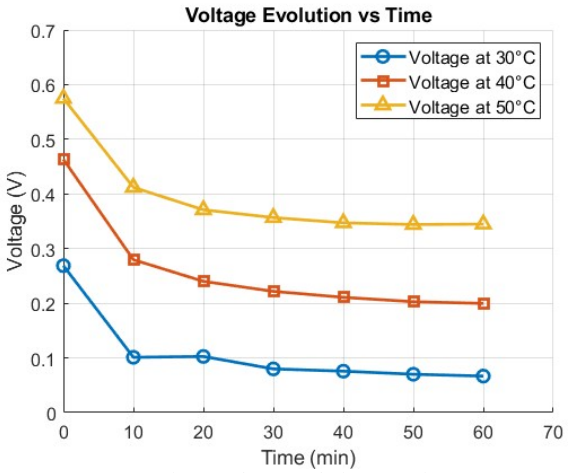


Fig 9. Voltage evolution over time

Fig 9 represents the output voltage evolution over the 60 minutes of the experiment.

The results show that the system reaches stability after approximately 30 minutes. Therefore, the measurements taken at the 60-minute mark can be considered stable data. Table I presents the data recorded after 60 minutes of operation.

Table I: Voltage and temperature gradient data after 60 minutes

Heating Temp (°C)	30.00	40.00	50.00
Voltage after 60 minutes (V)	0.066	0.200	0.345
TEG gradient after 60 minutes (°C)	9.50	5.75	2.00

To gain a better understanding, the temperature evolution on both sides of the rock was also analyzed, as shown in Figs. 10, 11, and 12.

From the plots in Figs. 10, 11, and 12, a sharp temperature rise can be observed on the contact side of the rock during the first 10 minutes. In contrast, the opposite side exhibits a more gradual and consistent temperature increase. Furthermore, during the final 20 minutes, the temperature difference between the two sides becomes nearly constant.

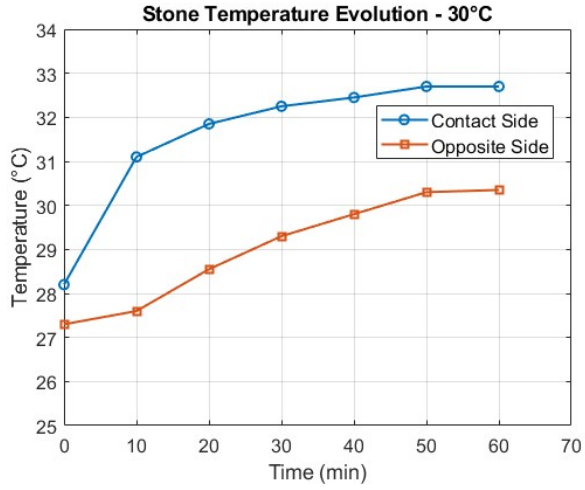


Fig 10. Temperature measurement of the rock sides on 30 °C heating

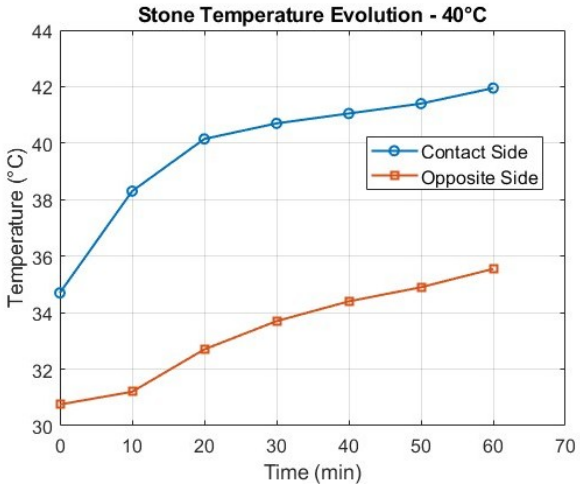


Fig 11. Temperature measurement of the rock sides on 40 °C heating

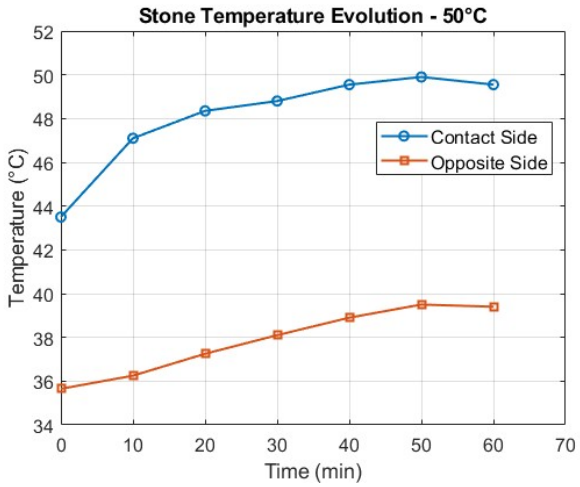


Fig 12. Temperature measurement of the rock sides on 50 °C heating

Also to have better insights into the temperature evolution of the stone, Table II presents the temperature of each side of the stone before and after the experiment.

Table II: Stone temperature evolution

	Temperature of the stone side in contact with TEG (°C)			Temperature at the opposite side of the stone (°C)		
Heating Temp (°C)	30.00	40.00	50.00	30.00	40.00	50.00
Minute 0	27.30	34.70	43.50	27.30	30.75	35.65
Minute 60	32.70	41.95	49.55	30.35	35.55	39.40

This table gives insights about the heat propagation speed through the stone under different heat intensity.

IV. Conclusion

This study examined the performance of TEGs when coupled with Pietra Modica, a local Sicilian stone, used as a dissipative layer to induce a thermal gradient. The investigation focused on three key aspects: (i) the output voltage as a function of the thermal gradient, (ii) the thermal behavior of the system over time, and (iii) the evolution of the output voltage during a 60-minute heating cycle.

The output voltage was measured under three different heating conditions, and the temperature gradient across the stone was continuously monitored. Surface temperatures on both sides of the stone were analyzed to evaluate its thermal absorption and propagation characteristics. Results indicate that the system tends to reach thermal and electrical stability approximately 30–40 minutes after the beginning of the experiment.

The findings highlight the suitability of this approach for the development of autonomous sensing systems in buildings and surfaces of historical and artistic significance, where similar types of stone are often present.

The study is currently ongoing and is being extended to include other types of stone, with the aim of comparing performance as a function of the contact surface properties and varying TEG configurations.

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Development of Analytical Models for the Electromagnetic Field Analysis of a Three-phase DD-PMSGs for Wind Turbine Applications

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***Abstract*—Wind energy technology is becoming increasingly popular due to its maturity and potential for significant growth in renewable energy. Direct drive generators (DDGs) decrease power loss, noise, vibration, and maintenance requirements by eliminating the gearbox and transmission elements found in wind turbines. This paper presents an improved analytical model for the airgap electromagnetic field of direct drive permanent magnet synchronous generators (DD-PMSGs), which includes slotting effects, winding distribution, flux leakages, and higher-order harmonics. The model combines the winding function technique with an equivalent magnetic circuit to create a computationally efficient framework for capturing important electromagnetic phenomena. Beyond enhancing accuracy, the proposed model allows for sensitivity studies and incorporation into multiphysics environments, providing useful insights for design optimization, cost reduction, and vibration analysis in next-generation wind turbines. Vibration mitigation contributes to increased energy efficiency, reduced environmental impacts, and improves the overall performance of wind turbines, leading toward sustainability. Validation against finite element (FE) simulations in Ansys Electronics Desktop shows high agreement, proving the model's value for both research and industrial applications.**

***Index Terms*—Direct-drive generators, magnetic flux density, finite element analysis, wind turbines, winding function approach, analytical model, equivalent magnetic circuit**

I. Introduction

Wind energy has established itself as a sustainable alternative to fossil fuels, aiding in the reduction of CO2 emissions[1]. Moreover, wind energy technology is a mature type of renewable energy with a relatively low Levelized Cost of Energy (LCOE). However, progress is being made to make it more affordable [2, 3]. Doubly-fed Induction Generators (DFIGs) and Direct-Drive Generators (DDGs) are the two most common types of generators of wind turbines, with a tendency toward DDGs [4]. Utilising DDG technology, the gearboxes of offshore wind turbines are eliminated, resulting in higher efficiency and reliability, and lower noise, vibration, downtime rates, and maintenance requirements [4, 5]. Further design improvements require a robust model taking into account various aspects of the DDG function.

Some of the analytical methods used to represent the governing equations of generators include:

- Exact Subdomain Analysis
- Magnetic Equivalent Circuit
- Maxwell Stress Tensor
- Winding Function Approach
- Conformal Mapping Method
- Energy Approach

while numerical methods are classified into:

- Two-Dimensional (2D) Finite Element Methods (FEMs)
- Three-Dimensional (3D) FEMs

[6, 7]. The expressions found through analytical methods are based on some assumptions and simplifications, whereas the

EPSRC and FEMM Hub

FE method is more accurate. However, the FE method has some practical limitations due to its time-consuming nature [7]. The analytical model, in addition to reducing the time required to obtain results, enables sensitivity analysis, which facilitates design improvements. Furthermore, the integration of the models into multiphysics is a merit of the analytical method.

The design variant of this study is an X-Rotor wind turbine. The X-shaped rotor of this turbine enjoys a hybrid vertical-horizontal axis wind turbine that assists in the decrease of the total cost of energy [8–11]. This study provides a set of governing equations for an ideal 3-phase DD-PMSG considering the slotting effect, winding distribution, stator current, and flux leakages of the PMs by using a magnetic circuit method. The winding function approach and equivalent magnetic circuit are utilized to derive the governing equations. The winding function approach is a principal aspect of machine analysis, describing the spatial field distribution in the airgap of the machine by winding function for all windings and winding currents [12–14]. On the other hand, an equivalent magnetic circuit is an analytical method that simplifies the analysis of complex magnetic structures by treating them as networks of magnetic elements to analyze magnetic field behavior. The main contribution of this paper is the creation of an analytical model that combines the improved magnetic circuit method and the winding function approach to capture slotting effects, winding distribution, flux leakages, and higher-order harmonics. Unlike existing magnetic circuit or winding function models, which address these factors separately, the proposed framework combines them into a cohesive formulation, providing both simplicity and sufficient accuracy. This innovation allows the model to be used not only as a reliable alternative to the FEM for predicting electromagnetic fields, but also as a foundation for vibration analysis, multiphysics integration, and design optimization via sensitivity studies. In the methodology section, analytical representations of the magnetic flux densities resulting from PM and stator winding, as well as the structural parameters of the X-Rotor DD-PMSG as a case study, are provided. The simulation and numerical results section compares the obtained results from analytical and FE methods. The conclusion section discusses the significance of the results and identifies opportunities for continued research.

II. Methodology

An improved magnetic circuit (IMC) model is proposed, consisting of two magnetomotive force (MMF) sources and the reluctance of the different parts. Permanent magnets (PMs) and MMF due to armature reaction are the sources of flux. Based on IMC presented in Fig. 1 for computing the main and leakage fluxes, the following parameters are defined in terms of physical dimensions as follows[15, 16]:

$$\alpha = \frac{H_{pm}}{\pi \mu_{pm} l_m} \ln\left(1 + \frac{\pi g_e}{H_{pm}}\right) \tag{1}$$

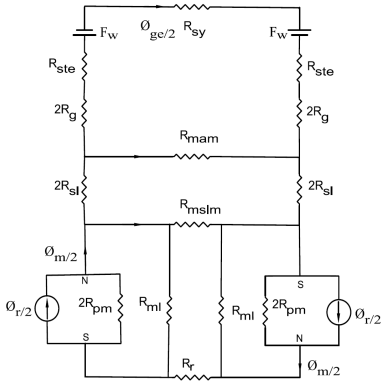


Fig. 1. A schematic IMC model[15].

$$\beta = \frac{H_{pm}}{\pi \mu_{pm} l_m} \ln\left(\frac{\delta + \pi g_e}{\delta + \pi l_{sl}}\right) \tag{2}$$

$$\gamma = \frac{\mu_{sl} H_{pm}}{\pi \mu_{pm} l_m} \ln\left(1 + \frac{\pi l_{sl}}{\delta}\right) \tag{3}$$

where H_{pm} is the magnet height, μ_{pm} is the relative permeability of the magnet, l_m is the length of the magnet, μ_{sl} is the relative permeability of the sleeve,l_{sl} is the length of the sleeve, g_e is the effective airgap length, and δ is the gap between magnet to magnet. In order to define the magnetic flux density under no-load conditions, the following parameters are defined using R_g, R_{pm}, R_{sy}, R_{ste}, R_r, R_{sl}, R_{sl}, R_{ml}, R_{mam}, and R_{mslm} which are reluctances of airgap, permanent magnet, stator yoke, stator tooth, rotor yoke, sleeve, magnet to rotor, magnet to magnet through air, and magnet to magnet through conducting sleeve, respectively[15].

$$R_F = R_B + 2R_C + R_r \tag{4}$$

$$R_B = \frac{R_E R_{pm}}{\gamma R_E + R_{pm}(R_{pm} + \beta R_D)} \tag{5}$$

$$R_E = R_D R_{pm} + 4R_{sl}(R_{pm} + \beta R_D) \tag{6}$$

$$R_D = R_{sy} + 4R_g + 2R_{ste} \tag{7}$$

$$R_C = \frac{2R_{pm}}{1 + 2\alpha} \tag{8}$$

$$R_A = \frac{R_D R_{pm}}{R_{pm} + \beta R_D} \tag{9}$$

In order to account for the slotting effect, Carter introduced the concept of effective air-gap length, which is used in place of the physical air-gap length. The effective airgap length can be obtained by Carter's factor K_c presented in Eq. (10) where g_1 is the physical airgap length, τ_s is the slot pitch, and γ is a factor defined as Eq. (11) [17, 18].

$$k_c = \frac{\tau_{\text{slot}}}{\tau_{\text{slot}} - g_1\,\gamma_1} \tag{10}$$

$$\gamma_1 = \frac{4}{\pi}\left[\frac{w_s}{2g_1}\arctan\left(\frac{w_s}{2g_1}\right) - \ln\left(\sqrt{1+\left(\frac{w_s}{2g_1}\right)^2}\right)\right] \tag{11}$$

The effective airgap length is

$$g_{\text{e}} = k_c\, g_1 \tag{12}$$

Under no-load conditions, the airgap flux density, B_g, using IMC can be derived as [15, 16]:

$$B_g = \frac{4R_{pm}^3\, C_\phi}{(R_{pm}+\beta R_D)(R_{pm}+\gamma(R_A+4R_{sl}))R_F\,(1+2\alpha)}\, B_r \tag{13}$$

where C_ϕ is the airgap flux concentration factor. In the case of arc-shaped magnets, the distribution of the magnetic flux density in the airgap is flat-topped, as there are odd harmonic components. Eq. (14) includes fundamental and harmonic components of the magnetic flux density distribution in the airgap with the peak value presented in Eq. (15). β is two times of the angular length of the magnet [15, 16].

$$B_g(\theta_e) = \sum_{k=1,3,5}^{\infty} B_{gk}\,\sin(k\,\theta_e) \tag{14}$$

$$B_{gk} = \frac{4}{\pi}\left(\frac{\pi}{2}-\beta\right)\frac{B_g}{k^2}\,\cos(k\beta)\,\sin\left(\frac{k\pi}{2}\right) \tag{15}$$

Under loading conditions besides the MMF source due to the PMs, there is a winding MMF. With respect to the characteristics of the DDG system, including the turn function, $n_x(\phi)$, and inverse airgap function $g^{-1}(\phi,\theta)$, the winding function describing the distribution of the winding in slots can be obtained by Eq. (16). The resultant MMF due to the winding is dependent on the winding function and phase currents shown in Eqs. (17)–(19) [13].

$$N_x(\phi,\theta) = n_x(\phi) - \frac{1}{2\pi\,\langle g^{-1}(\phi,\theta)\rangle}\int_0^{2\pi} n_x(\phi)\, g^{-1}(\phi,\theta)\, d\phi \tag{16}$$

$$I_a(\omega_e t) = \sum_{k=1,3,5,\ldots}^{\infty} I_k\,\cos\big(k(\omega_e t-\theta_d)\big) \tag{17}$$

$$I_b(\omega_e t) = \sum_{k=1,3,5,\ldots}^{\infty} I_k\,\cos\big(k(\omega_e t-\theta_d-2\pi/3)\big) \tag{18}$$

$$I_c(\omega_e t) = \sum_{k=1,3,5,\ldots}^{\infty} I_k\,\cos\big(k(\omega_e t-\theta_d-4\pi/3)\big) \tag{19}$$

Accordingly, the resultant MMF due to the three-phase winding is:

$$MMF = N_a\, I_a(\omega_e t) + N_b\, I_b(\omega_e t) + N_c\, I_c(\omega_e t) \tag{20}$$

Taking the slotting effect into account, the magnetic flux density created by winding is

$$B_{\text{winding}} = \mu_0\, g^{-1}(\phi,\theta)\, MMF \tag{21}$$

The total airgap magnetic flux density, according to Eq. (22), is the summation of the winding and PM magnetic flux densities as

$$B_{\text{total}} = B_g + B_{\text{winding}} \tag{22}$$

To validate the analytical model, a PMSG is simulated in Ansys Electronic Desktop, a FE commercial software. PMSG parameters are presented in Table I. Fig. 2 shows the 2D representation of the machine's structure.

TABLE I
PARAMETERS OF THE X-ROTOR DD-PMSG.

Parameter	Symbol	Value	Unit
Mean Stator Radius	r_s	0.9245	m
Mean Rotor Radius	r_r	0.7647	m
Mean Airgap Radius	r_g	0.84	m
Airgap Length	g	0.01	m
Angular Pole Pitch	θ_p	45	degrees
Effective Airgap Length	g_e		m
Free Space Permeability	μ_0	$4\pi \times 10^{-7}$	
Permanent Magnet Relative Permeability	μ_{PM}	1.1	
Iron Relative Permeability	μ_{PM}	2000	
Height of the Stator Tooth	h_δ	0.03	m
Gap Between the Magnets	δ	0.1056	m
Stator Yoke Length	L_{ry}	0.1125	m
Rotor Yoke Length	L_{sy}	0.1125	m
Remanent Flux Density	B_r	0.925	T
Pole Embrace	α_{PM}	0.84	
Flux Concentration Factor	C_ϕ	1	
Height of Magnets	H_{PM}	0.014	m
Slot Pitch	τ_s	0.02	m
Tooth Width	W_t	0.006	m
No. of Slots	S	264	
No. of Pole Pairs	P	4	
Rated Power	p	2.5	MW
Rated Speed	ω	372	rpm

III. SIMULATION AND NUMERICAL RESULTS

Based on the presented equations and the X-Rotor DD-PMSG parameters presented in Table I, an analytical model is developed. Fig.3 shows the inverse airgap function versus electrical angle and its Fourier series approximation.

The winding functions for three phases, their Fourier, and symmetrical three-phase currents are shown in Fig.4. The first harmonic of the symmetrical three-phase currents presented in Eqs. (17)–(19) are modelled within ANSYS. The peak currents, electrical angular frequency, and phase shift are 600 A, 157.08 rad/s, and 2.5 rad, respectively. After setting up the

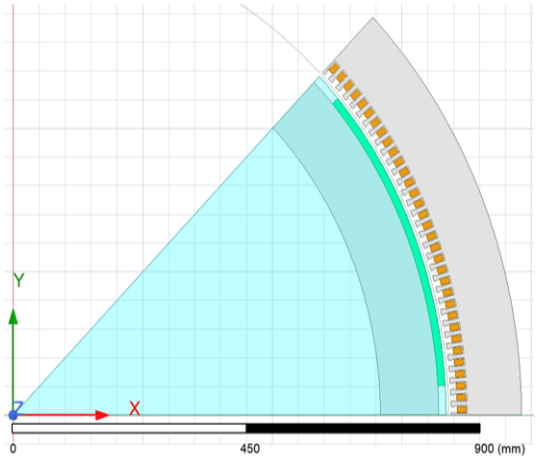


Fig. 2. The geometrical representation of the PMSG model.

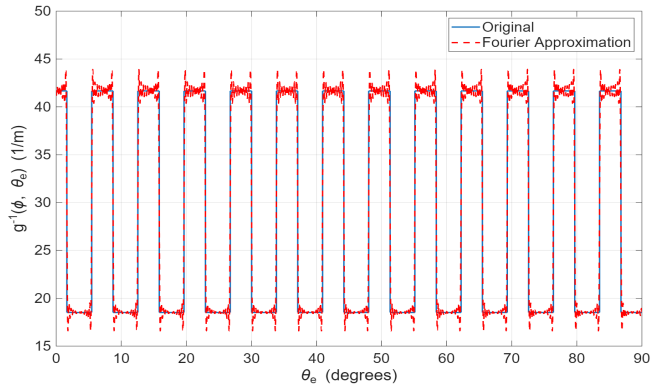
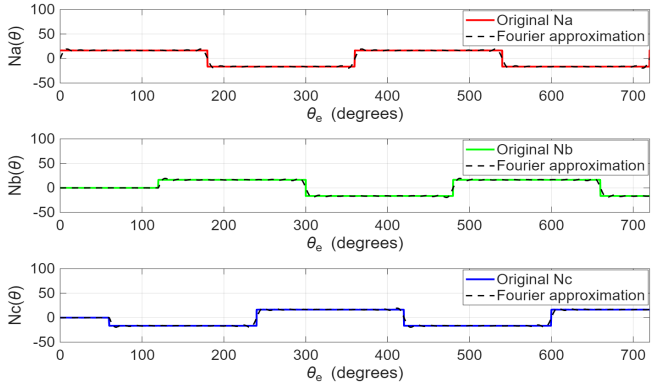
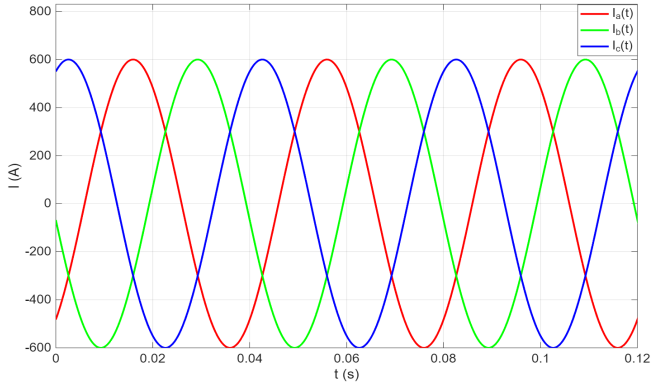


Fig. 3. The inverse airgap function versus electrical angle.



(a)



(b)

Fig. 4. (a) Turn functions versus electrical angle and (b) the three-phase currents versus time in stator windings .

stator excitation, the airgap magnetic flux densities produced by PM and winding are calculated according to Eqs.14 and 21.

Fig.5 shows the magnetic flux density distribution in the PMSG resulting from FE simulation.

Fig.6 compares the FE and analytical results of the magnetic flux density of the PMs and winding. It exhibits a very good agreement between the results. The high-frequency fluctuations in the FE results are because the effect of slots is neglected in the analytical model. Regardless of this, the analytical model predicts the electromagnetic field accurately.

Fig.7 depicts the winding magnetic flux density of theoretical and FE results. There is about a 15 percent error between the obtained results and a mismatch at the peaks that could be due to neglecting the tangential magnetic flux density, which is under investigation.

These figures confirm the capability of the analytical model for evaluating the electromagnetic field of PMSG. Compared to FEM, the suggested analytical model reduces computing time, allowing for faster design iterations and more efficient

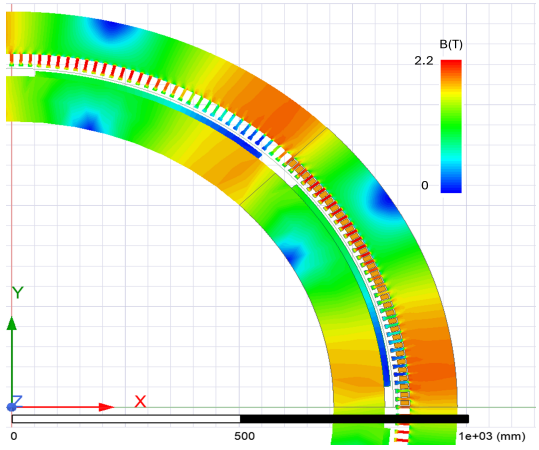


Fig. 5. Magnetic flux density map in the PMSG obtained from FE simulation.

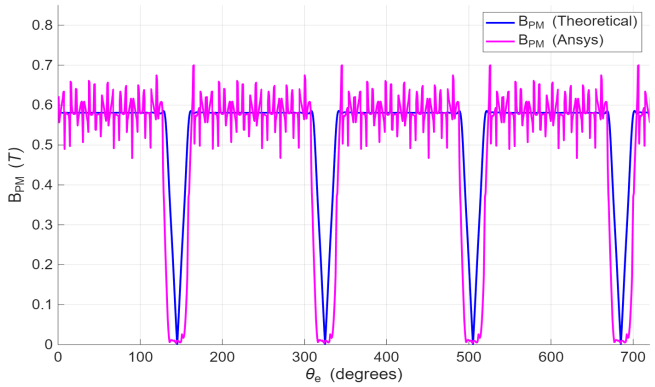


Fig. 6. PM magnetic flux density versus electrical angle.

sensitivity analysis. By capturing the influence of characteristics such as airgap length, magnet geometry, and slotting, designers may maximize performance without having to run many complex simulations. This makes the model useful for expediting development and facilitating multiphysics integration in DD-PMSG design.

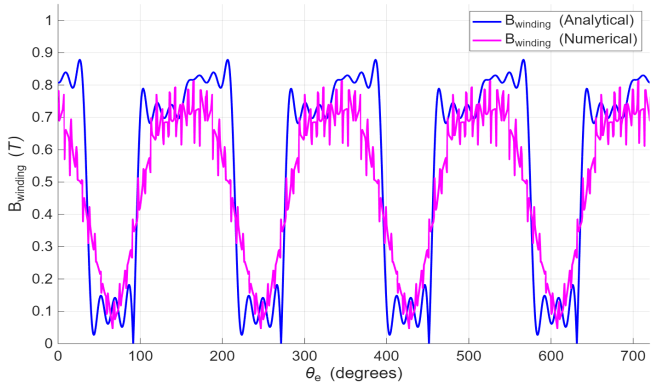


Fig. 7. Winding magnetic flux density versus electrical angle.

IV. Conclusion

This paper developed an analytical model for estimating the electromagnetic field of DD-PMSGs, which combined the improved magnetic circuit method with the winding function approach to account for slotting effects, winding distribution, flux leakages, and higher-order harmonics. Validation against FEM revealed excellent agreement, supporting the model's correctness and usefulness for rapid design iterations, sensitivity analysis, and multiphysics integration. By lowering computing effort while maintaining integrity, the suggested framework serves as a useful tool for both academic research and industrial applications in next-generation wind turbine design. Furthermore, sensitivity analysis and multiphysics integration lead to optimization, energy efficiency enhancement, and performance improvement of the wind turbine generators. Future study will focus on expanding the model to include unbalanced magnetic forces, eccentricity effects, and tangential flux components, which will improve its prediction capability and relevance to vibration and reliability investigations.

Acknowledgment

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A Smart Hydroponic System for Sustainable and Health-Centric Agriculture

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***Abstract*—This work presents the design and implementation of an intelligent monitoring and control system for nutrient solutions in hydroponic crops, based on analog pH, electrical conductivity (EC) and temperature sensors, along with an ESP32 microcontroller. By fitting double exponential mathematical models, the pH and EC values are accurately estimated from the measured voltage. The system integrates with the Blynk platform for real-time visualization, sending alerts through mobile notifications, and remote control of a recirculation pump. The system was tested in real world conditions, demonstrating stable operation, low energy consumption, and ease of operation. This solution aligns with the principles of sustainability and digitalization proposed by the 5.0 Industry and Health paradigms, offering an accessible, efficient, and user-centered tool for smart agriculture.**

***Index Terms*—Hydroponics, remote monitoring, IoT, ESP32, Wi-Fi, sustainability, smart agriculture.**

I. Introduction

The growing global demand for food security and sustainable food production has become a global concern due to population growth [1]. Furthermore, rapid urbanization and environmental challenges have intensified the need for smart agricultural solutions [2]. In recent years, hydroponic agriculture has gained significant importance as an efficient and sustainable alternative to traditional soil-based agriculture [3]. By delivering essential nutrients directly into water, hydroponic systems can achieve higher yields, faster growth cycles, and more efficient resource utilization. However, the growing environment directly influences production; therefore, it is crucial to accurately and continuously monitor parameters such as the temperature of the nutrient solution, pH, electrical conductivity (EC), air temperature, and humidity to ensure optimal plant health and stability of the system. The integration of emerging technologies, including the Internet of Things (IoT), high-precision environmental sensors, and artificial intelligence-driven control algorithms, has facilitated the creation of completely automated and adaptive cultivation systems [4], [5]. Numerous research studies have examined IoT-based solutions, revealing their capacity to enhance system effectiveness and diminish human interaction. The study [6] introduced an IoT-enabled hydroponic monitoring device based on NodeMCU microcontrollers and Blynk for real-time remote monitoring along with the control of nutritional components in a nutrifilm system. The work reported in [7] introduces a broad edge-AI-Cloud IoT framework for better strawberry production control using data analytics and ML methods to optimally enhance harvest timing and resource use. The study referenced in [8] describes an agricultural management system for lettuce grown using NFT (Nutrient Film Technique), which includes automated monitoring of fertilizers and water, and has been developed using various sensors to reduce production costs.

On the other hand, Health 5.0 with highly technological urban agriculture, such as intelligent hydroponics, is a key player for an adequate diet and sustainable food consumption, through accessible and sustainable technologies [9]. Moreover, as described in the recent literature on cyberphysical Agricultural Systems (Agri-CPS) and the concept related to digital twins, edge computing methodologies are essential to promote smart, autonomous and resilient growing environments [10].

This paper presents a modular and easily deployable hydroponic monitoring platform that connects pH, Electrical

Conductivity (EC), Hydroponic Solution Temperature, Air Temperature, and humidity sensors with a water pump actuator. This is a Wi-Fi only capable system that interfaces with Blynk to visualize and control the system remotely. We hope that this work will drive the design of the system toward being simpler, less expensive to build, and more accessible in academic, community, and small to medium scale production settings with a technical and economically feasible pathway. This work is organized as follows: Section II outlines the materials and methods; Section III presents the experimental and functional results of the system; finally, Section IV presents the conclusions of the study.

II. Materials and Methods

A. General Integration Architecture

The proposed smart monitoring system applied to hydroponic crops is based on an IoT platform with a four-layer architecture, including a perception layer, a network layer, an intermediate layer, and an application layer. The main components of the proposed system are illustrated in Fig. 1. In the perception layer, the system incorporates specific sensors to monitor the main physicochemical and environmental parameters of the hydroponic system in real time: temperature, CE and pH of the nutrient solution, together with air temperature and humidity. This layer also includes actuators, such as the water pump, that allow automatic interventions in the system based on detected conditions. The network layer is responsible for the transmission of data to the management server. This design uses Wi-Fi communication, allowing for continuous transmission of information from the microcontroller to the remote control platform. At the processing level, data are managed through the Blynk platform, which enables storage, visualization, and basic processing of the received data. This platform allows for the configuration of rules, notifications, and visualization of historical trends, facilitating a first level of analysis and remote monitoring. Finally, the application layer consists of Blynk's user interfaces, available on both mobile devices and web browsers. These interfaces allow the operator to monitor the parameters of the hydroponic system in real time, receive alerts, and perform manual or automatic control actions on a pump, thus optimizing daily crop management.

The system uses an ESP32 WROOM-32 microcontroller as the central control unit, connected to various sensors and actuators through a simple breadboard arrangement. The pH sensor and the EC sensor provide analog voltage outputs that are connected to the analog-to-digital channels (ADCs) of the ESP32. The temperature of nutrient solutions is measured using a DS18B20 digital sensor, while the ambient temperature and humidity are monitored using a DHT11 sensor. Both digital sensors are interfaced directly via GPIO pins. A direct current (DC) water pump is controlled by a relay module, which is activated through one of the ESP32's digital output pins, enabling automated nutrient solutions circulation when needed. The entire system is powered by an external DC

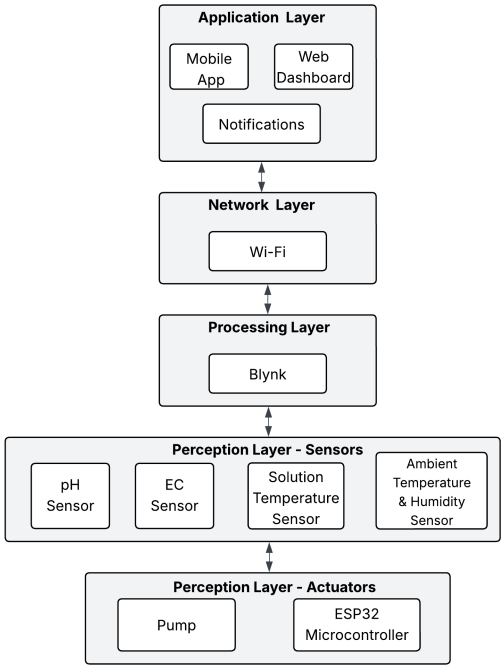


Fig. 1. IoT System Architecture: Layers and Components.

supply, with a main switch for manual control and safety. The ESP32 handles both data acquisition and wireless communication, transmitting real-time sensor readings to the Blynk cloud platform over Wi-Fi for remote monitoring and control. Fig. 2 shows the circuit diagram of the proposed system.

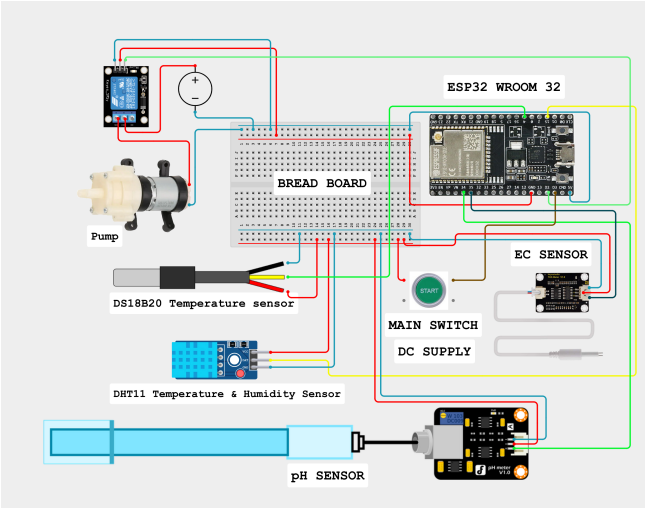


Fig. 2. Circuit diagram of the automated hydroponic system.

B. Mathematical modeling for sensor calibration

1) Relationship between Voltage and pH: Voltage measurements were collected for a series of known pH standard solutions, and the average results for each calibration point are presented in Table I.

TABLE I
PH AND VOLTAGE MEASUREMENTS OF DIFFERENT SAMPLES

Sample	*pH*	*Voltage (V)*
Standard solution 1	4	3.146
Standard solution 2	7	2.488
Standard solution 3	9.06	2.223
Standard solution 4	9.86	2.051

Voltages measured with analog pH sensor.

The development of the mathematical model was based on a set of experimental data obtained from voltage (V) measurements of the pH sensor immersed in solutions with known pH values. The relationship between the recorded voltage and the pH value was assumed to be nonlinear, which motivated the use of a double exponential model, expressed in Eq. (1).

$$\hat{pH}(V) = ae^{bV} + ce^{dV}, \tag{1}$$

Where:

- V is the voltage measured by the sensor,
- $\hat{pH}(V)$ is the estimated pH,
- $a, b, c, d \in \mathbb{R}$ are the parameters to be determined.

Consider the set of measurements $\{(V_i, pH_i)\}_{i=1}^{n}$. The parameter estimation problem is formulated as the minimization of the sum of squared errors (SSE), expressed in Eq. (2).

$$SSE(a,b,c,d) = \sum_{i=1}^{n} \left[pH_i - \left(ae^{bV_i} + ce^{dV_i}\right)\right]^2 \tag{2}$$

The optimization procedure is set out according to Eq. (3).

$$\min_{a,b,c,d} SSE(a,b,c,d) \tag{3}$$

This constitutes a non-linear least squares problem that cannot be solved analytically due to the exponential dependence on b and d. Consequently, iterative techniques such as the Levenberg-Marquardt algorithm [11] are used, which progressively adjust the parameters until convergence is reached. The corresponding first-order condition system is established as delineated in Eq. (4) - Eq. (7).

$$\frac{\partial SSE}{\partial a} = -2\sum_{i=1}^{n} e_i\, e^{bV_i} = 0 \tag{4}$$

$$\frac{\partial SSE}{\partial b} = -2\sum_{i=1}^{n} e_i\, aV_i e^{bV_i} = 0 \tag{5}$$

$$\frac{\partial SSE}{\partial c} = -2\sum_{i=1}^{n} e_i\, e^{dV_i} = 0 \tag{6}$$

$$\frac{\partial SSE}{\partial d} = -2\sum_{i=1}^{n} e_i\, cV_i e^{dV_i} = 0 \tag{7}$$

Here, $e_i = pH_i - (ae^{bV_i} + ce^{dV_i})$ represents the residual error.

Consequently, the final model is expressed according to the formulation presented in Eq. (8).

$$\hat{pH}(V) = 66.31\, e^{-0.8972V} - 2.266 \times 10^{15}\, e^{-17.44V}. \tag{8}$$

The fit exhibits a residual quadratic error $SSE = 0.02115$ and a determination coefficient $R^2 = 0.999$, indicating a good agreement between the model and the experimental data.

2) Relationship between Voltage and Electrical Conductivity (EC): A mathematical model was created to characterize electrical conductivity (EC) as a function of voltage employing experimental data from solutions with known conductivities. The solutions were evaluated with an analog sensor that produced a voltage signal proportional to the conductivity of the sample. Table II presents the experimental values, including the electrical conductivity measurements in mS/cm and the related voltages in volts (V).

TABLE II
EXPERIMENTAL DATA ON ELECTRICAL CONDUCTIVITY AND VOLTAGE

Sample	Electrical Conductivity (EC) (mS/cm)	Voltage (V)
Standar Solution 1	0.098	0.035
Standar Solution 2	1.341	1.427
Standar Solution 3	1.852	1.952
Standar Solution 4	6.16	2.326

The correlation between voltage (V) and electrical conductivity (EC) demonstrates nonlinear characteristics that can be articulated using a second-order exponential model, analogous to the methodology used in pH calibration, as delineated in Eq. (9).

$$\widehat{EC}(V) = ae^{bV} + ce^{dV}. \tag{9}$$

As in the case of pH, the parameters a, b, c, d are estimated using nonlinear least squares, minimizing the sum of squared errors as indicated in Eq. (10).

$$SSE(a,b,c,d) = \sum_{i=1}^{n} \left[EC_i - \left(ae^{bV_i} + ce^{dV_i}\right)\right]^2 \tag{10}$$

The numerical optimization procedure (Levenberg–Marquardt) is applied in the same way as described for pH. Consequently, the resulting model for the estimated electrical conductivity $\widehat{EC}$ is presented in Eq. (11).

$$\widehat{EC}(V) = 3.847 \times 10^{-16} e^{15.78V} + 0.287 e^{0.9749V}. \tag{11}$$

The model shows a precise fit, with an SSE value of 0.0814 and a coefficient of determination $R^2 = 0.9961$, which demonstrates adequate agreement between the model and the experimental data.

C. Optimal ranges for nutritional solutions in hydroponics

The success of a hydroponic system is largely dependent on the precise control of the physicochemical conditions of the nutrient solution, which serves as the medium for the

transport of essential elements for plant development. The availability of nutrients, root assimilation, and stability of the growing environment are directly influenced by the pH, electrical conductivity (EC) and temperature of the solution, which are the most important factors.

Table III presents a summary of the optimal parameters recommended for hydroponic cultivation [12].

TABLE III
RECOMMENDED RANGES FOR NUTRIENT SOLUTION IN HYDROPONICS

Parameter	Optimal range	Units
pH	5 – 7.5	None
Electrical Conductivity (EC)	0.8 – 3.5	MilliSiemens per centimeter ($\mathrm{mS/cm}$)
Nutrient solution temperature	18 – 24	Degrees Celsius ($^{\circ}\mathrm{C}$)

TABLE IV
CALIBRATION RESULTS FOR THE PH SENSOR AFTER TEN REPEATED MEASUREMENTS.

pH Reference	Voltage (V) Reference	pH (Our prototype)	Voltage (V) (Our prototype)
4.00	3.146	3.920 $\pm$ 0.028	4.153 $\pm$ 0.035
7.00	2.488	6.946 $\pm$ 0.037	2.515 $\pm$ 0.030
9.86	2.051	9.843 $\pm$ 0.034	2.045 $\pm$ 0.011
9.06	2.223	9.092 $\pm$ 0.032	2.205 $\pm$ 0.017

TABLE V
CALIBRATION RESULTS FOR THE EC SENSOR AFTER TEN REPEATED MEASUREMENTS.

EC (mS/cm) Reference	Voltage (V) Reference	EC (mS/cm) (Our prototype)	Voltage (V) (Our prototype)
0.098	0.035	0.13 $\pm$ 0.009	0.031 $\pm$ 0.002
1.341	1.427	1.25 $\pm$ 0.019	1.377 $\pm$ 0.015
6.160	2.326	6.17 $\pm$ 0.035	2.326 $\pm$ 0.016
1.852	1.952	1.86 $\pm$ 0.022	1.914 $\pm$ 0.012

III. RESULTS

The experimental results from the calibration and validation processes show that the IoT-based monitoring system for hydroponic applications is accurate and stable. The complete system was continuously functionally tested in a real hydroponic cultivation setting. Throughout the assessment period, the system functioned reliably and independently, periodically measuring pH, electrical conductivity (EC), and temperature, which were effectively sent to the Blynk platform for remote monitoring.The monitoring system has been complemented with an alert notification and remote control feature, using the Blynk IoT platform. This integration allows the user to receive real-time notifications when the measured values of critical variables are outside the established ranges (see Section IV), as well as to manually operate system components, such as the recirculation pump.

A. Model Validation and Comparative Analysis

To evaluate the precision and stability of the developed sensing system, ten repeated measurements were performed for each calibration point of the pH and EC sensors. The obtained data were statistically analyzed to compute the mean and standard deviation, allowing the assessment of the repeatability and consistency of the proposed prototype. Tables IV and V summarize the results obtained for the pH and EC sensors, respectively. The small standard deviations observed in all cases indicate high repeatability and minimal measurement fluctuations. Subsequently, experimental validation was conducted by comparing the measurements from the developed prototype against those obtained with standard laboratory instruments. Fig. 3 presents the comparative results for both the pH and EC sensors, showing the relationship between the standard solutions (reference) and the measurements recorded by our prototype.

As illustrated in Fig. 3a, the pH sensor demonstrates a strong correlation with the reference instrument, achieving a mean absolute error (MAE) of 0.015, root mean square error (RMSE) of 0.0020, and a coefficient of determination (R^2) of 0.999. These results confirm that the proposed exponential calibration accurately models the voltage-pH relationship of the solution.

Similarly, Fig. 3b shows the results for the EC sensor. The measured values from the prototype exhibit excellent agreement with the reference data, with MAE = 0.023, RMSE = 0.031, and $R^2 = 0.999$. The minimal residuals verify that the calibration effectively represents the nonlinear voltage-conductivity behavior across the full measurement range.

1) Uncertainty Analysis: To quantify the measurement reliability, an uncertainty analysis was carried out considering both sensor resolution and repeatability. The combined standard uncertainty (u_c) was estimated as:

$$u_c = \sqrt{u_r^2 + u_{rep}^2}, \tag{12}$$

where u_r is the resolution uncertainty and u_{rep} is the standard deviation obtained from the repeated measurements. The expanded uncertainty (U) for a 95% confidence level ($k = 2$) is given by Eq. (13).

$$U = k \times u_c, \tag{13}$$

Based on the statistical results in Tables IV and V, the estimated expanded uncertainties were approximately ± 0.066 pH and ± 0.047 mS/cm for the pH and EC sensors, respectively. These low uncertainty values confirm that the proposed system provides highly precise, repeatable, and reliable readings, ensuring consistent performance for continuous hydroponic monitoring. Therefore, the Internet of Things-based sensing system that was developed demonstrates a high correlation with laboratory instruments, a high level of repeatability, and a low level of uncertainty, which demonstrates that it is suitable for real-time monitoring of nutrient solutions in hydroponic system applications.

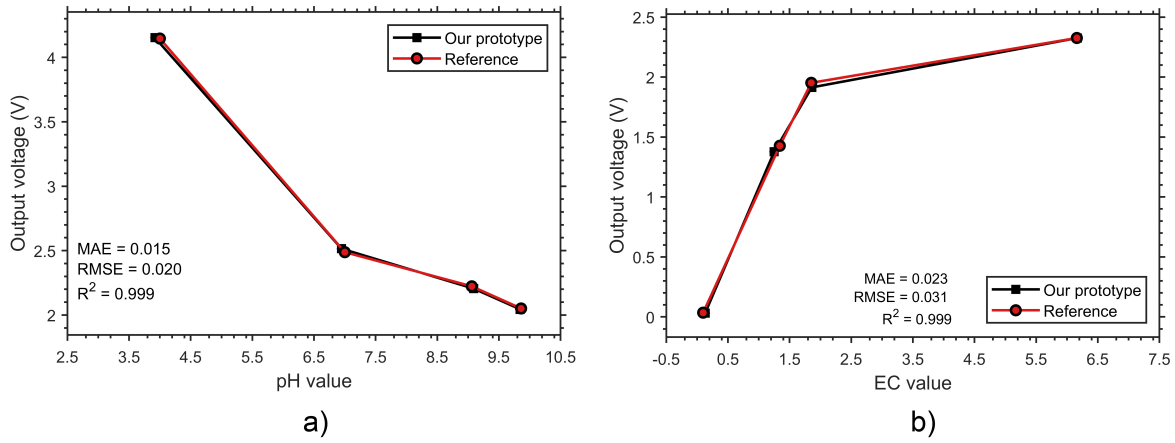


Fig. 3. Comparative results between standard solution measurements (reference) and the developed prototype for (a) pH and (b) EC.

B. Email notifications and alerts

A dual automated notification is generated when any parameters, including pH, electrical conductivity (EC), or temperature, exceed the optimal range.

- *Push notification:* The Blynk mobile app will immediately display a message that specifies the type of alert and the measured value.
- *Notification to email:* Event details are sent to the registered user's email address.

This dual notification method ensures that the user is informed, regardless of whether they are currently connected to the mobile application. The functionality and examples of notifications used are illustrated in Fig. 4.

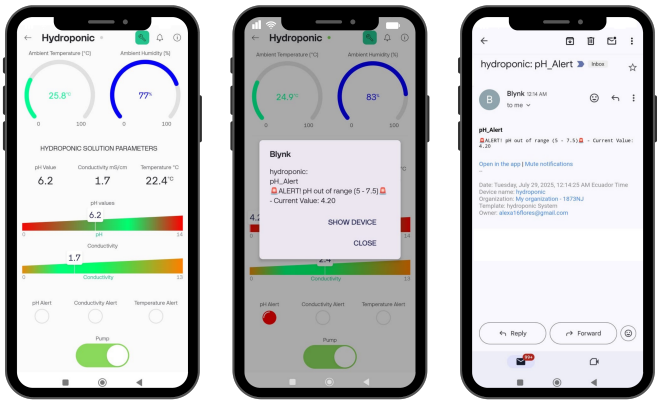


Fig. 4. Functional Overview and Examples of Notifications. a) Normal Ranges, b) Push Notification, c) Email Notification.

C. Automatic and remote pump control

The system includes a pump that autonomously activates three times a day at predetermined intervals to circulate the solution through the crop, in addition to monitoring the variables. Internal timers are implemented to program the activation logic into the microcontroller. Furthermore, the Blynk mobile app provides the user with the ability to manually regulate the pump utilizing a virtual toggle button. This option enables the following actions:

- Turn-on or off of the pump in real time from any location with Internet access.
- Temporarily override the automatic logic if immediate intervention or system maintenance is required.

Measurements were shown in real time via the mobile application, and it was verified that alarms were successfully activated when values outside the established ideal ranges were identified. In addition, the automatic start-up of the recirculation pump was verified at scheduled times, as well as its manual activation using the virtual button incorporated in the application. The user was able to remotely operate the system from any location with Internet access, receiving push notifications and emails in the case of critical events. Fig. 5 illustrates the operational hydroponic system, which features connected sensors and an activated pump. Table VI summarizes the significant events documented throughout the testing phase, which includes variations in physicochemical parameters and user interactions through the mobile application.

TABLE VI
SYSTEM EVENT AND ALERT LOG

Test	Variable	Event	Notification
1	pH = 7.1	Out of range	Push + Email
2	EC = 2.9	Within range	–
3	Pump	Manual activation	Mobile user
4	Temp = 25°C	High temperature	Push

IV. CONCLUSIONS

A system for automated monitoring and control of hydroponic nutrient solutions was developed and implemented, capable of real-time measurement of essential variables such as pH, electrical conductivity (EC) and temperature through



Fig. 5. Real-Time Operation of the Hydroponic System.

sensors connected to an ESP32 microcontroller. Double exponential models were calibrated using experimental data, facilitating precise estimations of pH and EC based on voltage. Integration with the Blynk platform facilitated remote visualization, automated notifications (both push and email), and automatic and manual control of the recirculation pump. This system exhibited consistent, continuous, and efficient performance, serving as a cost-effective, scalable, and replicable solution. In addition, its distributed design and interoperability establish it as a significant contribution to sustainable innovation within the Industry 5.0 framework, fostering human-centered digitalization, mindful automation, and intelligent resource management. This proposal improves food sustainability by using accessible and efficient technologies that promote human and environmental well-being from a Health 5.0 perspective.

Future endeavors involve integrating artificial intelligence for predictive analysis of critical conditions, utilizing cloud storage for historical variable traceability, and expanding into interconnected agricultural environments through long-range low-energy communication technologies such us LoRa, which are especially beneficial in rural areas with limited connectivity. Additionally, the current prototype was tested with only a few sensors in a small-scale hydroponic setup. Future experiments will focus on testing scalability with more sensor nodes to see how well the system works in real agricultural settings.

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A Metrological Framework for Sustainable Cyber-Physical Systems

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***Abstract*—Metrology is pivotal in "smart" ecosystems where digital technologies combined with physical processes sampled by sensors enable monitoring and controlling the world in real-time, namely cyber-physical systems (CPS). The integration of metrology principles into CPS is crucial for the assessment and optimization of its efficiency in terms of energy consumption, resource utilization, costs, as well as environmental and social impacts. This paper presents a novel framework that integrates sensing, edge processing, artificial intelligence, and system-level assessments of CPS sustainability bridging measurement science and sustainable computing practices towards environmentally responsible digital transformation. To demonstrate this framework suitability and effectiveness, the sustainability assessment of a case study based on a Long Short-Term Memory (LSTM) model deployed on a CPS is reported in the paper.**

***Index Terms*—Metrology, cyber-physical systems (CPS), compute continuum, low-power, sustainability**

I. Introduction

Cyber-physical systems (CPS) are technological advanced systems that integrate computational components with physical processes communicating through a network. The adoption of low-power solutions and the demand for executing advanced computational algorithms, particularly those based on Artificial Intelligence (AI) for predictive analytics, are reshaping the design and operation of CPS. They are required to simultaneously achieve high levels of responsiveness and computational performance while maintaining strict constraints on energy efficiency and sustainability. Modern CPS must address new challenges characterizing complex scenarios (i.e., robotics, autonomous vehicles, Internet of Things, smart cities) where both computational power and real-time capabilities are critical. For example, minimize cyber threats such as Economic Denial of Sustainability (EDoS) or Fraudulent Resource Consumption (FRC) attacks [1] requires systems capable of reacting within extremely short time intervals to guaranty resilience and service continuity. Similarly, AI-based predictive models deployed in industrial automation, smart grids, and connected mobility demand efficient resource management, ensuring that advanced analytics can be performed within low-power operating envelopes to minimize environmental impact.

In such a context, metrology provides the scientific foundation to ensure the accuracy, traceability, and comparability of measurements across digital infrastructures. Reliable and standardized quantification of performance indicators (i.e. energy consumption, latency, throughput) is essential to plan system architecture capacity and to balance the conflicting requirements of advanced computational performance and sustainable operation. In addition, standardized metrology approaches support interoperability and promote the definition of internationally recognized benchmarks, which are required to assess, compare, and improve CPS on a scale.

This work investigates the interplay between metrology and sustainability in next-generation CPS, focusing on LoRaWAN® as Low-Power, Wide-Area (LPWA) networking specification [2] and AI-driven predictive analytics. By linking rigorous measurement practices to the objectives of sustainable digital transformation, the work highlights the strategic role of metrology as both a technical enabler and a policy-supporting instrument for the development of sustainable CPS.

The paper is organized as follows: Section II presents and discusses *background* and *motivations*; a *metrological framework* is presented and discussed in Section III; an experimental *use case* concerning a cyber–physical AI-IoT infrastructure is reported in Section IV. Finally, results are presented and discussed in Section V. In conclusion, Section VI provides the final remarks and directions for future work.

II. Background and Related Works

The *United States National Institute of Standards and Technology (NIST)* defines **metrology** as "the science of measurement and its application". Metrology is applied to CPS to improve the precision, automation, and intelligence of these systems. Measurement data are integrated with physical processes and digital control.

In [3], the environmental sustainability of ICT infrastructures was investigated using the dynamic fourth lane of the Italian A4 motorway as a case study. Life Cycle Assessment (LCA) combined with Monte Carlo simulations was employed to quantify embodied greenhouse gas emissions. Beginning with this analysis, a metrology-based methodology, compliant with ISO/ITU standards and the GUM framework, was developed in [4] to establish a comprehensive sustainability balance. The four-step probabilistic model quantifies lifecycle impacts and avoided emissions, highlighting measurable one-year reductions and supporting the contribution of ICT to sustainability goals.

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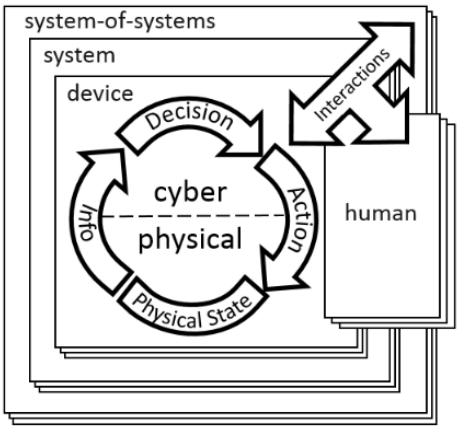


Fig. 1. CPS Conceptual Model from [9].

The acquisition and processing of large-scale datasets required for AI training have significant energy implications within edge–cloud infrastructures, raising sustainability concerns. In [5], a case study on Hyperspectral Imaging (HSI) demonstrates how material variability and contamination influence dataset generation, underscoring the need to balance metrological accuracy with computational and environmental efficiency.

The relevance of Internet of Things (IoT) to sustainable mechatronics is discussed in [6]. Satisfying Functional Requirements (FRs) of sustainable mechatronic systems, that are defined in terms of openness, scalability, dynamics, privacy, and security, require sustainable IoT-based solutions [7] in data acquisition, transmission, processes, and utilization. However, traditional reliability-centered approaches are proving insufficient [8]: AI becomes an asset of CPS, resulting in novel architectures to be designed with sustainable practices. In CPS with IoT and AI as core assets, sustainability Key Performance Indicators (KPIs) should comprehensively account for the operational efficiency of devices and networks, alongside the environmental footprint and performance effectiveness of AI models.

III. Proposed Approach

In this Section, we propose a metrological framework for CPS integrating both the IoT and AI paradigms, and including LoRaWAN as networking specification. The main novelty is presented and discussed.

A. Architecture

Based on the NIST conceptual model of a CPS [9], the framework is structured into three main components, which are *the device, the system*, and *the system of systems*, as shown in Figure 1.

Each component, in turn, includes three functional layers, i.e. *Sensing/Actuating (I/O)*, *Processing*, and *Networking*, corresponding to the specific resource categories exploited. Moreover, we consider a set of technical KPIs, as shown in Table I. However, KPIs alone do not reveal which functional layer of the CPS architecture they primarily influence. Therefore, in order to enable a more structured interpretation, we organize the same KPIs according to their dominant association with the three CPS layers for each CPS component, as shown in Table II. This mapping clarifies the operational domain of each metric, facilitating layer-specific optimization strategies (e.g., low-power sensing, edge AI efficiency, or network load balancing). The overlap of certain KPIs across multiple layers reflects the intrinsic interdependence of CPS components.

TABLE I
Sustainability KPIs for LoRaWAN AI-IoT CPS

Parameter	KPI	Unit / Metric
Number of Packets	Packet Transmission Rate	packets/s
Packet Size	Average Payload	bytes
Time-on-Air	Communication Energy	ms / kJ
Latency	End-to-End Response Time	ms
Throughput	Data Rate	kbps / Mbps
Node Energy	Energy per Operation	kJ / operation
Network Load	Load Balancing Efficiency	%
AI Operations	Energy per Inference / Training	kJ
Duty Cycle	Node Active Time	%

TABLE II
Mapping of Sustainability KPIs to CPS Layers

CPS Layer	Associated KPIs
Sensing / Actuating (I/O)	Average Payload (Packet Size); Node Active Time (Duty Cycle); Energy per Operation (Node Energy); Energy per Inference / Training (if on-device AI)
Processing	End-to-End Response Time (Latency); Data Rate (Throughput); Load Balancing Efficiency; Energy per Inference / Training (if edge/cloud AI)
Networking	Packet Transmission Rate (Number of Packets); Communication Energy (Time-on-Air); Data Rate (Throughput); End-to-End Response Time (Latency); Load Balancing Efficiency

B. Novelty

Compared with the *state-of-the-art*, the presented framework supports scalable assessment from individual devices to complete systems and even system-of-systems, integrating layer-specific and system-level KPIs to enable a quantitative cross-layer evaluation that jointly considers energy, performance, and environmental impact.

Recent contributions have advanced specific aspects of IoT/Edge/AI integration. Resource-efficient federated LoRaWAN frameworks [10] and coalition-based edge learning approaches [11] address device-level constraints and incentive mechanisms, yet do not extend to system-level sustainability metrics. Healthcare-oriented solutions, such as IoT-based preeclampsia monitoring [12] and edge-enabled heart rate detection [13], demonstrate high accuracy and low latency but remain domain-specific and largely omit carbon footprint or holistic KPI analysis. Similarly, IoT-based agricultural decision systems [14] emphasize application-level utility without federated learning or cross-layer evaluation.

In contrast, the proposed framework introduces a unified methodology that simultaneously covers IoT/LoRaWAN, Edge, and AI/Federated Learning layers, while explicitly incorporating system-level KPIs such as total energy con-

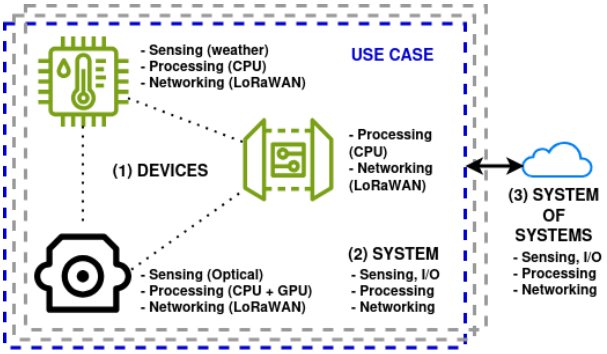


Fig. 2. Use Case Scenario reproducing the CPS Conceptual Model depicted in Figure 1.

sumption, carbon footprint, and load balancing efficiency. This comprehensive cross-layer perspective enables a more generalizable and sustainability-aware evaluation that is not addressed by existing works.

In this study, the most recent contributions were identified and selected from the IEEE Xplore Digital Library.

IV. Case Study: Metrological Evaluation of Energy and Sustainability KPIs in a LoRaWAN AI-IoT Network

A. Experimental Scenario and Measurement Methodology

The use case concerns a cyber–physical AI-IoT infrastructure designed for urban environment and mobility monitoring. It is part of a research and development project for traffic monitoring and prediction in several municipalities in Sicily. The system is deployed in a parking area, and its network has a star topology. It consists of ten sensor nodes connected via a **LoRaWAN** link (Spreading Factor SF7, duty cycle 1%) to a *Milesight UG-67* gateway running the *ChirpStack* network server. Nodes are deployed approximately 470 meters from the gateway and transmit periodic payloads every minute. The gateway antenna is placed at height of 12 meters with a gain of 11,4 dBi, and the node antennas at 6 meters with a gain of 2 dBi.

A schematic representation of the use case scenario is represented in Figure 2. It translates the theoretical model depicted in Figure 1 into the experimental scenario. `Sensing`, `Processing` and `Networking` are distinguished and specified at all the three layers, that are: (1) Devices, (2) System, and (3) System of Systems (i.e., the cloud). Three node classes, whose technology has been provided by the innovative company *SmartMe.io*, are investigated:

1) **Environmental Station** (1 unit): Raspberry Pi 4, 12 V supply;
2) **Parking Nodes** (6 units): Jetson Nano (5 V rail via DC–DC from 24 V), optical sensor;
3) **Traffic Nodes** (3 units): Jetson Nano (5 V rail via DC–DC from 24 V), optical sensor.

The Time-on-Air (ToA) for each LoRaWAN packet - calculated for SF7, 125 kHz bandwidth, coding rate 4/5, and payload of 50 bytes - is approximately 56 ms. With 1 packet/minute, each node transmits 1440 packets/day, defining the duty cycle and ensuring compliance with *EU 868 MHz* regulatory limits.

Electrical current was measured at the DC input of each node with 0.5% accuracy instruments. AI inference was kept active at 100% load for all Jetson nodes to characterize the upper-bound energy profile. AI inference was characterized as a Long Short-Term Memory (LSTM) model requiring 10 GFLOPS per inference, executed every minute with duration 20 ms.

B. Energy Estimation and Measurement

Energy accounting explicitly covers sensing, processing, and networking functions, allowing fine-grained monitoring of how each operational component contributes to the overall energy budget. This bottom-up approach supports scalable energy analysis from individual devices to the network-wide and system-of-systems levels.

1) Theoretical estimation (component-based): The *sensing* energy for a node under continuous full load is:

$$E_{\text{sens}} = P_{\text{sens}} \cdot 24 \text{ h} \tag{1}$$

where P_{sens} is the combined power (W) of optical sensors, illumination, and sensor controllers.

The compute or *processing* energy (CPU+GPU) for a node under continuous full load is:

$$E_{\text{proc}} = P_{\text{CPU+GPU}} \cdot 24 \text{ h} \tag{2}$$

where $P_{\text{CPU+GPU}}$ means the steady power (W) drawn by the processing subsystem at 100% utilization.

The *networking* (LoRaWAN transmission) energy is:

$$E_{\text{net}} = P_{\text{TX}} \cdot N_{\text{pkt/day}} \cdot \text{ToA} \tag{3}$$

where P_{TX} is the RF TX output power (W), $N_{\text{pkt/day}}$ is packets per day, and ToA is seconds per packet.

DC-DC and distribution losses are estimated as:

$$E_{\text{loss}} = (1 - \eta_{\text{conv}}) \cdot (E_{\text{sens}} + E_{\text{proc}}) \tag{4}$$

where η_{conv} is the converter efficiency (e.g., 0.90-0.95).

Total estimated energy per node (i.e., the device):

$$E_{\text{est}} = E_{\text{sens}} + E_{\text{proc}} + E_{\text{net}} + E_{\text{loss}} \tag{5}$$

where E_{est} is the daily energy budget (kWh/day) used for design and sizing.

2) AI compute estimate from GFLOPS (per-inference): In our use case, the LSTM network requires $G_{\text{AI}} = 10$ GFLOPS per inference; the Jetson peak is $G_{\text{peak}} = 472$ GFLOPS at $P_{\text{peak}} = 10$ W. Assuming first-order linear scaling of compute power with achieved GFLOPS:

$$P_{\text{AI}} = P_{\text{peak}} \cdot \frac{G_{\text{AI}}}{G_{\text{peak}}} \tag{6}$$

where P_{AI} is the instantaneous power attributable to compute when running the LSTM.

Energy per inference:

$$E_{\text{inf}} = P_{\text{AI}} \cdot t_{\text{inf}} \tag{7}$$

where t_{inf} is inference duration (s). Daily AI energy (compute-only) is:

$$E_{\text{AI,est}} = E_{\text{inf}} \cdot N_{\text{inf/day}} \tag{8}$$

where $N_{\text{inf/day}} = 1440$ (1 inference-per-minute with 20 ms duration).

3) Real measurements: The daily energy consumption of each node is obtained from DC measurements on the supply rail, combined with the energy required for LoRaWAN transmissions, as follows:

$$E_{\text{meas}} = V_{\text{sup}} \cdot \overline{I}_{\text{meas}} \cdot 24\ \text{h} + E_{\text{LoRa}} \tag{9}$$

where V_{sup} denotes the supply voltage, equal to 12 V for the environmental node and 5 V (Jetson rail) for the Jetson-based nodes. The term $\overline{I}_{\text{meas}}$ represents the *average measured DC current* over typical operation, with values of 0.197 A (environmental), 0.679 A (parking), and 0.892 A (traffic). The LoRaWAN transmission energy E_{LoRa} accounts for the additional energy used during packet transmission events.

The gateway energy consumption is evaluated at the PoE injector output as:

$$E_{\text{GW}} = P_{\text{GW}} \cdot 24\ \text{h} \tag{10}$$

where P_{GW} is the active power (in watts) drawn by the UG-67 gateway, including the ChirpStack server and LTE modem operation.

AI energy from measurements (delta method):

$$E_{\text{AI,meas}} = E_{\text{meas}} - E_{\text{sensor}} - E_{\text{baseline}} \tag{11}$$

where E_{baseline} includes always-on system overheads (OS, radio idle, microcontrollers) measured with inference disabled.

AI accuracy is evaluated based on comparison of node inferences with reference data, while energy consumption is monitored on 15-minute aggregated windows.

V. Results

Table III reports the measured values for each node class multi-layer KPIs based on the measured currents and the estimation framework. CO_2 figures are calculated using the emission factor 0.215 kg CO_2/kWh (ISPRA, 2024).

For clarity, the comparative estimates vs measurements are reported in Table IV.

Theoretical estimation based on the Jetson's GFLOPS ratio indicates a negligible compute-only AI energy. However, real measurements reveal higher values due to system-level overheads (e.g., memory access, I/O, and wake-up cycles), confirming the need to account for full-node power consumption in sustainability assessments. The main share of the sustainability footprint is infrastructural, rather than compute-only AI energy. This is a consequence of sparse inference scheduling (20 ms every minute) and high performance of GPU acceleration which compresses computation into short bursts. GPUs enable sub-100 ms response to inference peaks.

TABLE III
Energy and System KPIs by Functional Layer and Device Type

Layer / KPI	Environmental (1x)	Parking (6x)	Traffic (3x)
Layer 1 – Sensing			
Sensing Energy (kWh/24h, per node)	0.018	0.062	0.079
Sensing Energy (kWh/24h, subtotal)	0.018	0.372	0.237
Duty Cycle (%)	0.13	0.13	0.13
Layer 2 – Processing			
Processing Energy (kWh/24h, per node)	0.032	0.210	0.386
Processing Energy (kWh/24h, subtotal)	0.032	1.260	1.158
AI Energy (kWh/24h, per node)	–	0.047	0.063
Latency (ms)	120	80	75
Layer 3 – Networking			
Communication Energy (kWh/24h, per node)	0.006	0.052	0.072
Communication Energy (kWh/24h, subtotal)	0.006	0.312	0.216
Time-on-Air (ms)	56	56	56
Availability (% uptime)	99.2	99.0	99.0
Aggregated System View (Nodes + Gateway)			
Nodes total (kWh/24h)	3.611		
Gateway Energy E_{GW} (kWh/24h)	0.086		
Total System Energy E_{system} (kWh/24h)	**3.697**		
CO_2 Emissions ($kgCO_2$/24h)	0.795 (using 0.215 $kgCO_2$/kWh)		

A CPU-only or cloud-offloading approach would result in larger latency and possibly higher system-level energy (network uplink, cloud processing), reducing responsiveness for time-critical tasks. Component models (GFLOPS-based) are useful to estimate compute energy, but full-system measurements are necessary to capture conversion losses and wakeup overheads that materially affect total energy and CO_2.

LoRa TX energy per node (ToA-based) is orders of magnitude smaller than sensing and processing energy consumption, leaving headroom for additional nodes under regulatory duty-cycle constraints.

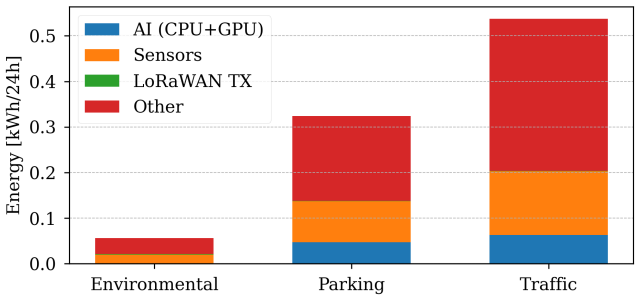


Fig. 3. Measured energy per node type and framework layer.

Figure 3 shows the measured energy consumption for the three node classes, highlighting the rising energy demand of

TABLE IV
COMPARATIVE TABLE OF ESTIMATED VS MEASURED ENERGY AND CO_2

Node Type	**Supply (V)**	**Estimated Energy E_{est} (kWh/day)**	**Measured Energy E_{meas} (kWh/day)**	**Est. CO_2 (kg/day)**	**Meas. CO_2 (kg/day)**
Environmental	12	0.168	0.056	0.036	0.012
Parking (per node)	24/5	0.420	0.324	0.090	0.070
Traffic (per node)	24/5	0.420	0.537	0.090	0.115
Gateway UG67	PoE	0.086	0.086	0.018	0.018

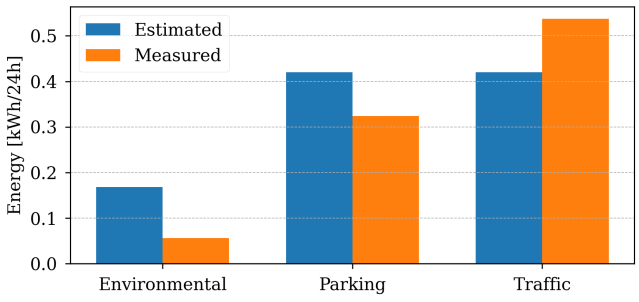


Fig. 4. Comparison between estimated and measured energy consumption.

edge nodes performing AI inference. The environmental node records the lowest energy use, while the traffic monitoring unit, relying on continuous GPU-based inference, has the highest daily consumption. Figure 4 compares estimated and measured values. Theoretical models tend to overestimate consumption for low-load nodes (environmental and parking) but slightly underestimate it for high-performance traffic nodes. This underscores the need for metrological measurements to refine estimation models and better quantify AI-related power overheads.

VI. CONCLUSIONS AND FUTURE WORK

This paper presented a metrological framework integrating sensing, edge processing, AI and system-level assessment of sustainable CPS. A case study based on adopting LSTM model deployed on a AI-IoT LoRaWAN CPS proved compute-only AI energy is negligible compared with the overall system-level sustainability impact, that is mainly dictated by infrastructure and baseline operation. The framework supports design decisions that reconcile real-time edge AI needs with sustainability goals, and highlights the importance of measuring whole-node energy (not only CPU/GPU) to obtain reliable KPI estimates. Future work will focus on extending the proposed framework toward the adoption of federated learning techniques, which could further enhance scalability, data privacy, and model adaptability across large-scale distributed AI-IoT nodes.

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Integrated energy-based assessment of settlement-induced crack patterns of Pietà dei Turchini church in Naples

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***Abstract*—The preservation of historical masonry buildings is a crucial challenge, particularly in light of modern monitoring and digital technologies, given the exceptional value of Italy's and Europe's architectural heritage. Masonry, however, is a highly peculiar material whose mechanical behaviour differs markedly from that of conventional structural materials. As a result, standard material models and finite element codes cannot reliably describe the stability of such constructions. Moreover, due to its unilateral response, cracking is common; therefore, monitoring systems must be suitably designed, utilising appropriate electronic devices and advanced sensing technologies.**

The aim of this work is to illustrate the combined use of two numerical methods developed within the framework of Heyman's model for normal, rigid, no-tension materials: the Continuous Displacement for Fractures (CDF) and the Continuous Airy-based for Stress Singularities (CASS) methods. A concluding discussion highlights the complementarities between the two approaches through their application to a case study involving the lateral wall of the Church of Santa Maria Incoronatella della Pietà dei Turchini, offering insights into suitable monitoring system solutions that can be coupled with these models to effectively support the preservation of historic masonry heritage.

***Index Terms*—masonry structures, energy minimisation, displacement-based approaches, force-based approaches, structural monitoring**

I. Introduction

Historic masonry buildings represent a substantial portion of Italy's and Europe's architectural heritage, encompassing civil, military, and religious constructions. Their preservation is a task of paramount importance for both cultural and strategic reasons. Many engineering aspects are involved in their monitoring and conservation. On the one hand, significant challenges arise in efficiently tracking their structural response, which requires the appropriate adoption of electronic measurements, sensors, and data acquisition systems [1]–[4]. On the other hand, a deeper understanding of their structural behaviour is needed, achieved through the adoption of appropriate models capable of predicting the consequences of foundation settlements [5]–[8], including those enhanced by artificial intelligence [9], as well as their response to seismic actions [10]–[12]. Related to the latter point, a significant part of recent research has focused on modelling the behaviour of masonry structures by developing more suitable methodologies, material models, and numerical approaches [13], [14]. Masonry is a peculiar material [15], characterised by markedly different behaviours in tension and compression, with an almost negligible tensile capacity. Therefore, the use of standard modelling strategies based on the Finite Element Method, traditionally conceived for materials that react to both tension and compression [16]–[19],may lead to erroneous results. To overcome these difficulties, several researchers have proposed alternative strategies, either by adopting more sophisticated material models within the Finite Element framework or by developing entirely different approaches based on alternative numerical paradigms. The Finite Element Method treats the material as a continuum and needs ad-hoc material models to account for its peculiarities, including a damage model and different other parameters to account for its behaviour under tension and compression [20]–[23]. The main disadvantage is that FEM is unable to model a complete absence of reaction under tension, as well as strong rigidity in compression, resulting in a highly ill-conditioned stiffness matrix [24].

The Discrete Element Method (DEM), on the contrary, models the masonry as a set of rigid blocks, interconnected through ad hoc contact strategies among blocks [25], [26], and working under an explicit framework which allows to avoid numerical issues typical of the Finite Element Method, preserving the ability to model the specific behavior of masonry structures [27], [28]. However, some disadvantages arise when attempting to reproduce the exact geometry and block discretisation of large structures, resulting in an increased number of potential degrees of freedom. Other approaches consider the stereotomy of the buildings explicitly, and the orientation of the joints [29], [30].

Alternative approaches are directly inspired by Heyman's formulation of masonry material [31], [32], which assumes a total absence of tensile strength, complete rigidity in compression, and rigidity in shear. This idealisation defines the

so-called Normal, Rigid, No-Tension (NRNT) material. Under this assumption, a range of methodologies has been developed in recent years, either displacement-based or force-based, and capable of modelling both in-plane structural behaviour and complex three-dimensional configurations such as vaults and domes [33]–[39]. NODARGI QUI.

This paper explores the integration of two complementary mesh-independent methods derived from the NRNT Heyman model: the Continuous Displacement for Fracture (CDF) method [40]–[42] and the Continuous Airy-Based for Stress Singularities (CASS) method [43]–[45]. The former is a displacement-based approach capable of predicting fracture patterns, while the latter identifies preferential stress trajectories—particularly stress concentrations—developing within the structure [46]. After a brief introduction, both techniques are applied to the lateral wall of the nave of the Church of Santa Maria Incoronatella della Pietà dei Turchini in Naples. Numerical simulations are presented to demonstrate the coherence between the results of the two methods, in terms of predicted stress fields and corresponding crack patterns. Finally, concluding remarks highlight the strengths and limitations of potential monitoring strategies that can be adopted to detect unilateral behaviour associated with concentrated stresses and cracking.

II. Theoretical background

In this section, the fundamentals of the Heyman model for masonry structures are presented, starting from the formulation of the Boundary Value Problem (BVP) shown in Figure 1. The problem is defined on a continuous domain Ω, whose boundary is partitioned into $\partial\Omega_N$ (the Neumann boundary, where contact loads are prescribed) and $\partial\Omega_D$ (the Dirichlet boundary, where displacements, such as settlements, are imposed).

The BVP is formulated as follows:

$$\nabla \cdot \mathbf{T} + \mathbf{b} = \mathbf{0} \quad , \qquad \mathbf{x} \in \Omega \tag{1a}$$

$$\mathbf{E} = \frac{1}{2}\left(\nabla \mathbf{u} + \nabla \mathbf{u}^T\right) \quad , \qquad \mathbf{x} \in \Omega \tag{1b}$$

$$\mathbf{T}\mathbf{n} = \bar{\mathbf{s}} \qquad \mathbf{x} \in \partial\Omega_N \tag{1c}$$

$$\mathbf{u} = \bar{\mathbf{u}} \qquad \mathbf{x} \in \partial\Omega_D \tag{1d}$$

$$\mathbf{T} \in \mathrm{Sym}^- \, , \, \mathbf{E} \in \mathrm{Sym}^+ \, , \, \mathbf{T} \cdot \mathbf{E} = 0 \quad , \quad \mathbf{x} \in \Omega \tag{1e}$$

where $\mathbf{T}$ is the symmetric stress tensor, $\mathbf{E}$ the symmetric infinitesimal deformation tensor, $\mathbf{b}$ the internal volume loads, $\mathbf{x}$ the position vector, $\mathbf{u}$ the displacement field, $\mathbf{n}$ the unit outward normal to the boundary, and Sym^- and Sym^+ denote the sets of negative and positive semidefinite tensors, respectively. Conditions (1e) represent specific material restrictions for unilateral material, and are the mathematical representation of the Heyman assumptions: a complete inability of reaction in tension, complete rigidity in compression, no sliding collapse. This restrictions, also known as the normality conditions for the Heyman material, lead to important consequences in terms of the relationship between stress and deformation, allowing to divide the domain into three subregions: a biaxial compression zone Ω_1, where deformation is not allowed; a zone under an uniaxial stress regime, where opening deformation is allowed only in the direction perpendicular to the stress; and an unstressed zone, where deformation in opening are allowed in all directions.

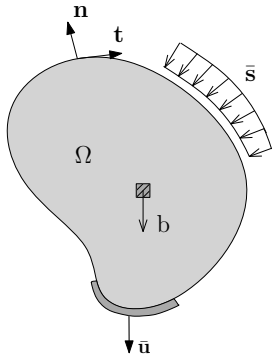


Fig. 1: Representation of the domain with the adopted nomenclature.

BVP (1) can be solved using two variational formulations, represented by the functional, the Total Potential Energy $\mathcal{E}_p(\mathbf{u})$, and the Total Complementary Energy $\mathcal{E}_c(\mathbf{T})$. The first is a function of the displacement field and can be expressed as:

$$\mathcal{E}_p(\mathbf{u}) = -\int_{\partial\Omega_N} \bar{\mathbf{s}} \cdot \mathbf{u} d\Gamma - \int_{\Omega} \mathbf{b} \cdot \mathbf{u} d\Omega \tag{2}$$

while, the second, function of the stress field $\mathbf{T}$, as

$$\mathcal{E}_c(\mathbf{T}) = -\int_{\partial\Omega_D} \mathbf{T}\mathbf{n} \cdot \bar{\mathbf{u}} d\Gamma \tag{3}$$

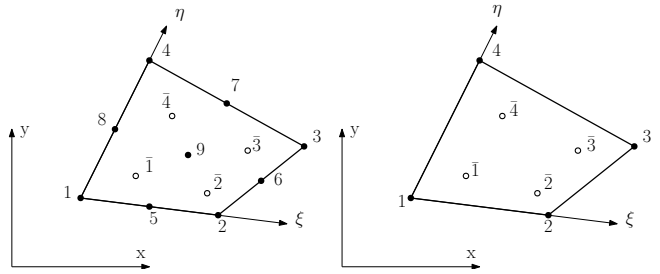
By minimising either functional, one obtains a displacement-based or a stress-based solution. In this way, one can derive either a displacement-based method or a force-based method. The former constitutes the basis of the CDF method, while the latter underlies the CASS method. It is worth noting that the two solutions obtained as minima of the two problems are mutually consistent, in the sense that they both satisfy the original BVP. Consequently, the coupled BVP can be solved by adopting either a displacement-based or a stress-based approach. In the following section, an outline of both methods is provided and their similarities and complementarities are highlighted.

A. CDF method

The CDF method is a displacement-based strategy derived from the minimisation of a suitable discretisation of the Total Potential Energy. Unlike the Piecewise Rigid Displacement approach [47], it employs a continuous displacement field. The goal is to use a smooth kinematic field to localise concentrated deformations along narrow bands, thereby remaining mesh-independent, which distinguishes it from rigid block-based approaches.

The domain is discretised in 9-node second-order quadrilateral elements (Figure 2a), having the nodal displacement as the primal variable, such that

$$\mathbf{u}(\mathbf{x}) = \mathbf{N}\hat{\mathbf{u}} \, , \tag{4}$$



(a) The 9-node CDF element (b) The 4-node CASS element

Fig. 2: Different finite elements adopted for the discretised problems.

being $\hat{\mathbf{u}}$ the nodal degrees of freedom, and $\mathbf{N}$ a matrix collecting the element shape function; from such a discretisation, after recurring to a parent element to enforce element continuity in a parent domain $\xi - \eta$, it is possible to compute point-wise the deformation tensor as

$$\mathbf{E} = \mathbf{A}\hat{\mathbf{u}}\,, \tag{5}$$

Since only C^0 continuity is guaranteed for such a discretisation, the deformation is not assured to be continuous at the element interface; therefore, the constraint (1e) is checked in the Gauss quadrature points $\bar{k}$ (white circles in Figure 3), as

$$\mathbf{E}_k = \mathbf{E}(\bar{\mathbf{x}}_k) = \mathbf{A}_k\hat{\mathbf{u}} \in Sym^+\,, \tag{6}$$

which ends up in the form

$$\mathbf{A}\hat{\mathbf{u}} \geq \mathbf{0}\,, \tag{7}$$

with $\mathbf{A}$ being a N-row matrix and N the total number of Gauss points of the whole discretised domain. The constraint on the displacement at the Dirichlet boundary (Eq. (1d)), is represented in the form

$$\mathbf{B}_{\partial\Omega}\hat{\mathbf{u}} = \bar{\mathbf{u}}\,, \tag{8}$$

with $\mathbf{B}_{\partial\Omega}$ a M-row matrix and M the number of constrained degrees od freedom. Finally, the discretised Total Potential Energy reads

$$\mathcal{E}_p(\hat{\mathbf{u}}) = -\mathbf{g}^T\hat{\mathbf{u}}\,, \tag{9}$$

and the BVP solution is the minimum of the following convex programming problem

$$\begin{aligned} \mathcal{E}_p(\hat{\mathbf{u}}^0) \quad &= \min \mathcal{E}_p(\hat{\mathbf{u}})\,, \\ \text{s.t.} \quad &\mathbf{A}\mathbf{u} \geq \mathbf{0}\,, \\ &\mathbf{B}_{\partial\Omega}\hat{\mathbf{u}} = \hat{\mathbf{u}}\,. \end{aligned} \tag{10}$$

B. CASS method

The CASS is a force-based method originating from the minimisation of the Total Complementary Energy. In order to reduce the number of numerical constraints, the Airy stress potential F is introduced, in order to define the space of equilibrated stress fields from the beginning:

$$\mathbf{T} = \mathbf{R}^T\mathbf{H}(F)\mathbf{R} + \mathbf{B}_F\,, \tag{11}$$

with $\mathbf{R}$ a $\pi/2$ rotation tensor about the axis perpendicular to the 2D domain, $\mathbf{H}$ is the Hessian operator acting on the scalar function F, and $\mathbf{B}_F$ a tensor accounting for the specific internal load distribution $\mathbf{b}$, such that

$$\nabla \cdot \mathbf{B}_F = -\mathbf{b}\,. \tag{12}$$

Condition (11) automatically satisfies the internal equilibrium (1a), significantly reducing the numerical constraints associated with the minimisation problem. Therefore, the consequent discretised problem only has to be constrained to external equilibrium and material compatibility. The discretised version of the problem implies a geometrical discretisation, which consists of a quadrilateral partition of the domain, adopting the Airy stress function as the primal variable.

Since the Airy version of the equilibrium implies continuity of the slope of the Airy stress potential across the elements, a C^1-continuous element class is chosen, specifically a 4-nodes plate-type elements (see Figure 2b), assuming as nodal degrees of freedom the Airy stress potential and its derivatives in the Cartesian directions, that is

$$F(\mathbf{x}) = \mathbf{N}_F\left(\hat{\boldsymbol{\phi}}, \hat{\boldsymbol{\phi}}_{,x}, \hat{\boldsymbol{\phi}}_{,y}\right)\,, \tag{13}$$

being $\hat{\boldsymbol{\phi}}$ the vector of the nodal degrees of freedom and $\mathbf{N}_F$ the matrix of the shape function. After a suitable algebraic manipulation, implying calculation of derivatives on geometrically deformed elements, again in a parent domain $\xi - \eta$, the values of the stresses are recovered in internal points $\bar{k}$, since second derivatives are not conserved in the chosen discretisation across the element interface; therefore

$$\mathbf{T}_{ij,k} = \mathbf{T}_{ij}(\mathbf{x}_k) = \mathbf{K}_{ij}\hat{\boldsymbol{\phi}}\,, \tag{14}$$

with $\mathbf{T}_{ij,k}$ the stress component $\mathbf{T}_{ij}$ evaluated in the internal point $\mathbf{x}_k$, and $\mathbf{K}_{ij}$ a matrix standing for the discrete counterpart of the Hessian of the Airy stress potential on the adopted discretisation. Further details on the geometrical transformation are reported in [45]. The material constraint on the stress (1e) leads to a discrete problem of the type

$$\mathbf{C}\hat{\boldsymbol{\phi}} \leq \mathbf{0} \tag{15}$$

with $\mathbf{C}$ standing for a conic operator acting on the discrete Airy stress potential to enforce the material constraints; The external equilibrium (1c) on the Neuman boundary again as a function of the Airy stress potential, as

$$\mathbf{K}_{\partial\Omega}\hat{\boldsymbol{\phi}} = \hat{\mathbf{s}} \tag{16}$$

with $\mathbf{K}_{\partial\Omega}$ a suitable matrix collecting the Airy definition of the emerging stress at the loaded boundary.

Finally the Total Complementary Energy $\mathcal{E}_c(\hat{\mathbf{T}})$ is rewritten in terms of the Airy stress potential and its discretization $\hat{\boldsymbol{\phi}}$, in the form

$$\mathcal{E}_c(\hat{\mathbf{T}}) = -\mathbf{h}^T\hat{\boldsymbol{\phi}} \tag{17}$$

The discretised stress-based BVP solution is obtained as the minimum of the following second-order constraint optimisation problem:

$$\begin{aligned} \mathcal{E}_c(\hat{\boldsymbol{\phi}}^0) \quad &= \min \mathcal{E}_c(\hat{\boldsymbol{\phi}}) \\ \text{s.t.} \quad &\mathbf{C}\hat{\boldsymbol{\phi}} \leq \mathbf{0} \\ &\mathbf{K}_{\partial\Omega}\hat{\boldsymbol{\phi}} = \hat{\mathbf{s}} \end{aligned} \tag{18}$$

From the comparison of Problems (10) and (18) it can be seen the complementarity of these two approaches, being the first a kinematical approach while the second a static approach; in the first case, the solution exist if the constraints allow the potential to have a finite minimum; in the second case, a static solution exists if the constraints allow the development of a non-void set of statically admissible solution.

III. The Case Study: Santa Maria Incoronatella della Pietà dei Turchini in Naples

The two proposed methods are applied to the case study of the Church of Santa Maria Incoronatella della Pietà dei Turchini, a XVII century building located in Via Medina, in the historical center of Naples. During its history, a diffuse crack pattern due to foundation displacements interested this church. The fractures, detected before the recent restoration works, are depicted in Figure 3.

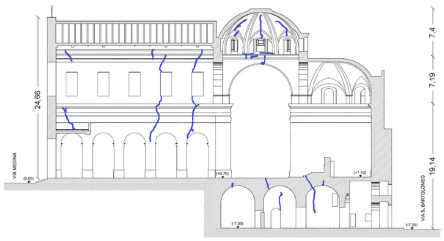


Fig. 3: Cross section of the church of Santa Maria Incoronatella della Pietà dei Turchini with its detected crack pattern.

This crack pattern was essentially the effect of a piecewise rigid body mechanism through which the masonry structure responded to the ground displacements.

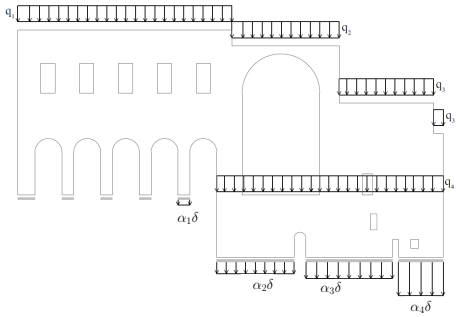


Fig. 4: Domain, loads and settlements for the case study of Santa Maria Incoronatella della Pietà dei Turchini.

The domain of the case study is represented in Figure 4, and is subjeted to the loads $q_1 = q_3 = 96.1$ kN/m, $q_2 = q_4 = 57.7$ kN/m. The soil settlements are defined through a common factor $\delta = 0.002$ mm, and scaled through ad-hoc coefficients α_1, ..., α_4, which will be varied during the following investigation. In the following, two studies are performed considering two different settlement shapes. The correspondence between the obtained deformation and stress patterns will be analysed to highlight the complementarities of the methods and their strengths and weaknesses.

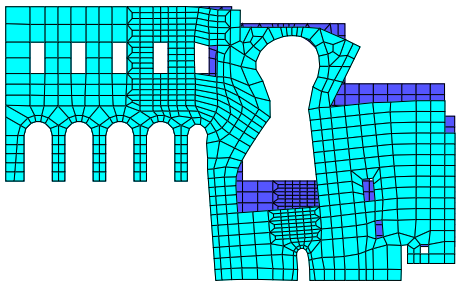


Fig. 5: CDF deformed configuration for scenario 1 ($\alpha_1 = 0$, $\alpha_2 = \alpha_3 = 2$, $\alpha_4 = 1$).

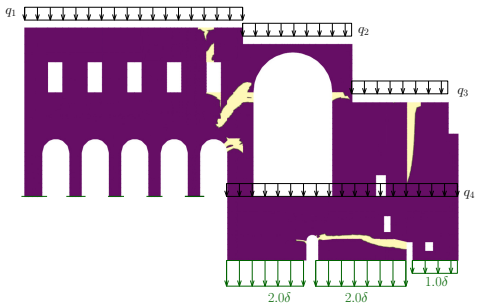


Fig. 6: CDF cracked (yellow) regions in scenario 1 ($\alpha_1 = 0$, $\alpha_2 = \alpha_3 = 2$, $\alpha_4 = 1$).

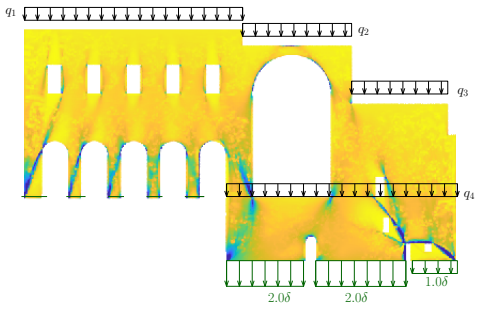


Fig. 7: CASS minimum principal stress in scenario 1 ($\alpha_1 = 0$, $\alpha_2 = \alpha_3 = 2$, $\alpha_4 = 1$). Blue indicates higher stress, while yellow unloaded zones.

The first case considers the settlement defined by the following values $\alpha_1 = 0$, $\alpha_2 = \alpha_3 = 2$, $\alpha_4 = 1$. The CDF solution presents the deformed shape of Figure 5, while the deformation field is shown in Figure 6. The corresponding CASS stress pattern is shown in Figure 7.

In particular it can be noticed that the cracked zones of Figure 5 (yellow areas) correspond or to unloaded zones in Figure 7, as, for example, the strain that develops on the right of the domain corresponds to an unstressed zone; the same on the last window on the left part of the church, before the central naive arch.

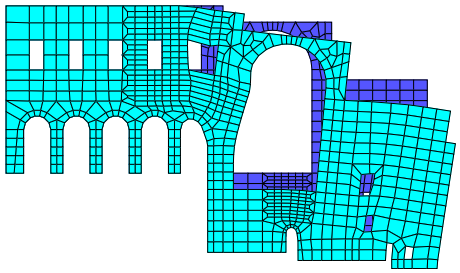


Fig. 8: CDF deformed configuration for scenario 2 ($\alpha_1 = 0$, $\alpha_2 = 1$, $\alpha_3 = 1.5$, $\alpha_4 = 2$).

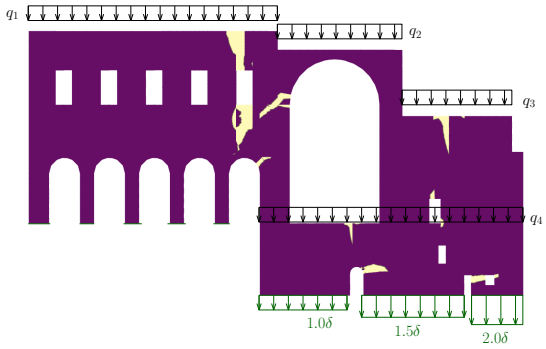


Fig. 9: CDF cracked (yellow) regions in scenario 2 ($\alpha_1 = 0$, $\alpha_2 = 1$, $\alpha_3 = 1.5$, $\alpha_4 = 2$).

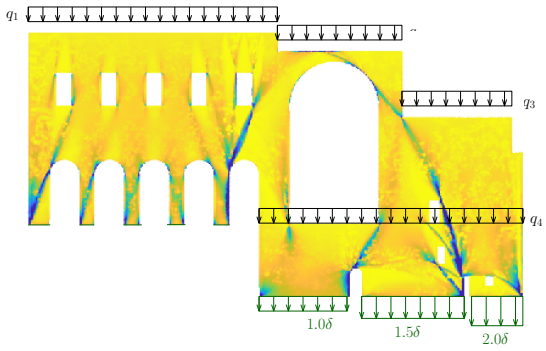


Fig. 10: CASS minimum principal stress in scenario 2 ($\alpha_1 = 0$, $\alpha_2 = 1$, $\alpha_3 = 1.5$, $\alpha_4 = 2$). Blue indicates higher stress, while yellow unloaded zones.

In the second case the settlement parameters are $\alpha_1 = 0$, $\alpha_2 = 1$, $\alpha_3 = 1.5$, $\alpha_4 = 2$. Again, the solution is found with the CDF method to track displacements and deformations, and with the CASS method to check the corresponding stress pattern. The deformed configuration of the structure is depicted in Figure 8, the deformation field in Figure 9, and the stress pattern in Figure 10. It can be noticed that the strong deformation on the last window before the arch, as well before the windows itself, corresponds to an unloaded zone in the stress pattern of Figure 10; a similar behaviour appears on the left of the arch, as well as on the right of both doors on the inferior floor of the structure, where an horizontal crack corresponds to unloaded zones, or to strong uniaxial stresses.

IV. Conclusion

This paper examines the complementary application of two energy-based, mesh-independent methods, namely the CDF and CASS methods. Both approaches are applied to the case study of Santa Maria Incoronatella della Pietà dei Turchini, considering two possible settlement scenarios. In both cases, localised crack patterns develop, and the corresponding CASS stress-based solution matches the CDF displacement-based one with remarkable consistency.

From the analysis of the results, it emerges that adequate monitoring should rely on systems and sensors capable of detecting concentrated stresses and discontinuities associated with fracture. In this regard, the use of low-cost monitoring systems based on optical markers has significantly advanced the field of dynamic tracking and structural analysis. Compared to expensive systems based on laser or ultrasonic technologies, such systems offer a pragmatic and economical alternative to high-end solutions, which is particularly valuable in large-scale or long-term studies where budget constraints may limit the monitoring scope. Their main advantages include reduced installation and operational costs, ease of integration, and adaptability to varied environments without compromising essential accuracy.

Future developments of this work will involve integrating the proposed numerical methodologies with advanced sensing systems, aiming to combine computational techniques and structural monitoring within a unified framework.

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Assessing Seismic Vulnerability in Historic Masonry Aggregates: Limitations of Unit-Based Strengthening Approaches

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***Abstract*—Masonry aggregates in Italian town centers are hard to assess seismically due to irregular geometries, heterogeneous construction, and fragmented ownership. This study tests whether targeted strengthening of individual Structural Units (SUs) improves safety in an irregular aggregate in Arquata del Tronto (Italy). Nonlinear static (pushover) analyses using the Equivalent Frame Method evaluate two interventions—reinforced plaster and grout injection—considering unit-level response and aggregate behavior. Results show that localized retrofits can raise stiffness, strength, or ductility of treated units; however, these gains do not reliably translate into improvements at the aggregate scale. In several configurations, performance indices are unchanged or decline because of interaction effects, discontinuities, and shifts in load paths between retrofitted and non-retrofitted units. These findings reveal the limits of strategies based solely on isolated interventions and support integrated assessment and coordinated design at the aggregate level. When full-scale modeling is not feasible, risk reduction should prioritize preventing local collapse mechanisms as a first step while broader upgrades are planned. The study cautions against assuming that unit-level benefits superimpose at the system scale and stresses that effective seismic improvement in historic aggregates requires system-wide thinking, staged implementation, and careful attention to how retrofits redistribute forces across adjoining units.**

***Index Terms*—Seismic Vulnerability, Masonry Aggregates, Structural Units, Local Retrofitting, Pushover Analysis**

I. Introduction

Historic centers in Italy are largely composed of masonry buildings, the outcome of centuries of layered urban growth shaped by traditional techniques, locally available materials, and adaptation to site-specific topography and culture. Unlike modern standalone buildings, these structures often belong to aggregates—contiguous clusters formed by incremental additions, commonly without clear structural separations. As a result, load-bearing walls are frequently shared and connections between units can be weak or irregular, eroding the structural autonomy of individual buildings and making their seismic response dependent on the aggregate as a whole. Assessing single SUs in isolation is therefore inadequate: each unit's behavior is strongly conditioned by the boundary conditions, geometry, and mechanical properties of neighboring buildings. This aggregate effect demands a holistic seismic assessment that explicitly considers the behavior of all units within the cluster [1].

Evaluating the structural performance of masonry aggregates is technically challenging precisely because of inter-unit interaction, which critically shapes seismic response and introduces specific issues for modeling and verification [2], [3].

The seismic response of masonry aggregates is strongly conditioned by construction-related factors, foremost the type and quality of inter-unit connections. Because these joints often stem from staggered, unplanned building phases, they are frequently heterogeneous, weak, or discontinuous. During earthquakes, such conditions promote local phenomena—pounding, loss of confinement, and uneven stress transfer—between neighboring units. Typical features of historic aggregates, including flexible timber diaphragms with low in-plane stiffness and poor vertical–horizontal tying, inhibit box-like action and heighten the likelihood of out-of-plane failure mechanisms [4], [5].

Masonry aggregates are highly irregular in plan and elevation due to mismatched heights, wall thicknesses, and layouts. Seismic vulnerability is amplified by heterogeneous historic materials, variable textures, weak mortars, mixed techniques, and deterioration—making mechanical properties hard to characterize [6]. Moreover, missing or uncertain documentation (drawings, construction phases, past interventions) further undermines the reliability of seismic assessments.

National codes remain ill-suited to masonry aggregates: despite advances in seismic provisions, there is no standard method to capture inter-unit interactions and their global effects. Research has partly filled this gap with diverse empirical and numerical approaches, but a unified, codified framework is still missing.

Simplified methods offer quick first-pass screening of seismic vulnerability, well suited to large-scale surveys [7]–[9]. Hybrid approaches add refinement by coupling empirical evidence with lightweight numerical models, balancing nuance with modest data and computation [10].

For detailed, local assessments, advanced methods are used: FEM [11]–[14], Equivalent Frame Models (EFM) [15]–[18], DEM [19], [20], plus rigid-block/energy-based formulations [21]–[28], nonlinear dynamic analyses [29], [30], and AI/ML based solutions [31], [32]. These tools capture global behavior and local failure mechanisms, accounting for inter-unit interactions, geometric discontinuities, and material properties. Recent work further advances formulations, experiments, and computational tools targeting the complex response of masonry systems [33]–[38].

The case study is a masonry aggregate in the historic center of Arquata del Tronto (Italy), examined within the *Ricostruire Arquata* project [39]. The cluster is highly irregular in plan and elevation, and the sloping site, between uphill and downhill façades, further heightens seismic vulnerability. It was selected purely for research purposes as a representative example to investigate the seismic behavior of SUs in irregular historic compounds.

II. Cases studies

The case study, part of the multidisciplinary *Ricostruire Arquata* project [39], examines Aggregato B (via Gallo; Table 76 [39]) on the eastern side of Arquata del Tronto along a historic thoroughfare. The dense row, straight with walls perpendicular to the street and then curving near the Piazza Garibaldi promontory—the town's oldest core—lies on complex topography and has been altered by rear extensions and head-end changes [39]. Morphologically, it reflects a terrace-type, evolution (sixteenth-century remnants; eighteenth–nineteenth-century amalgamations; twentieth-century openings/balconies), and the 2016 earthquake caused widespread cracking and partial collapses—especially at the head and central blocks; tie rods limited some out-of-plane failures, but delayed safeguarding led to further deterioration [39].

This study investigates the global in-plane seismic response of a historic masonry aggregate by modelling five SUs, with emphasis on inter-unit interactions and geometric irregularities. While acknowledging local failure modes, the analysis prioritizes system-level behavior to elucidate the seismic dynamics of complex aggregates.

A. Geometry and numerical model

The via Gallo aggregate was modeled in 3Muri [40], [41] using plan documents and survey data from [39], yielding a 3D model of five adjacent SUs. The aggregate shows marked geometric irregularities: a curvilinear plan axis, uneven distribution of load-bearing walls, absence of compact or symmetric layout, no rigid diaphragms, and significant discontinuities—especially between the oldest units (SU5–SU4) and the rest. It is therefore plan-irregular. Vertical irregularity is also evident: SU5 and SU4 have notable elevation offsets relative to the other units due to site slope and phased construction, causing discontinuous mass and stiffness.

All floors are timber and were modeled as deformable diaphragms. SU1–SU3 have generally aligned floor levels (except the ground floor, following terrain slope), whereas SU4–SU5 show pronounced interstorey misalignments. Construction features are heterogeneous, with rubble masonry of irregular texture, variable properties, and inconsistent mortar quality. Masonry typology is described per NTC 2018 and Circular 7/2019 as irregular stone masonry with lime mortar. The SU subdivision is purely methodological to simulate localized retrofits; each SU retains its actual geometry and construction characteristics within the 3D model. The foundations were not modeled explicitly. Figure 1 reports the adopted nomenclature and the location of each SU.

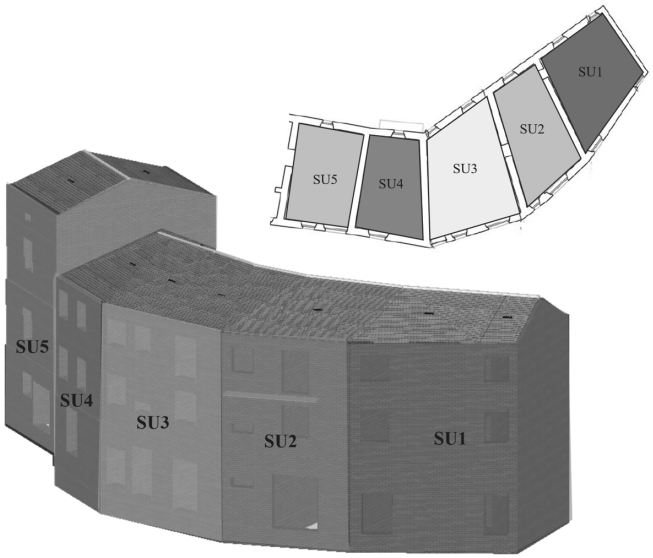


Fig. 1: Subdivision and identification of the SUs within the masonry aggregate, presented in axonometric and plan views.

The data sources used for the model presented different levels of accuracy and coverage, reflecting the heterogeneous nature of the available information. The architectural drawings from the *Ricostruire Arquata* project were produced at a scale of 1:50–1:100 and provided the main geometric framework, with an estimated uncertainty of about $\pm$2–3 cm on wall dimensions. Photographic surveys and manual measurements allowed local verification and correction of wall thicknesses and floor heights, with an accuracy of approximately $\pm$1 cm for direct measurements and $\pm$3–5 cm for indirect estimates.

The georeferenced topographic base, derived from traditional surveying and aerial photogrammetry, supplied elevation data with an average accuracy of $\pm$5 cm. In areas where data were missing or inconsistent (for example, on rear façades or between adjoining units), the geometry was completed through interpolation consistent with photographic evidence and measured dimensions.

Overall, the geometric reliability of the model is considered adequate for comparative and methodological seismic analyses. The residual uncertainty was accounted for by adopting Knowledge Level LC1 [42] and applying the corresponding confidence factor to the mechanical properties.

B. Materials

The masonry of the analyzed aggregate corresponds to *random rubble masonry*, a widespread typology in the region. Its mechanical parameters were derived from Table C8.5.I of [43], assuming Knowledge Level LC1 as defined in [42]. Accordingly, a confidence factor of 1.35 was applied to the nominal mechanical properties, reducing them for analytical purposes. Although Italian Building Codes [42], [43] formally allow nonlinear analyses only from LC2 onward, the present simulations were conducted for methodological purposes, aiming to explore global seismic behavior rather than design validation.

Two strengthening techniques were modeled: *reinforced plaster* and *grout injection*, following Table C8.5.II of [43]. Their effects were accounted for by applying code-based enhancement coefficients to both strength and stiffness parameters (E, G). When combined, the cumulative coefficient—limited to 3.5 as prescribed by the code—was adopted. Consequently, the elastic modulus (E) increased from approximately $870\,\mathrm{N/mm^2}$ to $3045\,\mathrm{N/mm^2}$, the shear modulus (G) from $290\,\mathrm{N/mm^2}$ to $1015\,\mathrm{N/mm^2}$, while the density remained $19\,\mathrm{kN/m^3}$ and the compressive strength rose from $100\,\mathrm{N/cm^2}$ to $350\,\mathrm{N/cm^2}$.

C. Data sources and processing pipeline

The three-dimensional model of the via Gallo aggregate was developed through an integrated workflow combining archival documentation, direct surveys, and geometric reconstruction within the 3Muri software. The main data sources included: (i) architectural drawings and sections from the *Ricostruire Arquata* project [39], providing the basic geometric framework (wall alignments, thicknesses, and floor heights); (ii) photographic surveys and manual on-site measurements collected during post-earthquake inspections; and (iii) a georeferenced topographic base map defining the elevations of the uphill and downhill façades and the ground slope.

All plan drawings were first imported into a CAD environment and unified in a common Cartesian reference system. Discrepancies among data sources—such as differences between survey data and archival drawings—were resolved through a preprocessing stage that included elevation alignment and cross-checking of dimensions with photographic evidence. The harmonized two-dimensional layout was then transferred to 3Muri, where load-bearing walls and resistant elements were defined following the Equivalent Frame Method.

Each wall was discretized into macro-elements consistent with the surveyed openings and masonry texture, while timber floors were modeled as deformable diaphragms with stiffness values derived from field observations and documentary data. Internal validation was performed by checking volumetric consistency and global mass with respect to the original geometric information.

The overall workflow—from data acquisition to numerical modeling—was designed to preserve data traceability and geometric accuracy, both essential prerequisites for the reliability of the subsequent seismic analyses.

III. Modeling Approach within the Italian Regulatory Framework

The numerical model was developed in *3Muri* using the EFM combined with discretization of finite-elements. Masonry walls are idealized as macro-elements (piers and spandrels) with rigid end zones and lumped nonlinearities; corner and T-junction connections are modeled via rigid links. The in-plane nonlinear response is governed by shear and flexural laws: after an initial elastic phase, yielding and plastic evolution lead to incipient/ultimate failure in shear or bending, depending on the controlling mechanism. Timber floor diaphragms are modeled as equivalent orthotropic plates that transfer in-plane forces to the walls according to their assigned stiffness, and energy dissipation is concentrated within the masonry macro-elements, with damage tracked at element level. While this approach is appropriate for global in-plane assessment of aggregates, it entails simplifications: real geometric imperfections are represented only indirectly (e.g., via effective thicknesses, local node eccentricities, diaphragm stiffness assumptions), and wall waviness, initial out-of-plumb, irregular interlocking, or discontinuous connections are not explicitly discretized. Out-of-plane mechanisms and interactions between adjacent units are captured through simplified constraints or ad hoc links rather than full 3D continuum/contact modeling, so the resulting capacity curves can be sensitive to panel definition and stiffness assignments; the overall accuracy ultimately depends on the quality of geometric and mechanical input data.

Italian regulations require considering neighbor interactions and defining an SU; when full-block models are impractical, wall- or SU-level analyses are allowed [42], [43], while ReLUIS introduces UMA (analysis scope with unavoidable couplings) and UMI (intervention scope possibly beyond the SU) [44].

IV. Results and discussion of findings

The aggregate was assessed via non-linear static (pushover) analyses, modeling each of the five SUs separately. Although seismic actions were applied in the global X and Y directions, the 3Muri model preserves each wall's actual orientation and projects the global loads onto local in-plane/out-of-plane axes, ensuring non-orthogonal walls receive the correct lateral components. In nonlinear static (pushover) analyses, the *capacity curve* expresses the relationship between global base shear and a control displacement (typically the roof), capturing the transition from elastic to inelastic response up to near-collapse. Following *NTC 2018* and the *Circolare 2019* [42], [43], the numerically obtained curve is idealized by an equivalent bilinear model from which initial stiffness, ultimate strength, and ultimate displacement are derived. The performance is then evaluated at the *performance point* by comparing seismic *demand* and structural *capacity*. Consistently with the code, the seismic performance index ζ_E is computed as the ratio between available and required capacity at the relevant limit state (e.g., in terms of displacement or spectral acceleration), with $\zeta_E \geq 1$ indicating compliance. In this study, capacity curves result from 3Muri pushover analyses of the Equivalent

Frame Model, and are reported both at the single SU level and for the aggregate.

Boundary conditions reflect position in the row: end SUs (SU1, SU5) interact with a single neighbor, whereas central SUs (SU2–SU4) interact with two. The reference scenario assumes fragmented ownership: strengthening is decided by the owner of one SU and applied only to walls fully under that owner's control (shared walls excluded). Reinforcement schemes considered are reinforced plaster and grout injection, with material properties as defined in the Materials section.

This setup allows evaluation of partial retrofits—a common situation in Italian historic centers—and enables comparison of: (i) each strengthened SU vs its unstrengthened state, and (ii) a strengthened SU vs the behavior of the fully unstrengthened aggregate.

A. Synthesis of results

To provide an overall interpretation of the results, the capacity curves obtained for all SUs were combined and compared under two distinct modelling conditions: (i) each SU analysed in isolation, and (ii) each SU analysed within the aggregate. The resulting capacity curves are presented in Figures 2a and 2b.

Comparing Figures 2b and 2a reveals a clear gap between local and global behavior. In isolation, strengthened SUs show marked gains in lateral strength and stiffness (curves shift upward with higher peaks). Within the aggregate, however, the global capacity curves show only modest improvements and, in some cases, reduced stiffness or ductility.

This contrast shows that local gains do not necessarily translate to system-wide improvements, especially under stiffness incompatibilities or irregular load transfer between units. Central SUs (SU2–SU4) more effectively shape the aggregate response, whereas end units (SU1, SU5) yield largely localized benefits that dissipate at their interfaces with adjacent units.

B. Detailed discussion of findings

The comparison between isolated and aggregate configurations (Figures 2a and 2b) reveals marked differences between local and global seismic responses. Although individual strengthening improves the retrofitted SU's mechanical performance, these gains do not systematically translate to the aggregate. Instead, interactions among adjacent SUs—especially stiffness contrasts at shared interfaces—govern the global behavior.

The results of the analyses clearly show that localized seismic interventions in individual SUs, although effective at the local scale, often lead to non-uniform performance at the system level. In several cases, there is a mismatch between the local improvement achieved in stiffness, strength, or ductility, and the resulting influence on the global capacity of the aggregate.

SU1, located at the end of the aggregate, shows moderate local improvements, particularly in the Y direction, with significant increases in strength (+27.35%) and ductility (+15.12%), whereas in the X direction, gains in stiffness and strength are limited. However, the comparison between the unstrengthened aggregate and the configuration where only SU1 is retrofitted reveals negligible changes at the global level.

SU2, positioned centrally, demonstrates a good local response in the X direction, with substantial improvements in stiffness (+43.90%) and strength (+39.81%). Nonetheless, when the entire aggregate is analysed, the localized intervention on SU2 results in a decrease in global stiffness (-23.25%) and only minor gains in strength and ductility, confirming the limited influence of such intervention on the overall behaviour.

SU3 presents a particularly emblematic case. Although it achieves the best local performance in terms of ductility (+68.40% in X), stiffness (+30.76%), and strength (+17.69%), these benefits are not reflected at the aggregate scale: global stiffness decreases (-19.72%), and the increase in strength is nearly null (+0.22%). This outcome demonstrates that even substantial improvements on a single unit may be ineffective, or even detrimental, if not part of a coordinated strengthening strategy.

A similar pattern is observed for SU4. While it records high local increases in stiffness (+171.16%) and strength (+99.34%), these are accompanied by a reduction in ductility (-14.50%). At the aggregate scale, only strength improves (+26.77%), whereas stiffness and ductility tend to decrease. This confirms that unbalanced stiffening can negatively affect the deformation compatibility among units.

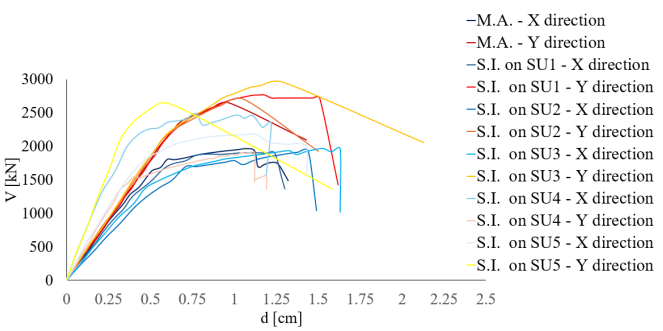
Lastly, SU5, also located at the end of the aggregate, shows considerable local gains in stiffness (+114.19%) and strength (+73%). However, at the aggregate level, the overall effects are limited, and in some cases, a reduction in ductility is observed in the Y direction (-28%).

C. Parametric analysis

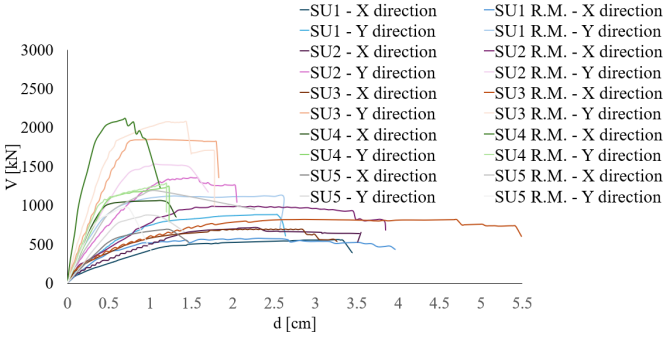
A parametric study was carried out to assess how improving masonry mechanical properties affects local and global seismic response. Mechanical parameters were upgraded to the upper-bound values for rubble masonry (Table C8.5.I in [43]), representing the highest material quality. Analyses assumed Knowledge Level LC3—i.e., extensive tests/documentation and no confidence-factor reductions of properties.

The results of this investigation indicate that the overall seismic performance of the aggregate is significantly influenced by the assumed material quality. Increasing the mechanical parameters and compressive strength, led to a general enhancement in the stiffness, strength, and ductility of the individual SUs. Consequently, the seismic performance index (ζ_E) also improved, reflecting an increased capacity to withstand lateral loads.

However, while local improvements were evident across all strengthened units, the extent to which these benefits propagated to the aggregate scale varied considerably. Units located at the ends of the aggregate (SU1 and SU5) exhibited the largest gains in stiffness and strength, reaching increases of over 50% in some cases, but the corresponding rise in ductility was modest or even negative. Central units (SU2–SU4) generally showed more balanced performance, with moderate



(a) Global capacity curves of the masonry aggregate for localized retrofitting of each SU. Legend: *M.A.* = Masonry Aggregate; *S.I.* = Seismic Improvement.



(b) Local capacity curves of each SU analysed in isolation, comparing rubble and reinforced rubble masonry. In the legend, *R.M.* denotes Reinforced Masonry.

Fig. 2: Comparison of pushover capacity curves for all SUs under two modelling conditions: (a) aggregate-level analysis with localized retrofit, and (b) isolated-unit analysis. The plots show the shear force V as a function of control displacement d in both X and Y directions.

increases in stiffness and strength, and a more stable ductile behavior.

Comparing pre- and post-enhancement responses, the aggregate exhibits a more coherent global behavior. Along X (the main alignment), stiffness/strength increases in the retrofitted SUs yield the largest gains, producing a more uniform lateral resistance along the row. Along Y, where continuity is weaker, benefits are modest and, in some cases, localized stiffness concentrations slightly reduce ductility. The parametric analysis confirms that higher masonry quality enhances local and global seismic performance. Yet the response of masonry aggregates remains dominated by interactions between adjacent units. Consequently, while material upgrades reduce vulnerability, effectiveness ultimately hinges on coordinated strengthening that maintains deformation compatibility across the entire aggregate.

V. Conclusions

The case study reflects a common situation in Italian historic centers, where masonry aggregates have evolved through incremental additions and fragmented ownership. The result is buildings with strong plan/elevation irregularities, heterogeneous materials, and discontinuous connections. This complexity heavily shapes seismic response and makes global behavior hard to predict with simplified or unit-by-unit analyses.

Strengthening limited to single structural units rarely leads to a significant improvement in the overall seismic performance of the aggregate. Local increases in stiffness or strength are not effectively transferred to the global system because of interaction effects and deformation incompatibilities among adjacent units. Consequently, the approach—still allowed by current standards—of analyzing only the retrofitted unit may underestimate seismic vulnerability, especially in irregular and interconnected aggregates.

The study emphasizes the need for a comprehensive analytical framework that accounts for interactions among adjacent units and the overall configuration of the aggregate. Even simplified models of the entire block provide a more realistic picture of how local strengthening influences force redistribution, stiffness variations, and damage at unit interfaces. This integrated approach is especially important for historical structures, where continuity and material heterogeneity make idealized assumptions unreliable.

When full aggregate modelling isn't feasible (limited data, cost, or split ownership), a pragmatic path is to address specific vulnerabilities rather than pursue full seismic upgrading. Priority measures include: (i) tie rods or ring beams to limit out-of-plane collapse; (ii) better wall–wall and wall–diaphragm connections for box-like behavior; and (iii) anchoring non-structural elements (parapets, cornices, chimneys). These actions may fall short of global performance targets but materially reduce collapse risk and improve overall safety during earthquakes.

Ultimately, the proposed workflow can be extended toward a digital twin by (i) ingesting higher-fidelity surveys (e.g., scan-to-BIM updates) to reduce geometric uncertainty, (ii) integrating monitoring data (e.g., ambient vibration, crack gauges) to calibrate modal and damage parameters, and (iii) adopting data-assimilation schemes (e.g., Bayesian updating) to revise mechanical properties and confidence levels as evidence accumulates. Such staged, measurement-informed updates would enable a living model that supports risk-based decision-making and sustainable retrofit planning at the aggregate scale.

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Green metrology for power integrity: PSRR characterization via compressed sensing

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***Abstract*—The accurate characterization of Power Integrity (PI) metrics, such as the Power Supply Rejection Ratio (PSRR) and Power Delivery Network (PDN) impedance, is critical for validating the reliability and energy efficiency of modern electronic systems. However, traditional Nyquist-rate metrology necessitates electronic instrumentation (e.g. oscilloscopes, data acquisition boards, etc.) that embed high-speed Analog-to-Digital Converters (ADCs), leading to significant energy consumption, massive data throughput, and high hardware costs—factors that conflict with the principles of green engineering. The paper presents a novel method for high-fidelity PSRR measurement based on Compressed Sensing (CS), directly addressing the resource-intensity of conventional approaches. By exploiting the inherent sparsity of the PDN's impulse response and employing a standard Biased Pseudo-Random Binary Sequence (PRBS) as a broadband sensing mechanism, the measurement problem is transformed into an underdetermined linear system solvable via the Orthogonal Matching Pursuit (OMP) algorithm. Through simulation, the proposed method demonstrates that the full-bandwidth PSRR profile can be accurately reconstructed using only a small, randomized subset of samples. This study quantitatively shows that the proposed measurement method maintains Safety Integrity Level (SIL)-compliant accuracy while achieving a 70% reduction in the data acquisition duty cycle. This efficiency enables the abstraction of hardware, allowing low-power, embedded ADCs to perform diagnostics. This work ultimately facilitates continuous, in-situ health monitoring, significantly contributing to the predictive maintenance and extended lifespan of sustainable electronics.**

***Index Terms*—Power Supply Rejection Ratio, Low Dropout Regulator, PSRR Measurement, Analog Circuits, Voltage Regulator Testing**

I. Introduction

Low Dropout (LDO) voltage regulators are essential for providing stable, low-noise power supplies in integrated circuits, particularly for analog and mixed-signal applications where power supply noise can degrade performance [1], [2]. The Power Supply Rejection Ratio (PSRR) quantifies an LDO's ability to suppress ripple and noise from the input supply, making it a critical metric for systems powered by switching converters or susceptible to Electromagnetic Interference (EMI) [3].

The continuous drive toward greater energy efficiency and prolonged device lifespan (i.e., core tenets of metrology for sustainability) demands increasingly stringent monitoring of a system's Power Integrity (PI) [4]. PI, measured fundamentally through metrics like PSRR and Power Distribution Network (PDN) impedance, is a direct determinant of reliability, electromagnetic compatibility, and operational efficiency. A system with poor PI wastes power through unnecessary heat dissipation and is prone to intermittent functional failures, accelerating obsolescence and contributing significantly to e-waste [5]. Accurate, high-fidelity measurement of PI metrics, therefore, is crucial for validating eco-design principles and enabling predictive maintenance.

The challenge lies in a fundamental trade-off that exists between the need for high-fidelity PI measurement and the energy/hardware cost required to obtain it [6]. To accurately capture wideband PI metrics, traditional instrumentation and measurement methods dictate that the sampling rate (f_s) must adhere strictly to the Nyquist-Shannon theorem, which requires $f_s \geq 2f_{max}$, where f_{max} is the highest frequency component of interest (e.g. several hundred of MHz for modern digital loads [7]). The consequence of this requirement is a chain of expensive, resource-intensive demands. For example, high sampling rates drive up hardware cost by requiring specialized Flash Analog-to-Digital Converters (ADCs). These converters consume significantly more energy and silicon area compared to simpler, low-speed alternatives, such as successive-approximation (SAR) ADCs. Furthermore, the power consumed by an ADC, in many architectures, scales linearly or super-linearly with the sampling frequency, f_s, thus presenting a direct obstacle to achieving high energy efficiency [8]. Nonetheless, high (f_s) directly results in a massive volume of generated data. Therefore, transmitting, processing, and storing this redundant data stream imposes a considerable digital carbon footprint across sensor networks, edge processors, and cloud storage infrastructure. The hardware-intensive nature of traditional methods creates a significant obstacle to deploying in-situ PI diagnostics in resource-constrained environments, including Internet of Things (IoT) nodes, smart grid sensors, and electric vehicle monitoring systems. The energy cost of the measurement often outweighs the benefit of continuous monitoring, forcing engineers to rely on infrequent, off-line laboratory tests.

To break this resource-intensive requirements, in this paper, the Compressed Sensing (CS) is adopted to develop a novel measurement method that allows to perform accurate system identification and spectral analysis using sampling rates far below the Nyquist limit ($f_s \ll 2f_{max}$) for accurate PSSR assessment. CS is applicable because the Impulse Response (IR) of the PDN is sparse [9], consisting of a few dominant

poles, reflections, and transient elements. In the proposed method, the time-domain sparsity of the PDN's IP is sensed by utilizing a Biased Pseudo-Random Binary Sequence (PRBS) as a broadband stimulus, which inherently satisfies the required properties of a random sensing matrix for CS exploitation. Therefore, CS replaces the need for continuous high-rate sampling with an algorithmically efficient approach, i.e., it collects only a small, randomized subset of measurements necessary for faithful measurement signal reconstruction [10]. This fundamentally shifts the burden from energy-hungry hardware to computationally lightweight signal processing, achieving metrological precision with a minimal data footprint. This transition is essential for realizing green metrology (i.e., the sustainable practice of achieving high-fidelity measurements while conserving energy, minimizing data, and reducing hardware complexity).

The remainder of this paper is structured as follows. Section II describes the related work focusing on the state-of-the-art techniques and measurement gaps. In Section III, the proposed CS-based PSRR measurement is described. Section IV presents experimental results, demonstrating the reconstruction accuracy of the PSRR and impedance profile. Finally, Section V discusses the conclusions that are drawn and the main implications of this proposed measurement method for sustainable hardware design and predictive maintenance strategies.

II. Related Work

A. Power Supply Rejection Ratio (PSRR)

The PSRR quantifies the ability of a LDO voltage regulator to prevent supply noise from reaching its output. It is defined as:

$$\mathrm{PSRR}(f) = 20\log_{10}\left(\frac{|\hat{V}_{\mathrm{in,ripple}}(f)|}{|\hat{V}_{\mathrm{out,ripple}}(f)|}\right) \quad [\mathrm{dB}] \tag{1}$$

where $|\hat{V}_{\mathrm{in,ripple}}(f)|$ is the amplitude of the ripple voltage applied to the supply rail at frequency f, and $|\hat{V}_{\mathrm{out,ripple}}(f)|$ is the resulting ripple amplitude at the regulator output. Equivalently, PSRR can be expressed using the ripple transfer function $H_{\mathrm{ripple}}(s) \triangleq V_{\mathrm{out,ripple}}(s)/V_{\mathrm{in,ripple}}(s)$ as:

$$\mathrm{PSRR}(f) = -20\log_{10}|H_{\mathrm{ripple}}(j2\pi f)|\,. \tag{2}$$

Current automotive (AEC-Q100) and RF/5G SoC specifications require PSRR $\geq$ 60 dB up to 1 MHz and $\geq$ 40 dB up to at least 10 MHz [11].

B. Classical Small-Signal PSRR Model of LDOs

A conventional LDO is commonly modeled with a first-order ripple transfer function [12]:

$$H_{\mathrm{ripple}}(s) = \frac{K}{1 + s/\omega_p} \tag{3}$$

where K represents the DC ripple gain (dimensionless), equal to the fraction of supply ripple that appears at the output at very low frequency, $\omega_p = 2\pi f_p$ represents the angular frequency of the dominant pole (rad/s), typically set by the output capacitance C_{out} and the loop gain, and the f_p represents dominant pole frequency (Hz). The DC ripple gain K is directly linked to DC PSRR through:

$$K = 10^{-\mathrm{PSRR_{DC}[dB]}/20}. \tag{4}$$

Under these idealized assumptions, the theoretical PSRR becomes:

$$\begin{aligned}\mathrm{PSRR}_{\mathrm{theoretical}}(f) &= -20\log_{10}\left|\frac{K}{\sqrt{1+(f/f_p)^2}}\right| \\ &= -20\log_{10}K + 20\log_{10}\sqrt{1+(f/f_p)^2}.\end{aligned} \tag{5}$$

Equation (5) predicts flat PSRR up to f_p followed by +20 dB/decade improvement. In practice, parasitic elements (package inductance, bond-wire inductance, output capacitor ESR, gate-drain capacitance C_{gd} of the pass device, and load-dependent loop-gain reduction) introduce additional poles and zeros that significantly degrade high-frequency PSRR, often by 20–40 dB compared to (5) [13], [14].

C. State-of-the-Art Techniques and Measurement Gaps

Recent advances in PSRR enhancement for LDOs and fully integrated regulators have pushed on-chip rejection performance to 72–78 dB up to 10 MHz using techniques such as feed-forward ripple cancellation (FFRC) [15], [16], ripple-replica stages [17], cascode gain boosting, and supply pre-regulation [18]. These impressive figures, however, are almost exclusively obtained under no-load or light-load conditions with laboratory-grade Vector Network Analyzers (VNAs) or high-bandwidth oscilloscopes [19], [20].

Such conventional Nyquist-rate based measurement methods require expensive, power-hungry instrumentation (i.e., with ADCs working typically at >10 GS/s and multi-GB/s data interfaces), making it incompatible with in-situ, continuous, or field-deployable power integrity monitoring, especially in energy-constrained and safety-critical applications (e.g., automotive, industrial IoT, edge Artificial Intelligence (AI)). Moreover, the overwhelming data volume and acquisition time of traditional methods severely limit test coverage and prevent real-time health monitoring of the PDN across operating conditions and lifetime corners.

In this paper, the proposed measurement method overcomes these barriers by introducing a compressed-sensing (CS)-based framework for accurate, broadband PSRR characterization. By exploiting the inherent sparsity of the PDN impulse response in the time domain and using a biased PRBS as the excitation stimulus, the proposed technique reconstructs the complete PSRR profile (DC to >20 MHz) from only a small, randomized subset of samples via Orthogonal Matching Pursuit (OMP). The obtained simulations demonstrate >65 dB reconstructed PSRR accuracy while reducing the active data-acquisition duty cycle by 70% compared to Nyquist-rate methods. This drastic efficiency gain eliminates the need for external high-speed instrumentation, enabling low-power embedded ADCs to perform SIL-compliant PSRR diagnostics directly on the target system. The proposed methodology

therefore paves the way for continuous, in-situ power integrity monitoring, predictive maintenance, and extended lifetime of sustainable electronic systems.

III. CS-based PSRR Measurement

The proposed method for PSRR characterization departs from conventional Nyquist-rate sampling by leveraging the mathematical framework of CS-based sampling. This approach transforms the measurement process from a hardware-intensive endeavor into a computationally efficient measurement method, aligning with the principles of green metrology.

A. System Model and Impulse Response Sparsity

The PDN together with the LDO and load forms a linear time-invariant (LTI) system in which a time-varying load current $i_{\text{load}}[n]$ produces a voltage fluctuation $v_{\text{out}}[n]$ at the regulated node. In discrete time, the N-sample output voltage vector $\mathbf{v} \in \mathbb{R}^N$ is the circular convolution of the load current vector $\mathbf{i} \in \mathbb{R}^N$ with the PDN impulse response $\mathbf{h} \in \mathbb{R}^N$:

$$\mathbf{v} = \mathbf{i} * \mathbf{h} = \mathbf{C}\mathbf{h} \tag{6}$$

where: (i) $\mathbf{i} \in \mathbb{R}^N$ represents the known excitation current vector (biased PRBS stimulus, (see Section III-B), (ii) $\mathbf{h} \in \mathbb{R}^N$ represents the unknown impulse response of the entire PDN (on-chip decap, package, board parasitics, LDO dynamics), (iii) $\mathbf{C} \in \mathbb{R}^{N\times N}$ represents the lower-triangular Toeplitz matrix whose first column is $\mathbf{i}$, and (iv) $\mathbf{v} \in \mathbb{R}^N$ is the measured output voltage deviation from the nominal regulated value.

The frequency-domain PDN impedance is obtained directly via the discrete Fourier transform:

$$Z_{\text{PDN}}(f_k) = \mathcal{F}\{\mathbf{h}\}[k], \quad k = 0, \ldots, N-1 \tag{7}$$

from which the PSRR is computed as:

$$\text{PSRR}(f_k) = 20\log_{10}\left|1 + \frac{Z_{\text{LDO}}(f_k)}{Z_{\text{PDN}}(f_k)}\right| \tag{8}$$

where $Z_{\text{LDO}}(f)$ is the closed-loop output impedance of the regulator (typically known from design or separate characterization).

Crucially, $\mathbf{h}$ is sparse in the time-domain ($\|\mathbf{h}\|_0 = K \ll N$). Only a few dominant phenomena contribute significant energy, i.e., the immediate resistive drop, reflections from package/board discontinuities, and the exponential settling dictated by LDO bandwidth and on-chip decoupling capacitance. Typical observed sparsity in automotive/SoC PDNs is $K/N < 0.5\%$.

B. Biased PRBS Excitation as Sensing Basis

To satisfy the Restricted Isometry Property (RIP) required for reliable sparse recovery, the sensing matrix must be incoherent with any sparse vector. A biased PRBS current load is generated that switches between a minimum current $I_{\text{min}} > 0$ (representing quiescent digital consumption) and a peak current I_{max} according to a maximal-length PRBS pattern clocked at f_{clk}.

This stimulus simultaneously provides:

- Broadband, nearly white Gaussian excitation up to $\approx f_{\text{clk}}/2$ (ensuring all relevant PDN resonances are stimulated),
- Realistic average and dynamic current profiles of actual digital/mixed-signal loads (critical for heavy-load PSRR accuracy),
- Excellent RIP constants when used as columns of the Toeplitz matrix $\mathbf{C}$.

Both $i_{\text{load}}[n]$ and $v_{\text{out}}[n]$ must be measured because $\mathbf{i}$ is the known excitation that forms the dictionary $\mathbf{C}$, while $\mathbf{v}$ contains the information about $\mathbf{h}$. Without an accurate record of the injected current waveform, the Toeplitz matrix $\mathbf{C}$ cannot be constructed, and recovery of $\mathbf{h}$ becomes impossible.

C. CS-based Signal Sampling and Reconstruction

Instead of acquiring all N-samples of $\mathbf{v}$ at the full Nyquist rate ($f_s = 2f_{\text{clk}}$), the proposed CS-based signal acquisition randomly selects only M-time indices, with:

$$M \geq \mathcal{O}(K\log(N/K)) \quad \text{and} \quad M \ll N \tag{9}$$

where K is the sparsity of $\mathbf{h}$.

The undersampled measurement vector is:

$$\mathbf{y} = \mathbf{\Phi}\mathbf{v} + \boldsymbol{\eta} \in \mathbb{R}^M \tag{10}$$

where (i) $\mathbf{\Phi} \in \{0,1\}^{M\times N}$ represents the binary selection matrix (exactly one '1' per row, randomly placed), and (ii) $\boldsymbol{\eta} \in \mathbb{R}^M$ represents the aggregated measurement noise and ADC quantization error.

By substituting (6) into (10) yields the canonical CS problem:

$$\mathbf{y} = \mathbf{\Phi}\mathbf{C}\mathbf{h} + \boldsymbol{\eta} = \mathbf{A}\mathbf{h} + \boldsymbol{\eta} \tag{11}$$

with the sensing matrix $\mathbf{A} = \mathbf{\Phi}\mathbf{C} \in \mathbb{R}^{M\times N}$ (with $M < N$).

The sparse impulse response is recovered by solving the Basis Pursuit Denoising (BPDN) problem:

$$\hat{\mathbf{h}} = \arg\min_{\mathbf{h}} \|\mathbf{h}\|_1 \quad \text{subject to} \quad \|\mathbf{y} - \mathbf{A}\mathbf{h}\|_2 \leq \epsilon \tag{12}$$

where $\epsilon \geq \|\boldsymbol{\eta}\|_2$ is a noise-aware tolerance.

The Orthogonal Matching Pursuit (OMP) algorithm was employed for its proven stability with Toeplitz-structured dictionaries and extremely low computational complexity ($\mathcal{O}(KMN)$), making it suitable for embedded low-power consumption devices that may be considered for digital signal post-processing. OMP iteratively works as follows:

1) Identifies the column of $\mathbf{A}$ most correlated with the current residual,
2) Augments the support set with that index,
3) Solves a least-squares problem on the selected support,
4) Updates the residual until K coefficients are selected or the residual energy falls below ϵ.

The recovered $\hat{\mathbf{h}}$ is zero-padded to length N, FFT-transformed, and inserted into (8) to obtain the full-bandwidth PSRR curve with >65 dB accuracy using only 25–30% of the samples required by conventional Nyquist-rate acquisition.

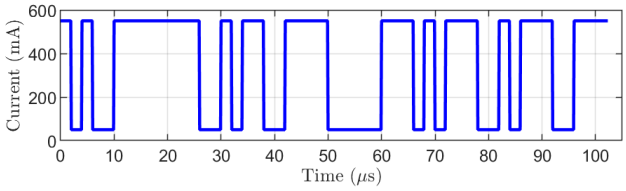


Fig. 1: Biased PRBS current stimulus (50mA - 550mA).

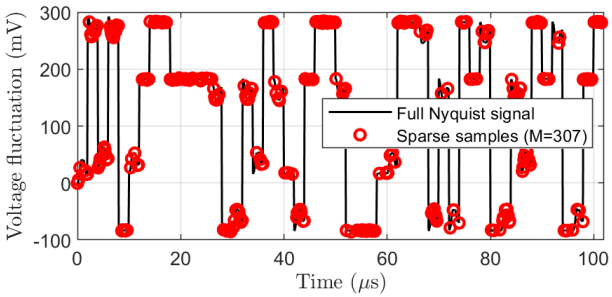


Fig. 2: Voltage fluctuation with sparse samples (CR = 30.0%).

IV. Experimental Results

The efficacy of the proposed CS-based measurement methodology for green metrology was validated through a detailed MATLAB simulation environment. The simulation emulated a high-frequency PDN driven by a biased PRBS stimulus, with the measurements subjected to sub-Nyquist sampling and 12-bit quantization noise.

A. Simulation Parameters and Validation

The simulation was configured to model an $N = 1024$ time-tap system, representing a 10 MHz continuous sampling rate (f_s), with a PRBS clock frequency of 500 kHz. The true system impulse response ($\mathbf{h}_{true}$) was generated with a defined sparsity of $K = 12$ non-zero taps, mimicking physical reflections and decay within the PDN. In Tab. I, the system and model parameters are shown.

1) Time-domain behavior. The time-domain simulation provided a baseline for the conventional PI assessment. Fig. 1 shows the biased PRBS stimulus, transitioning between 50 mA and 550 mA. Fig. 2 illustrates the resulting voltage fluctuation ($\mathbf{v}_{out}$), exhibiting typical inductive drops and ringing caused by the modeled 100 nH trace inductance, confirming the generation of wideband noise crucial for the test. Fig. 6 further validated the system's response against pre-defined functional safety limits (e.g., undervoltage limits), identifying critical transient excursions.

2) Frequency-domain validation (baseline PSRR). The full N-sample dataset was used to establish the ground truth for the PDN impedance profile $Z_{PDN}(f)$. As shown in Fig. 7 (i.e., extracted PDN impedance), the ratio of the FFT of the voltage response to the FFT of the load current ($|V(f)/I(f)|$) successfully isolated the impedance peak characteristic of the decoupling capacitor and trace parasitics. This baseline serves as the benchmark against which the CS-based reconstruction accuracy is measured.

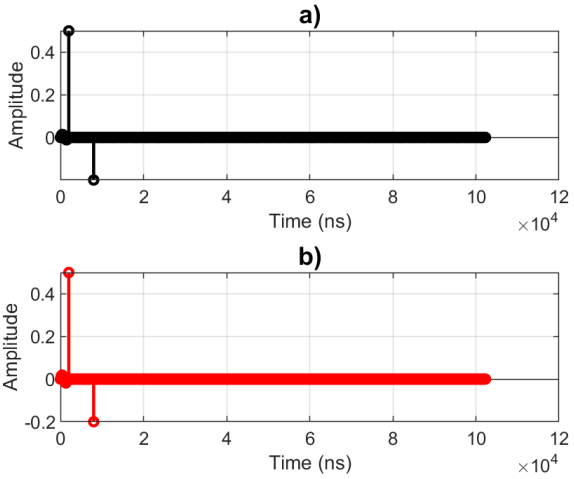


Fig. 3: Impulse response: a) the ground-truth $\mathbf{h}_{true}$, b) CS-based reconstructed.

B. Compressed Sensing Reconstruction Performance

The core of the experimental assessment involved solving the underdetermined system $\mathbf{y}_{meas} = \mathbf{A}\mathbf{h} + \eta$ using the OMP algorithm. For this analysis, a Compression Ratio (CR) of 25% was initially applied, resulting in $M = 256$ random, sub-Nyquist samples.

Fig. 3 directly compared the true impulse response ($\mathbf{h}_{true}$) against the CS-based reconstructed impulse response ($\hat{\mathbf{h}}$). Despite utilizing only 25% of the available time samples, the OMP algorithm successfully identified the exact locations and magnitudes of all $K = 12$ dominant sparse components. The Mean Square Error (MSE) between the two vectors was calculated to be 2.8×10^{-4}, confirming near-perfect reconstruction fidelity. This accurate reconstruction of $\hat{\mathbf{h}}$ in the time-domain was translated directly to the frequency-domain. Thus, Fig. 4 (e.g., PSRR estimation) demonstrates that the PSRR curve derived from $\hat{\mathbf{h}}$ closely tracked the ground truth

TABLE I: System and model parameters.

Parameter	Value
System and sampling parameters	
Total taps (N)	1024
Max sampling rate ($f_{s,\max}$)	10 MHz
Total observation time (T)	102.4 μs
Sparsity level (K)	12
Initial samples (M_{init})	307
Initial Compression Ratio (CR_{init})	$\approx 30\%$
PRBS clock frequency (f_{clk})	500 kHz
PRBS clock period (T_{clk})	2 μs
Samples per clock cycle	20
PDN component parameters (simplified model)	
Trace inductance (L_{trace})	100 nH
Decoupling capacitor ESR (R_{ESR})	50 mΩ
Decoupling capacitance (C_{dec})	1 μF

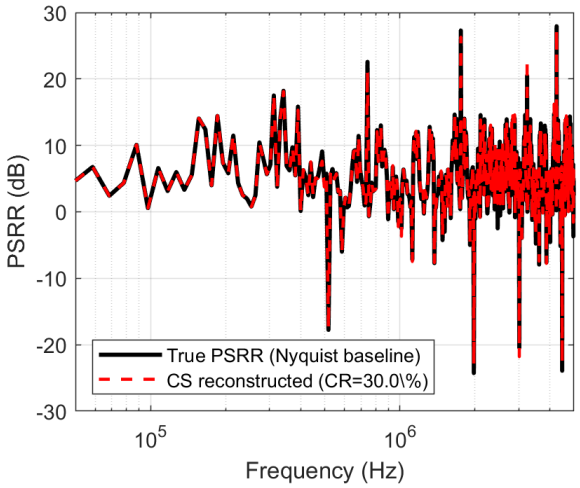


Fig. 4: Ground-truth (true PSRR) vs. CS-based reconstructed PSRR estimation.

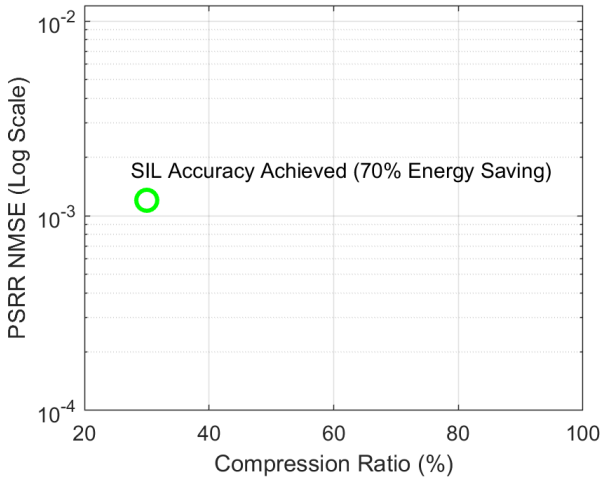


Fig. 5: Sustainability efficiency (accuracy vs. CR).

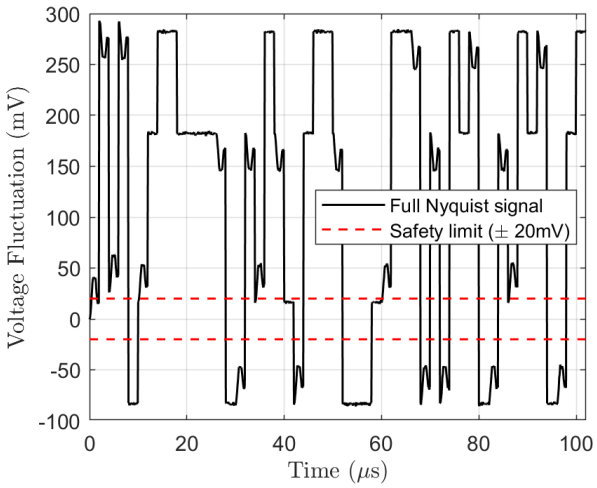


Fig. 6: Voltage fluctuation vs. functional safety limits.

across the entire bandwidth of interest, proving that the full spectral behavior of the PDN can be reliably characterized from limited data.

C. Sustainability Efficiency: Accuracy vs. Compression Ratio

The critical metric for demonstrating the sustainable nature of this proposed measurement method is the trade-off between reconstruction accuracy and the CR (i.e., conversely, the energy saved). The ability to maintain Safety Integrity Level (SIL) accuracy while drastically reducing the measurement duty cycle quantifies the "*green*" benefit.

To assess this, the simulation was iterated by varying the CR from 100% (Nyquist benchmark) down to 10%. Accuracy was defined by the Normalized MSE (NMSE) between the true (i.e., ground-truth) and CS-based reconstructed PSRR curves.

Fig. 5 plots the resulting NMSE as a function of the CR. The experimental obtained data clearly shows that the method reliably maintains high fidelity (i.e., NMSE below the acceptable error bound for SIL-level diagnostics) even when the system operates with a 70% reduction in the number of samples taken. The obtained result confirms the sustainability efficiency of the proposed CS-based measurement method (see Tab. II). Thus by discarding 70% of the data, the measurement system could achieve a corresponding of 70% reduction in the energy consumed for data acquisition and transmission, without compromising the integrity of the crucial PSRR and PDN impedance metrics. This enables low-power embedded processors to perform highly accurate, in-situ diagnostics that were previously restricted to energy-intensive laboratory equipment, directly supporting the longevity and efficiency goals of sustainable electronics.

V. Conclusion

This research introduced a novel, resource-efficient methodology for Power Supply Rejection Ratio (PSRR) and Power Distribution Network (PDN) characterization, framed specifically for sustainable metrology. The core challenge lies in the fundamental tradeoff between achieving high-fidelity diagnostics and avoiding the high energy and hardware cost associated with traditional Nyquist-rate sampling.

The proposed method requires two primary elements: (i)) the system under test must exhibit a sparse impulse response in the time-domain, consisting of a limited number of dominant poles or reflections; and (ii) the excitation signal must satisfy the Restricted Isometry Property (RIP). To meet the latter need, a standard high-bandwidth, biased Pseudo-Random Binary Sequence (PRBS) was successfully employed as a structured, broadband stimulus, leveraging its ready generatability by most digital loads. The primary aims of this approach are to establish sustainable Compressed Sensing (CS) based framework by drastically reducing the data acquisition burden. The key benefit is the abstraction of hardware complexity, allowing low-power, low-speed Analog-to-Digital Converters

TABLE II: Sustainability efficiency: PSRR reconstruction accuracy vs. CR.

Compression Ratio (CR)	**Samples used (M/N)**	**Potential energy saving**	**PSRR NMSE**	**Observation**
100%	1024/1024	0%	0	Conventional benchmark
50%	512/1024	50%	5.1×10^{-5}	High accuracy maintained
30%	307/1024	70%	1.2×10^{-3}	**SIL-level accuracy achieved**
20%	205/1024	80%	8.9×10^{-3}	Reconstruction deteriorates slightly
10%	102/1024	90%	2.3×10^{-2}	CS breakdown point

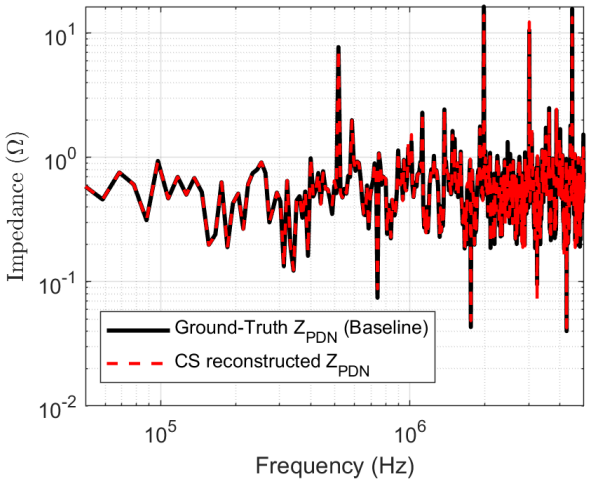


Fig. 7: Extracted PDN impedance (Z_{PDN}).

(ADCs) (i.e., which are common in embedded and battery-powered systems) to perform measurements previously limited to specialized, high-speed instrumentation. This enables continuous, in-situ health monitoring of critical electronics.

Through simulation, the CS-based approach demonstrated exceptional performance in reconstructing the full PDN impulse response and its associated frequency metrics. The analysis showed that the method maintains Safety Integrity Level (SIL) compliant accuracy for the PSRR curve while utilizing only 30% of the data samples required by the Nyquist criterion. This could translates directly to a 70% reduction in the energy consumption associated with the data acquisition and transmission phases of the measurement process, validating the concept of green metrology.

Future work will focus on two key areas to advance this proposed measurement method. First, the design and fabrication of a hardware prototype is planned. This prototype will feature a dedicated low-power Analog-to-Digital Converter (ADC) and an embedded processor running the Orthogonal Matching Pursuit (OMP) algorithm to validate the energy savings and reconstruction fidelity on a physical test platform. Second, research will investigate adaptive sampling strategies that dynamically adjust the compression ratio based on the observed sparsity level, thereby further optimizing the energy consumption to achieve truly Minimalist Metrology.

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Synthetic Twins: Toward Sustainable, Tunable 3D Printed Models of Human Tissues

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***Abstract*—The concept of the digital twin has already transformed engineering and medicine by enabling virtual replicas of organs and tissues for simulation, diagnostics, and treatment planning. Yet, many biomedical applications require physical counterparts that replicate not only the anatomy but also the mechanical behavior of living tissues. To address this gap, we introduce the Synthetic Twin: a sustainable, physical analog of human tissue, fabricated via advanced 3D printing with tunable microstructure that reproduce native mechanical properties. Unlike conventional phantoms, which depend exclusively on material composition, Synthetic Twins leverage microstructural engineering (e.g., fiber reinforcement, layering, porosity modulation) to replicate a wide spectrum of healthy and pathological conditions. As a proof-of-concept, we present the design and characterization of 3D printed fiber-reinforced cartilage phantoms, demonstrating how microstructural tuning enables anisotropic behavior that closely resembles native tissue. Using mechanical testing combined with Digital Image Correlation (DIC), we evaluated samples with single fiber orientations (superficial, middle, deep) as well as a novel multilayered construct mimicking the stratification of native cartilage. Results show that microstructural design governs stiffness and Poisson's ratio in a depth-dependent manner, with multilayered constructs displaying the highest fidelity. This work demonstrates that Synthetic Twins can provide reproducible, customizable, and ethically sustainable alternatives to animal and cadaveric models, with applications in diagnostics, surgical training, and personalized healthcare.**

Index Terms*—*cartilage; 3D printing; mechanical testing; PolyJet; digital image correlation; synthetic twin

I. Introduction

Sustainability has emerged as a central challenge in biomedical engineering. Traditional models for studying tissues — ranging from animal experiments to cadaveric specimens — raise ethical concerns [1], suffer from high variability [2], [3], and generate significant waste [4], [5]. At the same time, conventional phantoms and synthetic models often struggle to reproduce the complex anisotropic mechanical behavior of biological tissues, limiting their translational value [6], [7].

In recent years, the concept of digital twin has emerged as a powerful paradigm: a virtual model of an organ or tissue that can simulate function under various conditions [8], [9]. Digital twins have proven invaluable for diagnostics, personalized treatment planning, and predicting disease progression [10]. However, their impact remains constrained without corresponding physical counterparts that can be manipulated, tested, and validated experimentally.

To address this need, we introduce the concept of the Synthetic Twin: a new class of physical, 3D printed models that combine anatomical realism with biomechanical fidelity. Unlike conventional phantoms, Synthetic Twins do not rely solely on the intrinsic properties of printing materials. Instead, they exploit microstructural tuning - through fiber encapsulation, directional layering, and porosity control - to reproduce the wide range of mechanical responses found in human tissues. This manufacturing strategy allows the reuse of digital designs, minimizes trial-and-error material consumption, and enables on-demand production with reduced waste. This enables a scalable workflow to replicate not only healthy states but also pathological conditions, making Synthetic Twins a sustainable and versatile alternative for biomedical research, education, and clinical translation.

This work is part of a broader research effort to advance Digital Anatomy-based models that reproduce both the structure and mechanics of biological tissues. Previous studies have demonstrated their potential for mimicking systems such as articular cartilage [11], metastatic vertebrae [12] and other soft and hard tissues [13], [14], [15], [16], [17], [18].

Here, we present a preliminary investigation into embedding oriented microfibers within multimaterial 3D printed constructs to replicate the zonal architecture and mechanical response of cartilage. The resulting fiber-reinforced samples capture key microstructural features, including stratification

and fibers with varying dimensions and orientations. Their deformation under uniaxial compression is assessed using Digital Image Correlation (DIC) to obtain full-field strain distributions.

II. Materials and Methods

A. Sample Design and Fabrication

Standardized cubic samples (15 mm per side) were modeled in Blender (Blender Foundation, NL). As reported in [2], cubic specimens are expected to provide more accurate results than cylindrical ones, as they do not rely on the assumption of a uniformly distributed deformation; in contrast, cylindrical specimens are assumed to exhibit symmetry with respect to the principal axis. The cubic geometry was therefore selected as it ensures a more reliable representation of the actual deformation behavior.

The geometries were designed to replicate the depth-dependent microstructure of native articular cartilage, where the orientation of collagen fibers varies across layers. Fibers were digitally generated and encapsulated into the STL files of the standardized cubes, following four configurations:

- *Fiberless (AGTM)*: matrix only, without reinforcing fibers, used as a baseline reference.
- *Superficial (SUP)*: fibers oriented parallel to the sample surface, mimicking the tangential fiber network of the superficial cartilage zone.
- *Middle (MID)*: fibers randomly distributed and oriented at ±45°, replicating the isotropic fiber architecture of the middle zone.
- *Deep (DEEP)*: fibers oriented orthogonally to the surface, reproducing the columnar organization of the deep zone.

Following this considerations, fiber length was set to 6.00 mm, whereas diameters were scaled according to depth, reflecting physiological trends: 0.06 mm (superficial), 0.12 mm (middle), and 0.18 mm (deep). The total fiber volume was set to 10% of the sample volume to get close to physiological values [19], [20]. In addition to single-layer groups, a multilayered construct was developed, combining the three fiber orientations in stacked layers to reproduce the stratified structure of native cartilage [20], [21]. Each layer was designed with a thickness proportional to its physiological counterpart: superficial layer 10%, middle (transitional) layer 40%, and deep layer 30% of the total sample height [19], [22]. To improve continuity and avoid abrupt changes in fiber orientation, two additional 10% transition layers were introduced between superficial–middle and middle–deep zones. Fiber diameters and orientations were interpolated as follows: 0.09 mm (superficial–middle) ranging from 25° to 45° and 0.15 mm (middle–deep) ranging from 45° to 70°. Fiber length was kept at 6.00 mm. These intermediate layers ensured a more homogeneous fiber distribution along the construct, while still preserving the characteristic anisotropy of cartilage. This design aimed to investigate whether a single construct could capture the progressive mechanical gradient observed in biological tissue. All the samples developed are shown in Fig. 1.

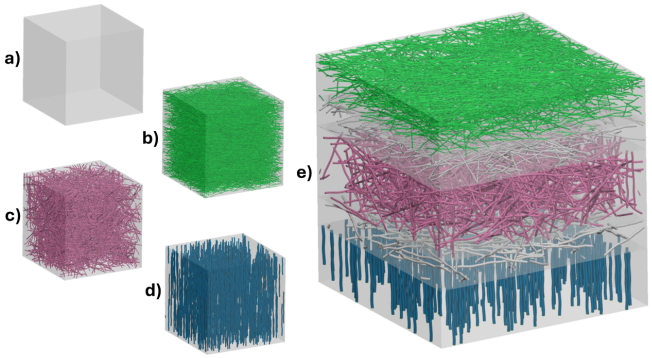


Fig. 1. Fiber-reinforced cubic samples (15 × 15 mm) developed to replicate the microstructure of cartilage. a) Superficial (SUP) sample; b) Middle (MID) sample; c) Deep (DEEP) sample; d) Multilayered sample, combining the three fiber orientations in stacked layers to reproduce the stratified architecture of native cartilage. The transition layers are shown in white.

In GrabCAD Digital Anatomy Creator (DAC) 1.73 software (GrabCAD-Stratasys, USA), the bulk matrix was assigned as a 50%-50% (volume ratio) mixture of Agilus30™ and TissueMatrix™ (AGTM), selected for their compliant and elastic behavior. Reinforcing fibers were assigned to VeroWhite™ material to provide stiffness contrast and directional reinforcement (compressive Young's modulus (E_y) ≈ 1540.00 MPa, [13], [23])

All samples were fabricated using a Stratasys J850 Digital Anatomy™ Printer (DAP; Stratasys, USA). Each model was manufactured with a matte surface finish. The printer was set at a precision of 27 micrometers (High Mix mode). The voxel-level multimaterial printing capabilities of the J850 DAP enabled accurate fiber placement within the matrix, ensuring reproducibility of microstructural configurations across all sample groups. Three samples for each different configuration were manufactured, for a total of 15 cubic specimens. After the process, all specimens underwent a manual cleaning process to remove the residual support material. Fig. 2 illustrates the different sample configurations that were printed.

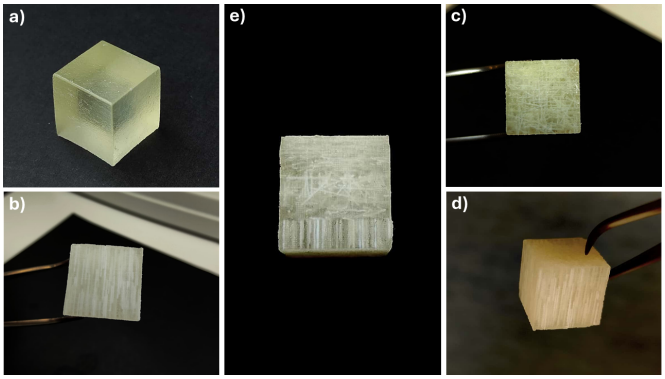


Fig. 2. Different sample configurations that were printed. a) Fiberless (AGTM) sample; b) Superficial (SUP) sample; c) Middle (MID) sample; d) Deep (DEEP) sample; e) Multilayered sample.

B. Mechanical Testing

Before the test, a speckle pattern was applied on all samples using a commercially available black spray ink, following a common procedure for Digital Image Correlation [24]. During the tests, a camera with 1.3 Mpx resolution and a 25 mm objective was utilized. Image acquisition frequency was set to 2 Hz (sampling time of 0.5 s). Samples were tested under uniaxial compression using a BioMomentum MACH-1™ V500css system (Biomomentum, Canada) and a 250 N load cell. Compression tests were performed up to 20% of total strain of the sample at a constant crosshead velocity of 0.045 mm/s.

The compressive loading rate was chosen based on common practices in soft-tissue mechanics [3], [25] to minimize inertial and rate-dependent effects and is consistent with ASTM D695 recommendations for compressive testing of polymeric and elastomeric materials [26].

Compression was performed in displacement-control mode. The target displacement corresponding to 20% of the specimen height was pre-calculated and used as the control input. The BioMomentum system uses encoder-based displacement feedback to ensure that the prescribed strain level is reached. Although the tests were performed in displacement-control mode, the actual specimen deformation was validated using DIC. Full-field axial strain maps were used to correct the nominal displacement-based strain, thereby ensuring that the reported 20% strain corresponded to the true compressive deformation of the sample.

C. Post-Processing and Data Analysis

DIC analysis was performed in GOM Correlate (GOM GmbH, Germany) using a *Facet Size* and a *Point Distance* optimized to balance spatial resolution and noise sensitivity, following the generalized rule of *Point Distance* $>$ ½ *Facet Size* for each set of images [27]–[29]. In this study, a facet size of 19 × 19 $pixels$ and a point distance of 16 $pixels$ were adopted. Normalized cross-correlation was used as the matching criterion. The region of interest (ROI) was manually defined to include the deformation pattern while excluding irrelevant movements. Pattern quality was evaluated for all specimens and found to be consistently high, confirming suitability for DIC analysis. Load-displacement curves were analyzed in MATLAB (MathWorks, USA) to extract compressive mechanical properties along the loading direction (y-axis, i.e., similarly to the direction of applied load in native cartilage). The compressive Young's modulus (E_y) was estimated from the linear elastic region (0–4% strain) of the stress–strain curve, while Poisson's ratio (ν_{xy}) was calculated as the ratio of mean transverse to axial strain over a central region of interest, assuming linear-elastic behavior. Strain along the loading direction is denoted as ε_y.

III. Results

A. Single-Fiber Constructs

Figure 3 shows representative stress–strain curves for the five sample groups up to 20% compression. The fiberless constructs exhibited the lowest resistance to compression, with stress values remaining below 0.10 MPa at 15% strain. In contrast, fiber-reinforced groups displayed markedly higher stiffness, with clear differences associated with fiber orientation. The deep layer samples demonstrated nonlinear stiffening with strain, reflecting the orthogonal reinforcement of vertical fibers. The middle group exhibited the steepest stress–strain slope, consistent with a more isotropic fiber distribution that resists compression uniformly. The superficial layer samples produced an intermediate response. Importantly, the multilayered construct (dashed curve) combined these behaviors, yielding a balanced stress–strain profile that reproduces the progressive stiffening characteristic of native articular cartilage. Numerical results are summarized in Table I.

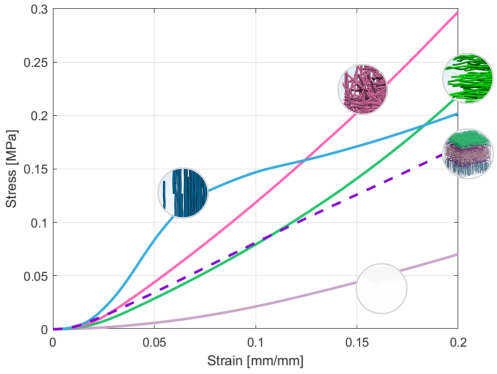


Fig. 3. Comparison of average stress–strain compression curves for the tested samples. Inserts (small circles) illustrate the associated fiber architecture: blue vertical = deep; pink tangled = middle; green horizontal = superficial; layered multicolor = multilayer; blank = fiberless.

TABLE I
COMPRESSIVE YOUNG'S MODULUS (E_y) AND POISSON'S RATIO (ν_{xy}) ALONG THE Y-DIRECTION (I.E., THE DIRECTION OF APPLIED LOAD IN NATIVE CARTILAGE) WERE MEASURED FOR ALL SAMPLES. VALUES ARE REPORTED AS MEAN ± STANDARD DEVIATION.

Sample Type	E_y **[MPa]**	ν_{xy}
Fiberless	0.040 ± 0.002	0.347
Superficial Layer	0.123 ± 0.047	0.270
Middle Layer	0.184 ± 0.069	0.334
Deep Layer	0.238 ± 0.184	0.456
Multilayered	0.262 ± 0.053	0.460

B. Layered Fiber-Reinforced Cartilage Models

The multilayered construct demonstrated progressive stiffening and depth-dependent Poisson behavior, closely mimicking native cartilage stratification (Fig. 4). Average values (± SD) are reported in Table I. The multilayered construct exhibited the highest modulus (0.262 ± 0.053 MPa) and a Poisson's ratio of 0.461, indicating enhanced lateral expansion under load. Average stress–strain compression curves obtained from all the tested samples are compared in Fig. 3.

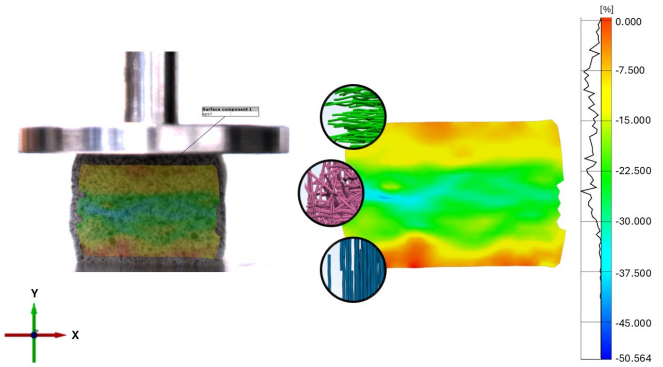


Fig. 4. DIC image at t = 60 s showing the distribution of ε_y in the multilayered sample. The DIC analysis clearly reveals the stratification ad highlights the different behavior of the layers, resulting from the distinct orientations of the embedded fibers. From top to bottom: superficial layer, middle layer and deep layer.

IV. Discussion

Several studies have shown that the compressive (confined/aggregate) modulus increases markedly from the superficial zone toward the deep zone [30], with superficial values typically on the order of 10^{-2}–10^{-1} MPa and substantially larger values in deeper zones depending on species and test mode [31], [32].

Although many literature reports show higher modulus values, there are several studies whose values are more comparable to those observed in our constructs. For example, [31] (bovine cartilage, superficial layer) report a compressive modulus of 0.079 ± 0.039 MPa for the superficial zone; similarly, indentation measurements in human femoral cartilage show values as low as 0.020 ± 0.003 MPa for the superficial zone [33]. Moreover, in immature bovine tissue, the superficial zone equilibrium modulus has been measured at 0.240 ± 0.050 MPa [34], very close to our middle- or deep-layer values.

Our multilayered constructs reproduced the depth-dependent mechanical trends widely reported for native articular cartilage [30]–[32]. In our samples the compressive modulus progresses from 0.12 MPa (superficial) to 0.24 MPa (deep), with the multilayered construct achieving 0.26 MPa — a pattern consistent with depth-dependent stiffening observed in cartilage (Table II). Full-field measurements and micromechanical tests in the literature attribute this behavior to gradients in collagen architecture and proteoglycan content that control fluid pressurization and matrix stiffness; similarly, we interpret our depth-wise stiffness increase as an effect of the layer-specific fiber architecture implemented in the Synthetic Twin [35], [36].

Depth- and rate-dependence of Poisson's ratio in cartilage has been documented (with ν varying by zone and loading regime), and optical/indentation studies report higher lateral expansion in deeper zones under unconfined compression [37], [38]. Our experimental ν values (Table I) follow the same trend, supporting the claim that microstructural layering (fiber orientation and density) can reproduce not only axial stiffness gradients but also the lateral deformation behavior that characterizes native cartilage.

TABLE II
Literature ranges for depth-dependent cartilage properties [31], [32].

Layer	E_y **[MPa]**	ν_{xy}
Superficial layer	0.05–0.2	0.1–0.3
Middle layer	0.1–0.4	0.2–0.4
Deep layer	0.3–1.0	0.3–0.5

Together, these comparisons indicate that microstructural engineering — here realized by layer-wise fiber encapsulation and orientation — is an effective route to reproduce physiologically relevant, depth-dependent mechanics in synthetic twins. Such agreement with the literature strengthens the validity of using layered, 3D printed constructs as physical counterparts to digital models for biomechanical testing and clinical validation.

V. Conclusions

We introduce the Synthetic Twin, a new paradigm for creating sustainable, tunable 3D printed tissue analogs that replicate both the structure and mechanics of native tissues. Using cartilage as a case study, we demonstrated how fiber orientation and layering can generate physiologically relevant stiffness and Poisson's ratio, with multilayered constructs achieving the closest approximation to native tissue stratification.

Future work will expand the framework to other tissues, leveraging microstructural tuning strategies such as porosity modulation, gradient layering, and fiber density control. Integration with digital twins will enable hybrid physical-digital ecosystems for diagnostics, surgical planning, and medical training. Ultimately, Synthetic Twins open a new pathway toward sustainable, reproducible, and personalized healthcare models, bridging the gap between computational prediction and physical experimentation.

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Generalizable and Sustainable Feature Selection for Medical Imaging: A Case Study in Knee Osteoarthritis

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***Abstract*—The growing use of machine learning in healthcare raises concerns about computational cost and environmental sustainability, particularly when working with high-dimensional datasets. In this work, we investigate the optimization of a scalable ensemble feature selection strategy for knee osteoarthritis classification using radiomic data from cartilages segmented on MRI. We explored threshold tuning to balance the trade-off between dimensionality reduction and predictive accuracy in a two-stage ensemble feature selection pipeline. Results show that models trained on optimized subsets of features achieve comparable or superior F1-scores to models trained on the full feature set, while requiring significantly fewer features. The performance increase compared to the full set is almost 20%, using only 4% of the features from the original dataset. Moreover, only 29 radiomic features have been demonstrated to be sufficient for distinguishing between healthy and degenerative knees. These findings demonstrate how sustainable feature selection can enhance technological efficiency and promote generalizable solutions in healthcare AI.**

***Index Terms*—feature selection, artificial intelligence, explainable AI, radiomics, osteoarthritis**

I. Introduction

The rapid growth of machine learning has led to transformative advances across domains, enabling increasingly accurate models, large-scale automated analyses, and data-driven decision-support tools that continue to push the boundaries of what technology can achieve. However, these advances come at a significant cost: the environmental and social impacts associated with training and deploying increasingly large-scale models. As demand for computational resources increases, so does the energy consumption of machine learning systems, raising concerns about the sustainability of the industry. Addressing these challenges requires not only technical innovation but also a broader rethinking of how efficiency, equity, and long-term environmental impact are incorporated into the design and evaluation of models [2]. In this context, interpretable models not only enhance transparency and trust but also support more sustainable choices by enabling practitioners to balance accuracy with efficiency and resource awareness [3].

This balance is particularly critical in healthcare, where interpretable models can guide sustainable decision-making in data-intensive applications. To address the dataset size and complexity demand, interpretable models that incorporate effective feature selection can help identify the most relevant variables, reduce redundancy, and minimize resource use, ultimately fostering more sustainable machine learning practices while supporting clinically meaningful insights [4].

Knee osteoarthritis (OA) is a widespread disease causing pain and physical disability in approximately 4% of the older adults [5]. The joint deterioration might cause joint stiffness, gait disturbances, and functional limitations [6] that can limit normal daily activities. Knee OA is usually assessed with the Kellgren-Lawrence (KL) and/or Ahlbäck grading systems [7], [8]. However, these metrics rely on visual inspection of X-ray and might therefore suffer from subjectivity and even miss early structural changes in knee-related tissues [9], [10].

For this reason, the use of AI tools for automatic diagnosis of OA is indisputable [11]. OA binary classification can be performed using deep learning tools, such as U-Net, on MRI images, yielding outstanding results. [12]. Even using less complex approaches, such as convolutional neural networks [13], helps in classifying OA; yet, this comes at the cost of accuracy. These tools are usually black boxes, and they do not provide an explanation for the decisions they make. Some approaches employ post-explainability techniques to highlight

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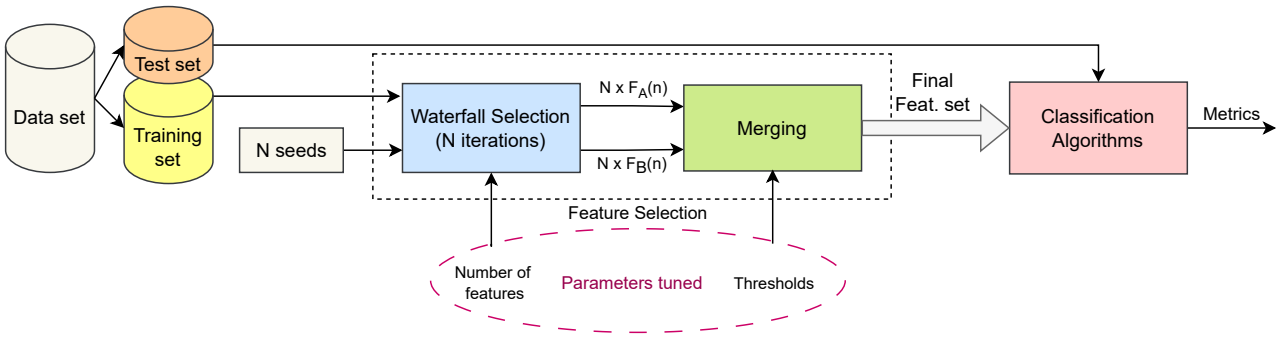


Fig. 1: Workflow adapted from [1], ©*Elsevier 2025*

what the network is doing [14] and make it clearer for humans to understand.

However, algorithms with an explainable nature, rather than relying on posterior analysis, should be preferred due to their implicit simplicity, faster training, and energetic and societal sustainability. To tackle this problem, explainable AI models (XAI) are getting widespread applications. XAI is typically applied to extract features and rank them [15]; in fact, feature selection approaches are used to evaluate the impact of features, focusing only on the most important ones. Nevertheless, the sustainability of a feature selection strategy is dependent on the computational efficiency of the feature selection algorithm itself. Optimizing the strategy is crucial for achieving faster results and lower consumption.

In this study, we investigate the impact of parameters on a feature selection strategy utilizing MRI radiomics data for OA classification.

II. Materials & Methods

A. Data and feature extraction

The dataset for this study is composed of 133 knee MRI images collected during two EU projects, RESTORE (https://restoreproject.eu/) and SINPAIN (https://www.osteoarthritis-sinpain.eu/). These projects aim to develop new solutions and therapies for the repair of knee OA cartilage. The images are from individuals with a diagnosis of OA and healthy volunteers, totaling 133 legs. The dataset is composed of 60.1% controls (n=80, C) and 39.9% degenerative (n=53, D), with an average age of 36.31 ± 13.98 for C subjects, and 61.7 ± 10.11 for patients D. The legs are considered independent from each other.

From MRI images, femoral, lateral tibial, medial tibial, and patellar cartilages were manually segmented through a validated workflow described by Ciliberti et al. and Aubonnet et al. [16], [17] using medical software MIMICS (Materialise Interactive Medical Image Control System, Materialise, Belgium).

From these segmented cartilages, radiomic features were extracted using the PyRadiomics library [18] for a total of 3368 features, 842 per cartilage. Radiomic features can reveal subtle patterns invisible to the naked eye by capturing the spatial relationships within tissues. The extracted features fall into several categories: first-order statistics, which describe the distribution of voxel intensities within the region of interest (e.g., mean, variance, skewness, kurtosis); shape-based features, which characterize the 2D and 3D geometry of anatomical structures (e.g., volume, surface area, compactness, sphericity); and texture features, which quantify the spatial arrangement of voxels through gray-level matrices such as the gray-level co-occurrence matrix (GLCM), gray-level run-length matrix (GLRLM), and gray-level size-zone matrix (GLSZM). Additionally, wavelet and filter-based features are derived by decomposing images into frequency components. This allows for the capture of some subtle patterns (such as small textures, faint edges, and local changes in intensity) that are undetectable from the raw image. The predictive power of these features on the same cartilage-related regions has been proved in several studies [19], [20].

After the extraction, as proposed by Angelone et al. [19], only features with a correlation coefficient smaller than 0.8 were retained, resulting in a reduced feature set of 581.

B. Feature Selection Strategy

The feature selection approach proposed by Maruotto et al. in [1] is a scalable ensemble method that integrates multiple strategies to ensure both dimensionality reduction and clinical interpretability; however, it involves setting thresholds that need to be specified. It works in two stages: waterfall selection and merging strategy. The first stage produces two feature sets: F_A and F_B. Both stages are repeated 50 times with different seeds.

F_A uses a tree-based model (Gradient Boosting) with L1 (LASSO) regularization to rank and filter features, discarding those below a set importance threshold (10^{-5}). The output is capped at a maximum of 50 features per iteration to balance accuracy, computational time, and clinician usability. This is the first threshold we want to exploit: what happens if we move the threshold from a fixed number to a relative one with respect to the original dataset dimensionality. To obtain F_B, then we apply a Backward Sequential Feature Selection (greedy elimination) on the reduced set from F_A, ensuring that model performance does not decrease by more than 1% at each

iteration, and it is run with 5-fold cross-validation (CV) for robustness.

To enhance stability, the pipeline is repeated 50 times with different random seeds, generating multiple subsets of features. These sets are merged through three strategies:

- Repetition (F_R): keeps features that recur across at least 75% of executions.
- Performance (F_P): keeps features that preserve performance during backward elimination.
- Weighted (F_W): retains the top 75% of features ranked by cumulative importance weights.

The final feature set F is the intersection of F_R, F_P, and F_W, ensuring that only features consistently important, stable, and performance-preserving are retained.

C. Optimization and evaluation metrics

Starting from the feature selection, as shown in Fig. 1, modifications occur in the core blocks of the system: waterfall selection and merging. The optimization of the feature selection focuses on two thresholds: the number of parameters in the waterfall feature selection and the percentiles in the merging part.

The effectiveness of the waterfall feature selection is influenced by the choice of the number of features to retain in the initial stage. We have tested four different parameters: 5%, 10%, 20%, and 35%, corresponding to: 29, 58, 116, 203 maximum features in the case of analysis. Once F_A and F_B are obtained, the merging strategy may differ. There are two percentiles to tune that change the number of features retained in the final set, allowing for F_W and F_R. In this case, an extensive analysis was conducted. We evaluated cross-validation performance by incrementing the threshold from 0 to 100 in steps of 1, using a Support Vector Machine (SVM) with a linear kernel, on each single set. From the trend of the mean CV F1 score, the maximum performative threshold is extracted, and the new subsets F'_W and F'_R are merged with F_P to obtain the final feature set F.

The SVM [21] with a linear kernel is a supervised learning algorithm designed for classification tasks, particularly effective when data are linearly separable or can be well-approximated by a linear boundary. The model works by finding the optimal hyperplane that maximizes the margin between classes, where the margin is defined as the distance between the hyperplane and the closest data points, known as support vectors. Unlike nonlinear kernels, the linear kernel computes the decision boundary directly in the original feature space without transforming the data into higher dimensions, making it computationally efficient for high-dimensional datasets such as those often encountered in healthcare. No SVM hyperparameter tuning was performed, as the aim of this study is to compare feature sets under identical experimental conditions. For this reason, the C parameter of the linear SVM was fixed at 1.

To guarantee the validity of the results, the training of each percentile variation has been done using a 5-fold CV, and a 20% test set was kept out.

	RF	**SVM**	**Features**
Baseline	0.75 ± 0.19	0.85 ± 0.08	581
5%	0.86 ± 0.09	0.96 ± 0.04	92
10%	0.85 ± 0.10	0.95 ± 0.04	107
20%	0.85 ± 0.10	0.95 ± 0.04	107
35%	0.86 ± 0.09	0.95 ± 0.04	107

TABLE I: CV F1 score and number of features used

	SVM	**Features**
5%	0.96 ± 0.03	29
10%	0.95 ± 0.04	42
20%	0.95 ± 0.04	42
35%	0.95 ± 0.04	42

TABLE II: Optimized sets CV F1 score and number of selected features in the final set

In healthcare machine learning applications [22], particularly in diagnostic or predictive tasks, the F1 score is often preferred over accuracy or other individual metrics as an evaluation metric because it balances precision and recall. Accuracy alone can be misleading in clinical contexts where datasets are imbalanced. Precision measures how many of the predicted positive cases are truly positive, while recall measures how many actual positive cases were correctly identified. The F1 score combines both into a single harmonic mean, ensuring that both false positives and false negatives are given equal weight. This balance is critical in healthcare, where missing a true case (low recall) could delay treatment, and misclassifying a healthy patient as diseased (low precision) could lead to unnecessary interventions. Thus, the F1 score provides a more reliable measure of model performance when both types of errors carry significant clinical consequences. We analyzed the mean and standard deviation (SD) across the 5-fold CV.

III. Results & Discussion

The methodological choices made in this study have implications for the resource-efficient selection of healthcare features. By identifying only the most predictive and clinically relevant radiomic descriptors, the dimensionality of the dataset can be substantially reduced, which in turn minimizes computational demand, lowers energy consumption during model training, and facilitates the integration of predictive tools into clinical workflows. This also suggests that future pipelines may not require the extraction of thousands of radiomic features; instead, computing only this small, high-value subset could provide an efficient and sustainable alternative for predicting disease outcomes.

The core idea behind the method is that not all radiomic features contribute equally to classification performance. By progressively filtering features, the pipeline isolates those descriptors that consistently carry the strongest predictive signal. Optimizing the thresholds that govern these steps improves both feature stability and computational efficiency, leading to smaller yet highly informative feature subsets.

The imbalance between the number of samples and the large feature space naturally raises concerns about sample adequacy and the potential risk of overfitting. In such high-dimensional

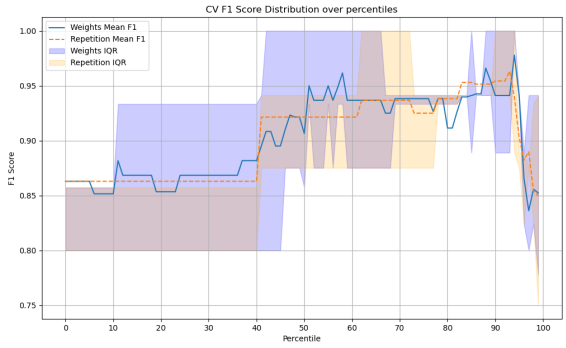


Fig. 2: F1 score trend when tuning features from 5% selection

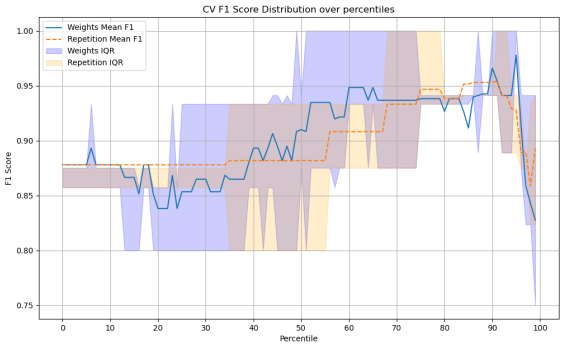


Fig. 3: F1 score trend when tuning features from 20% selection

settings, small variations in the data can strongly influence feature selection and model behavior. To mitigate this limitation, we employed 50 different random seeds and a validated feature selection approach, allowing the models to be trained and evaluated across multiple resampled configurations. This strategy increases the robustness of the results by reducing dependence on any single data split and provides a more reliable estimate of feature stability and model performance despite the limited sample size.

As reported by Maruotto et al. [1], the base algorithm tuned in this study requires an average of 437 seconds per fold on a 1.4 GHz Intel Core i5 quad-core, resulting in approximately six hours of computation to obtain the final feature set. Although this process is energy-intensive, the cost is incurred only once, thanks to a reliable feature selection approach. In this case, the resulting reduced feature set can be reused across analyses, offering a substantial long-term energy advantage compared with approaches that require repeated full-scale feature selection.

CV performances are comparable to test set performance; therefore, only CVs are preferred for reporting. Indeed, given the confirmation of generalizability provided by the test results, CV scores can provide more nuanced information and allow the assessment of stability across seeds.

Table I presents the mean performance of the pipeline when varying the percentage of features retained during the waterfall selection stage, compared against a baseline SVM model trained on the full feature set. The reported number of features is the dimensionality of the feature set at the end of the feature selection pipeline. For example, although the 10% configuration limits the size of $F_A(n)$ to 29 features, the complete selection process ultimately yields 107 features, which are then used to train the RF and SVM models during cross-validation and produce the reported performance values.

The results indicate that applying feature selection enables the model to concentrate on the most informative features, enhancing its ability to distinguish between C and D cases. As such, the performance across the reduced feature sets remains comparable, as does the number of features retained. In other words, the model's discriminative power does not depend on the volume of variables but rather on the stability and quality of the subset.

Despite this, perhaps due to the nature of the dataset and the information content, three of the feature selection methods retain the exact same number of features. But we can state that many more features could be removed; indeed, the best performative set is the smallest one. Additionally, it is worth noting that, in every seed iteration n, the number of features selected in $F_A(n)$ is always 29 when executing the 5% selection across seeds, but it varies in the other cases. For example, in one seed iteration, the selected feature number in $F_A(n)$ is 49, even though the most strict selection capped the number at 58, within the 10% allowance. This can explain why the final performances and feature set are so similar, even though they are not equal. This tuning is, in fact, already improving the feature selection strategy compared to the state-of-the-art [1], where the retained number of features was 237 with the same performance increase.

Moreover, this work also focuses on the analysis of merging parameters. As an example, Fig. 2 shows the trend of the mean F1 score when tuning the percentile of features retained from a 5% selection. It also displays the interquartile range (IQR) for every point; these values (mean and IQR) are calculated using 250 values corresponding to the same 5-folds across 50 different seed executions. Instead, Fig. 3 is showing the same plot for features tuned from a 20% selection. In both figures, the trend shows an increase in performance with the reduction in feature number, followed by a sudden drop after reaching the maximum F1 score. This is because the very important features are retained up to that point, after which discarding them results in a loss of performance. Additionally, the IQR is higher with a larger number of features, as different iterations and initializations can significantly influence the ability to discriminate. Instead, as it approaches the maximum, the IQR also begins to collapse towards the mean, demonstrating a more robust performance and indicating that only the most important features are retained. In both cases, the F1 score increases as less informative features are removed, reaching a peak when only the most relevant descriptors remain; performance then drops sharply once key predictive features are

discarded.

Since we were analyzing only one set at a time, we can merge them using the proposed approach, which involves a total agreement between the sets. This means that only the features considered important in all three sets F'_W, F'_R, and F_P are retained, effectively containing at maximum the same features of the smallest set among these. The final performances, after the merging stage and further tuning of the parameters, are reported in Table II. The optimized sets contain fewer features than the non-optimized ones, i.e., in the 10% case, there are only 42, and CV performances reach higher values with lower SD.

Compared to literature work, Angelone et al. [19] obtain 87.66 ± 3.3 F1 score using 50 features, while our methodology yielded improved classification performance and a reduced feature set.

This study also highlights the potential of using only 29 radiomic features extracted from cartilages segmented on MRI to effectively distinguish between healthy and degenerative individuals. Notably, these 29 descriptors correspond to less than 4% of the initial radiomic space, indicating that high predictive performance can be achieved with a very compact and stable feature subset. This points toward a minimal radiomic signature for knee degeneration that supports more efficient computation and clearer clinical interpretability.

IV. Conclusions

This work introduced an optimized feature selection pipeline for knee OA classification from MRI radiomics, focusing on both methodological performance and sustainability. By tuning parameters in the selection and merging stages, we demonstrated that models trained on curated subsets of features can achieve superior performance compared to those trained on the full dataset, while requiring significantly fewer features.

These findings underline two important outcomes. First, feature selection not only reduces dimensionality but also enhances stability and interpretability, making the models more clinically meaningful. Second, optimizing toward smaller, high-quality feature sets directly supports sustainable machine learning practices. We also showed that only 29 radiomic features are sufficient to distinguish between healthy and degenerative knee cartilages with a high F1-score. This marks how efficient, interpretable, and resource-conscious approaches can accelerate the integration of AI tools into healthcare without compromising clinical value. In this way, we move toward a sustainable paradigm in healthcare AI, where methodological efficiency directly supports clinical and societal impact.

Overall, our results demonstrate that efficient and interpretable feature selection can outperform high-dimensional models while utilizing only a fraction of the original data, thereby supporting both methodological performance and long-term sustainability in healthcare AI.

Future work could aim to strengthen the statistical reliability of the feature selection evaluation by analyzing significance testing and incorporating it in the selection approach.

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A Transfer Learning Approach for Detecting Buds of Posterior Teeth

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***Abstract*—Artificial Intelligence-based medical image analysis represents a critical step towards more sustainable and prevention-oriented diagnosis and healthcare. Early and accurate identification of dental anomalies in pediatric patients is an underexplored field of study, despite dental pathologies being one of the most costly medical conditions in the world. This study proposes a transfer learning approach for automatic detection of first and second premolar tooth buds on pediatric panoramic radiographs, through a YOLOv8 architecture, optimized on a labeled dataset of 619 images. Evaluation metrics such as mean Average Precision (mAP@50 = 0.984), Dice coefficient (0.847), and Structural Similarity Index Metric (SSIM = 0.947) demonstrate the effectiveness of the proposed method. However, the model performance decreases with more stringent localization criteria (mAP@50-95 = 0.610) and is sensitive to image quality, with degraded radiographs negatively impacting the detection accuracy. These limitations highlight the importance of high-quality image acquisition and suggest the need for further studies to improve generalization across different clinical acquisition conditions. Despite these challenges, the results suggest that the model could represent a first step in an automated early diagnosis and treatment planning pipeline.**

***Index Terms*—Pediatric dentistry, Orthopantograms, YOLOv8, Transfer learning**

I. Introduction

The rapid progress of artificial intelligence (AI) in the analysis of medical images for the development of automated diagnostic systems is reshaping healthcare models towards more sustainable, intelligent and prevention-oriented approaches [1]–[4]. In particular, it is noted that dental diseases affect approximately half of the world's population, with a significant prevalence across all age groups. The total economic burden, both direct and indirect, attributed to dental diseases was estimated at 544.41 billion dollars in 2015, ranking sixth among the most expensive diseases worldwide [5]. Therefore, the development of early and more sustainable diagnosis systems in this healthcare context is essential. In recent decades, the dental system has undergone significant digitalization, and numerous studies have focused on developing advanced image analysis techniques to enhance traditional diagnosis [6], [7] or to develop new diagnostic approaches based on intraoral photographic images [8], [9]. In the diagnosis of dental anomalies, Orthopantomograms (OPGs) are commonly used in clinical practice, especially for the evaluation of dental anomalies. This exam allows the visualization of all the hard tissues of the oral cavity and the skeletal structures. Precisely because of the simultaneous evaluation of many bone and dental structures, the analysis of these images is challenging and AI can be a valid support tool for diagnosis, avoiding waste of resources and time [10]–[12]. In recent years, several studies have explored the use of AI in the interpretation of OPGs for diagnostic purposes [13]–[17]. One of the most common applications is the detection and classification of dental caries, periodontal disease, and impacted teeth using convolutional neural networks (CNNs) [18], [19]. For example, Choi et al. [12] proposed a deep learning system capable of automatically detecting and classifying impacted mandibular third molars with high accuracy. Similarly, Hirunchavarod et al. [11] implemented an AI model to identify missing and supernumerary teeth, demonstrating the potential of CNNs to support comprehensive dental assessments.

Another promising direction involves the segmentation of anatomical structures within the panoramic image. This includes tooth segmentation, mandibular canal localization, and bone loss estimation, which are crucial for implant planning and periodontal diagnosis. Jundaeng et al. [20] have proposed an AI pipeline that segments individual teeth and measures bone levels to assess periodontal conditions. These tools show potential to improve diagnostic accuracy, reduce clinician workload, and facilitate large-scale dental screenings.

Despite these advances, the automatic identification of developing structures, such as tooth buds, in pediatric OPG images remains unexplored [21]. Most current models focus on the adult dentition and are not optimized for the complex variability observed in growing patients. Furthermore, the lack of annotated datasets for early dental development presents an additional challenge. These gaps highlight the need for targeted studies addressing the developmental aspects of dentition, particularly in pediatric populations, where timely intervention is essential. OPGs are particularly useful in diagnosing dentition development, allowing for the assessment of abnormalities at the time of eruption, which, if identified early, can improve treatment. In particular, second premolar bud formation is often delayed [22], and early assessment with automated image analysis techniques can represent an important step in defining therapeutic approaches that may vary based on several factors, such as the condition of the overlying primary molar: in some cases, the primary tooth must be extracted early, while in others, it must be preserved [23], [24]. Early diagnosis of delayed or abnormal bud development can help prevent complications such as impaction, ectopic eruption, or resorption of adjacent teeth. Therefore, a targeted system for automated tooth bud detection could represent a valuable clinical tool to support personalized treatment plans in pediatric patients. In particular, in this study the aim is to apply a Transfer Learning approach for the automatic identification of the first and second premolar tooth buds, both lower and upper, in pediatric patients. The second premolar is the tooth where most developmental disorders occur, causing damage also to the first molar. The formation of the second premolar buds is often delayed justifying the need for an automatic and early identification of these structures [25], [26]. In previous studies, a metric analysis of pantograph radiographs designed to predict the development of the second premolar has been attempted [27]. The paper presents a method to estimate the position of the second premolar bud based on tooth–bone indicators of other teeth to train neural models. However, automatic identification of tooth buds is still a little-explored task. This study, therefore, fills an important gap in the literature, aiming to expand the boundaries of artificial intelligence in pediatric dentistry. The integration of deep learning in this field could mark the beginning of a new era in which early-stage dental assessments will be increasingly precise, data-driven, and accessible.

II. Methods

A. Dataset

The dataset used for the present study was obtained from the Department of Oral and Maxillofacial Radiology at Isfahan University of Medical Sciences, Iran. This study was approved by the ethics committee of the School of Dentistry, Health Sciences and Advanced Medical Technologies of Isfahan University of Medical Sciences, and informed consent was waived by the ethics committee. This study includes pediatric panoramic radiographs acquired between January 2020 and December 2024 for participants aged 6 to 12 years, information for which is summarized in Table I. Images were obtained using two radiographic devices: Promax (Planmeca, Helsinki, Finland) and Papaya (Genoray, Gyeonggi-do, Korea), reflecting the instrumental variability typical of clinical practice, with different exposure settings. These parameters directly influence the image quality and the delivered radiation dose. In particular, a difference in the milliamperage (mA) and

exposure time values is observed, with Promax using a higher current (6.3 mA compared to 5 mA for Papaya) and a longer exposure time (15.8 s versus 12 s). The dataset comprises 619 intraoral panoramic radiographs, saved in JPEG format, with a resolution of 2200 × 1100 pixels. Two experienced radiologists labeled the buds of the permanent premolar teeth 4 and 5 (UR4, UR5, UL4, UL5, LL4, LL5, LR4, LR5) using the Labelme tool, resulting in a total of eight distinct classes. Here, U and L denote the upper and lower arches, respectively, while the second letter (R or L) indicates the right or left side. Not all images contain all eight classes: variations in developmental stage affect the visibility of the tooth bud, resulting in a heterogeneous but overall balanced class distribution in the dataset. In addition to the image files, the dataset includes corresponding annotation files in JSON format, which provide detailed information on the segmentation and classification of the dental elements of interest.

TABLE I: Subject informations

	TOT	Male	Female
Number of subjects	619	272	347
Age (avg ± std)	5.61 ± 0.69	5.73 ± 0.57	5.52 ± 0.76

B. Network architecture and implementation

In this study, a YOLOv8 (You Only Look Once, version 8) architecture, an object detection approach presented by Redmon et al. [28], was used to evaluate dental buds identification. The transfer learning approach was applied using a YOLOv8 model pre-trained on the COCO dataset. This model was then fine-tuned for the specific task of identifying and classifying buds of premolar teeth (UR4, UR5, UL4, UL5, LL4, LL5, LR4, LR5). This architecture treats object detection as a regression problem to spatially separated bounding boxes and their class probabilities, and the network can be optimized end-to-end directly on the detection performance. This architecture thus ensures an optimal trade-off between accuracy and computation speed. This one-stage model integrates an optimized architecture based on Cross Stage Partial Networks (CSP) to improve the efficiency of feature extraction, especially CSPDarknet, reducing information redundancy and preserving high generalization ability. In addition, its multi-scale structure enables adequate detection of small objects, which is essential for tooth bud identification in pediatric intraoral X-ray images. During training, the YOLOv8 model optimizes a composite loss function, which takes into account three main objectives: a Bounding Box Loss through a GIoU (Generalized Intersection over Union Loss), an Objectness Loss through a Binary Cross Entropy (BCE) between the probability of an object and the target value, and a Classification Loss through a Focal Loss. The dataset was split into training, validation, and test in a ratio of 7:2:1. 60 epochs and a batch size of 16 were used for training.

C. Evaluation metrics

To evaluate the performance of the trained YOLOv8 model, several metrics were adopted that allow for evaluating both the precision in object localization and the accuracy in classification. In particular, the Intersection over Union (IoU) was evaluated, which measures how much the predicted bounding box overlaps with the ground truth, and the mean Average Precision (mAP) was calculated as the average of all the Average Precision (AP) calculated for each class. The AP represents the area under the Precision–Recall curve. The mAP can be evaluated as mAP@50, i.e., the average of the APs calculated with IoU threshold $\geq$ 0.5, offering a more permissive evaluation, and as mAP@50-95, i.e., the average of the APs calculated on 10 IoU thresholds from 0.5 to 0.95, offering a more rigorous evaluation. These metrics evaluate the ability of the model to correctly localize and classify. Subsequently, in the context of qualitative image analysis, the Dice Coefficient and the Structural Similarity Index (SSIM) were also calculated. To provide a probabilistic interpretation of these results, the probability density function (PDF) was analyzed for the Dice, IoU, and SSIM metrics, offering insight into their distribution and variability across the dataset.

III. Results and Discussion

In this section, the results of the evaluation of the model on the independent test set are reported. The Fig. 1 shows a visual example of tooth bud detection in one of the best cases.

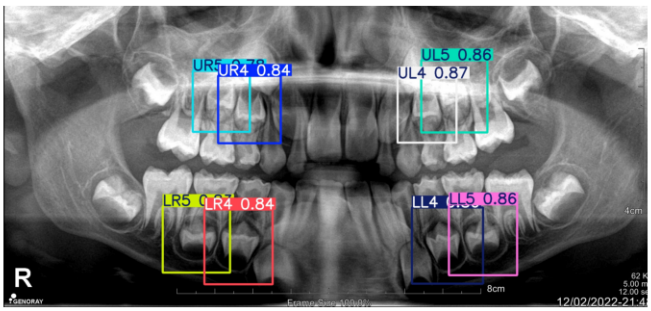


Fig. 1: Visual example of tooth bud detection in one of the best cases.

Table II shows encouraging and consistent performances for all the dental classes to be identified. In particular, Precision and Recall are both higher than 0.93 for each class, a result that demonstrates a clear distinction between correctly detected objects and false positives or negatives. The Precision close to 1 indicates a low incidence of type I errors (false positives), while the high Recall confirms the ability of the network to detect most of the real objects, with a low rate of false negatives. For the UL4 and UL5 classes, we have a precision that reaches values equal to 1.000, confirming a particularly effective learning for these categories. The best performances in terms of AP@50 were obtained by the UL5 (0.994), UL4 (0.993), and LR5 (0.992) classes, demonstrating a high accuracy in the positioning of the bounding box with a standard tolerance of 0.5 for the IoU. As for AP@50-95, which represents a more stringent metric as it evaluates the model performance on 10 increasing IoU thresholds from 0.5 to 0.95, significant values are still observed, above 0.57 in each class.

The LR4 class excels in this metric with a value of 0.666, suggesting that the model has learned not only to correctly detect but also to precisely position the bounding boxes even in more restrictive conditions. The Precision-Recall curve shown in Fig. 2 confirms what has already been observed. In particular, the thick blue curve represents the average of the performances on all the classes. The value mAP@50 = 0.984 indicates an excellent overall ability of the model to correctly detect the teeth and locate them reliably. The individual curves of the classes also show a high precision maintained even for high levels of recall, confirming the excellent balance between sensitivity and specificity of the model. Finally, for a global evaluation, Fig. 3 shows the distribution of similarity metrics between predictions and ground truths, evaluating IoU, Dice index and SSIM. The distribution of IoU is concentrated between 0.7 and 0.9, with an average of 0.768, indicating that on average over 76% of the area of the predicted bounding boxes is correctly overlapped with the real one. With an average of 0.847, the Dice score reflects a strong spatial overlap between prediction and ground truth. This metric penalizes marginal differences less than IoU, and is often preferred in the medical field for its ability to reflect the overall quality of identification. For SSIM, an average value of 0.947 indicates a high structural coherence between annotated images and predictions, suggesting that the network not only correctly identifies the position of the teeth, but also maintains fidelity in shape and visual details. The high performance per class, while maintaining high stability between classes, suggests that the fine-tuning process has led to a model that generalizes effectively, even in the presence of inter- and intra-class variability. However, it is observed that the mAP@50-95 of 0.610 is significantly lower than the mAP@50 of 0.984, suggesting that the model identifies the objects well, but does not localize them with great precision. A significant strength of this study is the model's ability to maintain high performance despite the variability in radiological equipment used for image acquisition. This heterogeneity more closely reflects real-world clinical practice conditions and enhances the system's generalizability and potential applicability across diverse healthcare settings.

TABLE II: Evaluation metrics per classes (Precision, Recall, AP@50, AP@50-95)

Class	Precision	Recall	AP@50	AP@50–95
UR4	0.934	0.937	0.956	0.570
UR5	0.961	0.952	0.983	0.578
UL4	1.000	0.960	0.993	0.615
UL5	1.000	0.957	0.994	0.602
LL4	0.990	0.952	0.986	0.617
LL5	0.993	0.952	0.986	0.581
LR4	0.968	0.961	0.981	0.666
LR5	0.983	0.943	0.992	0.653

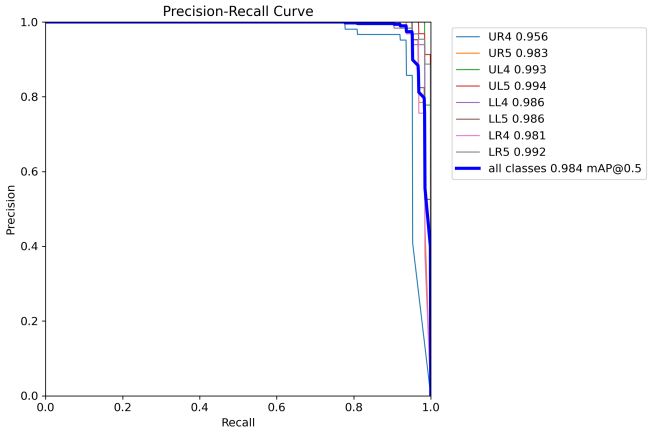


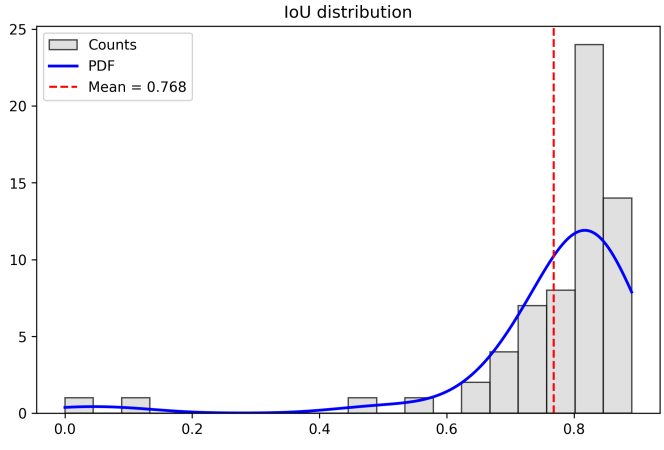
Fig. 2: Precision-Recall curve for each class. The curve shows the trade-off between precision and recall as the confidence threshold varies. A high area under the curve (AP) indicates good performance in distinguishing between correctly and incorrectly detected teeth.

IV. Conclusion

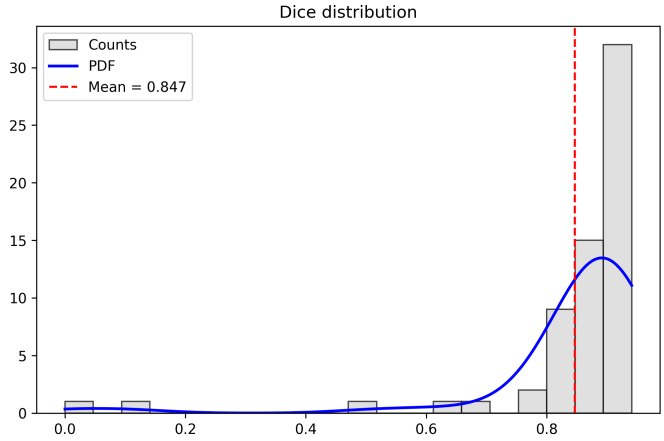
In conclusion, although the results are still preliminary, they represent a significant step toward integrating AI-based tools into pediatric dental diagnostics. This study demonstrates the potential of transfer learning techniques in pediatric dentistry, applying a YOLOv8 architecture to detect first and second premolar buds in panoramic radiographs, with encouraging results. Both class analysis and global image quality analysis showed good results, with an overall mAP@50 of 0.984, precision and recall above 0.93 in all classes, an IoU of 0.77 ± 0.09, a Dice of 0.85 ± 0.16 and a SSIM of 0.95 ± 0.01, confirming its reliability in detecting and classifying dental structures in pediatric patients. However, although the model performed well with an IoU threshold of 0.5, its accuracy decreased with more stringent localization criteria (mAP@50–95 = 0.610), suggesting the need to refine the spatial accuracy.

Beyond technical accuracy, the proposed method offers promising contributions in terms of care sustainability: early and automated identification of developing dental anomalies can reduce the need for repeat examinations, improve diagnostic efficiency, and support more targeted and timely interventions. This fits seamlessly with the broader goal of transitioning to preventive, patient-centered, and resource-efficient healthcare models.

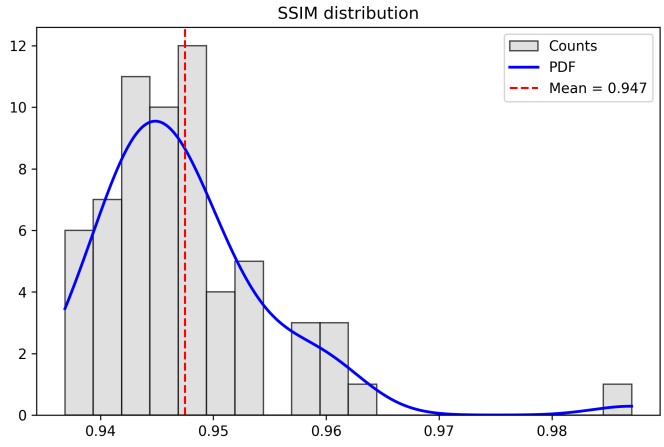
For future developments, it will be crucial to improve the model's robustness to suboptimal image quality, which is common in daily clinical practice. Furthermore, the introduction of explainable mechanisms (model interpretability) will be crucial for increasing healthcare professionals' trust, facilitating integration into clinical workflows, and ensuring the ethical and transparent use of AI.



(a) IoU



(b) Dice



(c) SSIM

Fig. 3: Distribution of metrics on the test set: (a) IoU, (b) Dice, and (c) SSIM. The red dashed line represents the mean. The blue line represents the Probability Density Function (PDF).

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Electromyographic Signatures of Postural Control: Insights into Gender Differences

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***Abstract*—Postural control (PC) ensures balance and body orientation through the integration of multisensory inputs and adaptive neuromuscular responses. Electromyography (EMG) is a key tool for investigating these mechanisms, providing insights into muscle activation patterns and strategies adopted to maintain stability. In this study, EMG signals were recorded from six calf muscles during a postural control task consisting of four experimental phases in a virtual reality environment: three static conditions (BASE, PRE, and POST) and one dynamic phase (MOV), characterised by mechanically induced perturbations generated by platform movement. Features extracted from EMG signals were analyzed to identify significant differences between gender and to determine which muscles, parameters and phase contributed most to group discrimination. Statistical and machine learning analyses consistently indicated that muscle activity patterns during postural tasks can discriminate between males and females, particularly under dynamic perturbation conditions. The soleus and tibialis anterior muscles contributed most consistently to gender discrimination, confirming their crucial role in maintaining balance and compensating for perturbations. The results aim to enhance understanding of the neuromuscular strategies underlying PC and to provide a quantitative basis for the development of intelligent and sustainable diagnostic tools for neuromuscular assessment and predictive health.**

***Index Terms*—Postural control, EMG, sustainable health, machine learning, feature selection.**

I. Introduction

The postural control (PC) system maintains balance and orientation of body segments, relying on reference values, multisensory inputs, flexible reactions, and adaptive responses for balance recovery and voluntary movement. Electromyography (EMG) is a powerful tool for studying PC, offering insights into how muscles coordinate to maintain balance and adapt to challenges [1]. Gender differences in PC have been reported across various age groups and conditions, with women often demonstrating superior balance control [2]. Ageing and clinical conditions, such as low back pain or muscle tone disorders, alter these activation patterns, often increasing coactivation or shifting cortical representations, which can compensate for or contribute to postural deficits [3]–[5]. EMG research consistently indicates that men and women show differences in muscle activation patterns, frequency characteristics, and fatigue responses. In repetitive tasks, women's endurance is predicted by higher initial EMG variability, while men's is linked to lower mutual information between muscle pairs, suggesting different fatigue mechanisms [6]. Women may employ different neuromuscular strategies, such as a greater reliance on thigh muscles versus gluteal muscles during certain movements [7], [8]. However, these variations depend on the specific muscle being studied and the nature of the task, rather than representing a general rule across all conditions. In this context, analyzing features extracted from EMG signals can offer a valuable perspective on whether and to what extent muscle activation patterns differ between men and women during PC. The application of feature selection techniques also makes it possible to identify which signal parameters contribute most to interindividual variability, thereby isolating the most informative features. In the present study, we analysed EMG signals acquired from six muscles during a PC task comprising four experimental phases: three static conditions (BASE, PRE and POST) and one dynamic phase (MOV), corresponding respectively to moments of quiet and mechanically induced perturbations resulting from platform movement. Recent advances in Machine Learning (ML) have expanded the potential of EMG analysis for identifying subtle physiological and behavioral differences across individuals. ML algorithms are increasingly used to decode muscle activity patterns, enabling applications ranging from gesture recognition to prosthetics. Incorporating gender information into model training proved to significantly increase classification performance in hand motions [9], [10]. The aim is to assess whether significant differences exist between men and women in EMG activity, and to determine which muscles and features

contribute most to the discrimination between the two groups during the BioVrSea. This analysis provides a foundation for a deeper understanding of the neuromuscular strategies underlying PC, to contribute to the development of sustainable and intelligent diagnostic tools for assistance and predictive health.

II. MATERIALS & METHODS

A. Cohort

The study involved 227 healthy participants (104 male, 123 female), recruited between 2021 and 2024, following ethical approval from the Icelandic Bioethics Committee (Approval Number: VSN-20-101, May 2020). All participants underwent screening to rule out any neurological or orthopedic conditions that might influence balance. To ensure a broad representation, volunteers aged 18 to 30 years were included.

B. BioVRSea Paradigm

BioVRSea [11]–[13], created at the motion sickness (MS) Laboratory within the Institute of Biomedical and Neural Engineering at Reykjavik University, is a novel multi-parameter platform that integrates virtual reality (VR) and biosignals monitoring. The system consists of VR headsets that immerse participants in a sea environment, a motion platform that reproduces wave-like movements with gradually increasing frequency and amplitude, and several biosensors, including electrocardiography (ECG), electroencephalography (EEG), and centre of pressure (CoP) recordings (see Fig. 1). By tracking both physiological responses and motor adjustments during demanding computer-based tasks, BioVRSea enables the evaluation of an individual's sensitivity to motion-related discomfort. In addition to research on MS, the laboratory utilizes this system to investigate PC deficits in patients with neurological disorders or those who have sustained concussions from sports injuries, with the goal of developing new diagnostic tools to enhance clinical practice. The BioVRSea acquisition protocol is divided into six sequential phases designed to assess balance and PC: baseline (BL), pre-phase (PRE), 25%-phase, 50%-phase, 75%-phase, and post-phase (POST). The three movement phases (25%, 50%, and 75%) are grouped together, and their measurements are averaged to form the movement mid-phase (MOV). During the BL phase, participants stand quietly on the platform with their arms at their sides, observing a static non-sea scenario for two minutes. In the PRE phase, only visual stimulation is provided: participants watch the virtual waves without using the safety bar. Next, while still in the PRE phase, participants are asked to hold the safety bar as both visual and motor stimuli are introduced. The platform then begins to move at progressively increasing intensities, with each MOV phase lasting 40 seconds. The POST phase mirrors the conditions of the PRE phase.

C. EMG Data Analysis

EMG were measured using six wireless sensors (Kiso ehf) with a sampling frequency of 1600 Hz. Electrodes were placed on the tibialis anterior (TA), gastrocnemius lateralis (GL), and soleus (S) muscles of both legs. EMG data were processed in MATLAB 2024b. After segmenting the signal into phases, a 4th-order Butterworth band-pass filter was applied, and line noise was removed using a sequence of notch filters at 50 Hz and its harmonics. Additional checks were performed to remove outliers related to electrode displacement. Finally, the signal of each phase was normalized to the maximum peak across all experimental phases. This normalization was performed per subject (within-person). Features in the time and frequency domains were computed.

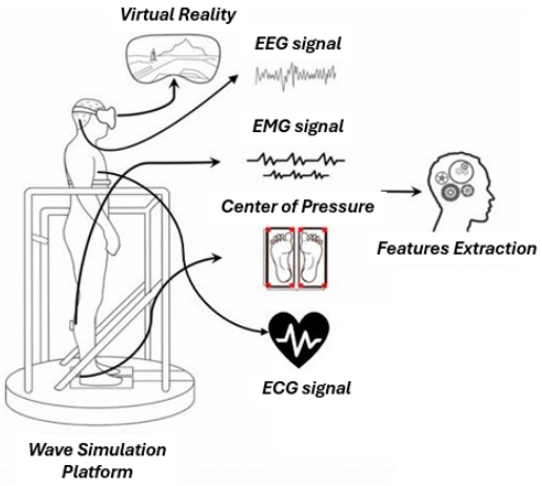


Fig. 1. BioVRSea Paradigm reproduced from [14], ©IEEE 2024.

D. EMG Statistical Analysis

Statistical analyses were performed separately for each experimental phase to examine differences in EMG responses. Depending on whether the data met the assumption of normality (tested using the Shapiro–Wilk test), either independent t-tests or Mann–Whitney U tests were used ($\alpha < 0.05$). Due to the high number of comparisons, the Bonferroni procedure is employed to control the family-wise error rate, thereby reducing the likelihood of false-positive findings across tests.

E. Machine Learning analysis

1) Dataset and feature pre-processing: ML analysis of EMG data focuses on feature selection to capture both the capability of discriminating between genders and the most important features for this purpose. This analysis has been repeated using features from each phase of the BioVRSea experiment: Baseline, PRE, MOV, and POST, as well as using all features together. The number of features extracted per phase is 336, and the composition of all the features is 1344. In both examples, dimensionality is an issue that needs to be faced; indeed, the number of samples is limited to 227, having more features than subjects. To ensure that all features contribute equally to the analysis, z-scaling normalization was applied prior to feature selection and model training. This normalization process transforms each feature to have a mean

of zero and a standard deviation (SD) of one, thereby removing the influence of differing scales or units among features. By standardizing the data in this way, algorithms sensitive to feature magnitude can perform more effectively, enabling a more reliable identification of the most discriminative EMG features across the experimental phases. The dataset has been divided into a training set (80%) and a test set (20%) in a stratified manner, ensuring that the same percentage of samples belonging to each class is present in both sets. Feature selection and training of the final model were performed on the training set, while the test set was used solely for testing purposes. The use of the held-out set provides valuable insights into potential overfitting issues and helps prevent data leakage.

2) Feature selection approach: The algorithm is based on ensemble feature selection by Maruotto et al. [15]. It combines multiple selection strategies to strike a balance between accuracy, interpretability, and computational efficiency. The method sequentially ranks and refines features based on their importance to model performance, then merges results from repeated runs to produce a stable, consensus set of key features. The feature selection approach is based on a two-step process. In the first stage (FS A), features are ranked using a Gradient Boosting (GB) model with an L1 regularization, which removes features with negligible importance values, thus focusing on the most contributive ones. In the second stage (FS B), a backward sequential feature selection is applied to the reduced set from FS A, iteratively removing features while maintaining model performance within a 1% tolerance. However, when using this algorithm, some parameters still need to be tuned: the number of features selected per iteration in the first step of the feature selection, and the percentile selection after the greedy examination. For this study, the number of features is set to 5% of the complete dimension of the analyzed dataset, corresponding to 67 features in the case of the bigger set and 17 for the single-phase analysis.

3) Evaluation metrics: Feature evaluation was performed by training a Support Vector Machine (SVM) classifier with a linear kernel and a Random Forest (RF) using only the selected features, combined with cross-validation (CV) to ensure the robustness and generalizability of the results. A stratified 5-fold CV procedure was employed to preserve the balance between classes across folds, providing a more reliable estimate of model performance, and averaging them across folds. The SVM algorithm was chosen for its effectiveness in high-dimensional spaces and its ability to find an optimal separating hyperplane that maximizes the margin between classes, which is particularly advantageous when the number of features exceeds the number of samples. The primary evaluation metric used was the F1-score, defined as the harmonic mean of precision and recall. Precision measures the proportion of correctly identified positive samples among all predicted positives, while recall quantifies the proportion of true positives correctly identified by the model. The F1-score, therefore, provides a balanced assessment of model accuracy, especially when both false positives and false negatives are of concern. Moreover, a held-out test set, excluded from the feature selection and model training phases, was used for the final evaluation to provide an unbiased assessment of the model's performance on unseen data corresponding to 20% of the dataset. This final test was performed on a retrained model using the entire training set. In this way we can compare the generalization capabilities of the algorithm in CV with the test set performances.

TABLE I
FEATURE SELECTION RESULTS: NUMBER OF FEATURES SELECTED AND MEAN $\pm$ SD CV F1 SCORE ON SVM AND TEST SET.

	Number of features	CV F1	Test F1
All	8	0.75 ± 0.06	0.836
Baseline	7	0.74 ± 0.05	0.779
PRE	141	0.70 ± 0.07	0.705
MOV	24	0.73 ± 0.06	**0.840**
POST	6	0.77 ± 0.06	0.705

III. RESULTS

Both statistical analysis and ML were able to discriminate gender across the experimental phases and among muscles. The following section presents the results of the statistical analysis and the ML approach.

A. Statistical analysis

From a statistical point of view, the TA muscle, both on the left and right sides, as well as the right side of the S muscle, can discriminate between males and females. Specifically, for the right S muscle, the BASE and PRE phases show the highest ability to differentiate gender, with 32 statistically significant features in each phase. Regarding the TA muscle, on the left side, the BASE and PRE phases also exhibit the strongest gender differentiation (29 and 28 significant features, respectively), while on the right side, the BASE and PRE phases show 17 and 13 significant features, respectively.

B. Machine learning

ML analysis also yields significant results in discriminating between genders. Table I reports the number of selected features after the selection algorithm and the F1 score (mean and SD) on CV metrics and on the test set using SVM algorithm. Among the models, the MOV phase achieved the highest test F1 score on the test set, indicating superior generalization performance, closely followed by the analysis using all features combined. According to the CV analysis, there is no dominance of one phase over the others, nor does the composition of all the phases show more capabilities in discriminating. It is worth noting that POST phases converge to a higher mean CV F1 score compared to the composition of the phases. Even if CV analysis is not a good enough approximation of the generalization performance, considering the differences with the hold-out set, SD does not change significantly among executions, maintaining a stable value. Table II reports the F1 score (mean and SD) on CV metrics and on the test set using the RF algorithm. Among the models, the PRE phase achieved the highest F1 score on the test set. Similarly, according to the CV analysis, there is no dominance

TABLE II
MEAN ± SD CV F1 SCORE AND TEST SET USING RF.

	CV F1	Test F1
All	0.76 ± 0.07	0.792
Baseline	0.75 ± 0.08	0.816
PRE	0.74 ± 0.07	**0.823**
MOV	0.72 ± 0.06	0.785
POST	0.75 ± 0.07	0.745

TABLE III
NUMBER OF FEATURES OF EACH MUSCLE IN EXECUTIONS

	GLL	GLR	SR	SL	TAR	TAL
All	3	0	1	0	2	2
Baseline	2	0	4	0	1	0
PRE	20	20	27	26	26	22
MOV	4	2	6	1	6	5
POST	3	0	0	0	1	2

of one phase over the others, nor does the composition of all the phases exhibit greater capabilities in discrimination. Also in this case, SV doesn't show a good generalization capability because the test performances are often 5% higher.

Table III summarizes the number of features extracted in each execution of the algorithm across the different input sets (all, baseline, pre, mov, post), as well as how many of these features correspond to each muscle. The number of selected features varied considerably between phases, ranging from 6 (POST) to 141 (PRE), reflecting differences in feature relevance under distinct experimental phases.

IV. DISCUSSIONS

The results of the statistical analysis revealed that the S and TA muscles exhibited the greatest discriminative potential between males and females, with significant differences mainly observed in the BASE and PRE phases. This indicates that gender-related differences in muscle activation can already emerge under static standing conditions, even in the absence of external perturbations. However, these findings only partially overlap with those of the ML approach, which highlighted the MOV phase as the most discriminative. This suggests that static and dynamic phases may reveal complementary aspects of sex-related neuromuscular strategies. The feature selection results reveal clear differences in the discriminative potential of EMG features across the experimental phases (Table I). In particular, the MOV phase demonstrated a more compact and effective feature set, with only 24 selected features achieving the highest test F1 score. The MOV phase, characterized by active balance recovery, appears to magnify gender-related differences in neuromuscular control, possibly due to sex-specific strategies in sensorimotor integration under mechanical perturbations. In contrast, the PRE phase did not yield strong predictors, as evidenced by both the large number of selected features (141) and the lowest F1 performance on both CV and test sets. This dispersion suggests that no single or small group of features dominated the classification process in PRE. The "All" condition, which aggregates features from all phases, achieved performance similar to MOV, indicating that movement-related features dominate the overall predictive capability of the dataset. However, this trend is reversed in the RF results (Table II), where the PRE phase emerges as the most informative. This suggests that gender-related differences may be subtle and that their detectability varies across algorithms, with each method emphasizing different aspects of the data. As shown in Table III, the distribution of selected features varies across phases, revealing that certain muscles contribute more consistently to gender discrimination. In the MOV phase, the most informative muscles were the SR, TAR, and GLL. The Baseline and POST phases, both characterized by fewer selected features and moderate F1 scores, further confirm this trend. During these static conditions, muscle activity is more homogeneous and less distinctive between genders, leading to weaker predictors. Interestingly, the "All" condition, which integrates features from every phase, achieved performance similar to MOV. These muscles play complementary roles in maintaining an upright stance: the S stabilizes the ankle joint against forward sway, while the TA counteracts dorsiflexion during corrective movements.

Taken the results together, the predominance of the S and TA in gender discrimination is consistent with their key roles in maintaining postural stability and counteracting forward sway. A preview study [16] has shown that gender-related differences exist in the size of individual skeletal fibers from the soleus and tibialis anterior muscles and that they may influence metabolism and the adaptive response to rehabilitation programs. Research consistently shows that gender differences in neuromuscular strategies during balance tasks tend to appear more clearly in muscles involved in fine PC, such as the TA and S, than in those mainly responsible for generating force, like the gastrocnemius. During balance tasks, women often display higher co-contraction between the TA and peroneus longus, suggesting a greater reliance on precise, automatic postural adjustments. Men, on the other hand, seem to depend more on overall force production and muscular strength [17]–[19]. The GL, which plays a larger role in dynamic and powerful movements, appears less affected by these gender-related differences in PC [20]. However, the analyses were limited to young and healthy participants; further investigations are needed to determine whether these patterns persist in clinical contexts or across different age groups. Looking ahead, integrating EMG measurements with ML models in longitudinal studies may facilitate the early identification of PC alterations, contributing to predictive medicine grounded in real physiological data, possibly taking into account gender differences.

V. CONCLUSION

This study investigated gender-related differences in PC by analysing surface EMG signals recorded from six lower-limb muscles during the BioVRSea paradigm. Statistical and ML analyses consistently indicated that muscle activation patterns during postural tasks can discriminate between males and females, both under dynamic and static perturbation. Among all experimental phases, the movement (MOV) phase exhib-

ited the most compact and informative feature set, achieving the highest classification performance, thus highlighting that gender differences in neuromuscular control emerge most clearly when balance is actively challenged. The S and TA muscles contributed most consistently to gender discrimination, confirming their crucial role in maintaining balance and compensating for perturbations. The limited discriminative power observed in static conditions (BASE and POST) suggests that gender-related differences are more pronounced in dynamic, adaptive responses rather than in steady-state posture. From a methodological standpoint, the combination of ensemble feature selection and SVM classification proved effective in identifying meaningful EMG biomarkers while maintaining good generalisation performance. These findings support the feasibility of using EMG-based metrics and ML for quantitative assessment of individual neuromuscular strategies. Future work will focus on defining linear mixed-effects models to account for within-subject variability across phases and muscles. Future studies should also integrate biomechanical, as CoP, and physiological, as EEG and ECG [21], [22] features to better characterise the coupling between central and peripheral mechanisms of balance control.

Overall, this work advances our understanding of the neurophysiological bases of PC and emphasises the importance of considering gender as a biological variable in both experimental design and diagnostic modelling. Future research should extend this approach to different age groups and clinical populations to explore how sex-specific neuromuscular strategies influence postural stability, rehabilitation, and predictive health assessment.

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ETHICS STATEMENT

All participants received detailed written information about the study and provided their signed informed consent. The research was conducted in accordance with the principles embodied in the Declaration of Helsinki by Icelandic statutory requirements. The study protocol was approved by the Icelandic National Bioethics Committee (no: VSN-20–101).

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Acoustic Emission Monitoring for Structural Health Assessment: The Case of the Geiger Key Bridge

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***Abstract*— The Acoustic Emission (AE) technique represents a non-destructive diagnostic tool for real-time monitoring of structures subject to progressive damage. The method relies on the detection of transient elastic waves generated by the sudden release of energy from localised sources within a material under stress. This paper presents an overview of the theoretical principles of AE and its diagnostic potential in the assessment of reinforced concrete (RC) structures, with particular attention to the application on the Geiger Key Bridge (Florida, USA). The bridge, built in the 1950s, showed extensive deterioration, prompting an experimental campaign aimed at verifying the applicability of AE-based monitoring to assess its residual structural integrity. The analysis focused on both qualitative parameters—Kaiser effect and Felicity ratio—and quantitative indices, such as the Historic and Severity Indices, following the "Intensity Analysis" approach. The results demonstrated the sensitivity of AE monitoring in detecting damage evolution and confirmed the degradation level of the bridge. The study highlights the effectiveness of AE as a sustainable and non-invasive methodology for structural health monitoring (SHM) of ageing infrastructure.**

***Keywords*—** *Acoustic emission, Structural health monitoring, Kaiser effect, Felicity ratio, Intensity analysis, Reinforced concrete bridges*

I. INTRODUCTION

The conservation and maintenance of ageing civil infrastructure constitute a pressing challenge in contemporary structural engineering, particularly in relation to sustainability and resilience goals. Bridges, tunnels, and historical buildings frequently exhibit progressive deterioration resulting from environmental exposure, material ageing, and insufficient maintenance. In this context, the development of reliable non-destructive testing (NDT) and structural health monitoring (SHM) techniques has become essential to ensure safety and to optimise maintenance strategies [1], [2].

Among the available NDT methods, Acoustic Emission (AE) analysis represents a particularly promising approach because it provides real-time information on damage evolution by detecting transient elastic waves generated by localised microstructural events within materials under stress. Unlike active NDT techniques such as ultrasonic testing or impact-echo, AE is a passive method that captures the spontaneous release of strain energy as cracks initiate and propagate, offering an early indication of structural degradation [3], [4].

The technique was first systematically applied to metals in the 1950s and subsequently extended to reinforced concrete (RC) and masonry structures in the late twentieth century. Research [5], [6] demonstrated the capability of AE parameters—particularly amplitude, rise time, and energy—to describe the fracture mechanisms in quasi-brittle materials. The introduction of the b-value analysis, derived from seismological studies by Gutenberg and Richter [7], enabled the correlation of AE event distribution with damage intensity, thus providing a quantitative measure of fracture evolution [8], [9].

Further advancements incorporated the Kaiser effect and the Felicity ratio to describe the material's memory of previous stress levels [10], [11]. These indicators allow for assessing the integrity and reactivation of damage in cyclic loading conditions, providing a practical criterion for on-site diagnosis. More recently, the Intensity Analysis (IA) approach, proposed by [12] and later refined by [13] introduced two composite indices—the Historic Index and Severity Index—that quantify structural deterioration and classify damage levels into diagnostic zones.

The applicability of AE monitoring has been extensively validated in laboratory and field studies. Numerous investigations have confirmed the technique's reliability for reinforced concrete [14], [15] and, more recently, for masonry structures, where AE faces additional challenges due to the heterogeneous composition and strong attenuation of the signal [4], [16], [17]. Despite these limitations, AE remains one of the few NDT techniques capable of correlating damage processes with real-time data acquisition, making it a valuable tool in sustainable infrastructure management.

This study builds upon this consolidated theoretical framework and presents the application of AE monitoring to a deteriorated reinforced concrete bridge—the Geiger Key Bridge—aimed at validating AE-based SHM methodologies for ageing infrastructure.

In the broader framework of sustainable infrastructure management, AE-based SHM can play a strategic role in shifting from reactive to predictive maintenance strategies. Traditional inspection procedures for bridge networks often rely on visual surveys and scheduled interventions, which may

fail to detect internal damage at an early stage and can lead either to unnecessary conservative measures or to delayed actions taken only after the appearance of visible distress. By contrast, AE monitoring provides continuous or quasi-continuous feedback on the internal damage processes, enabling the identification of critical members and the prioritisation of interventions within large asset portfolios [1], [2], [14].

From a sustainability perspective, this capability is particularly relevant for ageing bridges constructed with design standards that did not explicitly account for durability in aggressive environments. In such cases, it is neither economically nor environmentally viable to replace or heavily retrofit all structures. Instead, decisions must be informed by objective diagnostic evidence, so that limited resources can be allocated to the most vulnerable assets. AE techniques, when properly integrated into an SHM framework and combined with other NDT and analytical tools, can therefore support risk-informed decision-making and contribute to the optimisation of maintenance plans, extending the service life of existing infrastructure and reducing the overall environmental footprint of structural interventions [2], [4], [17].

Within this context, the present work focuses on a severely deteriorated concrete bridge located in a marine environment, where chloride-induced corrosion and mechanical degradation are particularly pronounced. The case study offers an opportunity to examine the performance of AE monitoring under challenging field conditions and to discuss its strengths and limitations with reference to real-world infrastructure management scenarios.

II. Principles and Diagnostic Parameters of the AE Technique

The Acoustic Emission (AE) technique is founded on the detection of transient elastic waves generated by the rapid release of energy from localised sources within a stressed material. As a passive and non-destructive monitoring method, AE enables the real-time identification of damage initiation and crack propagation without requiring external energy input, making it particularly suitable for structural health monitoring [1], [3].

When the applied load exceeds a critical stress threshold, micro- or macro-fractures within the material produce short-lived elastic waves that propagate through the solid and are captured by piezoelectric transducers. The recorded voltage signal—after amplification and filtering—represents an acoustic event, which contains the information necessary to characterise the fracture process [18]

Each AE signal is composed of a sequence of discrete pulses related to the mechanical response of the material under stress. A hit is defined as the detection of a transient signal that exceeds a predefined threshold at a specific sensor channel; it marks the transition from background noise to an identifiable emission [2]. When multiple hits are detected by several sensors and can be associated with the same physical source, they constitute a single acoustic event [19].

Two main categories of AE signals are typically distinguished:

- Continuous emissions: associated with low-energy processes such as friction or plastic deformation;
- Burst emissions: characterised by sharp transient pulses corresponding to microcrack initiation or sudden crack growth.

For the purpose of damage diagnosis, burst-type events are generally of primary interest because they correspond to discrete fracture phenomena directly linked to material deterioration.

A. Main Parameters for Damage Interpretation

The characterisation of AE signals relies on a set of measurable quantities that describe their temporal evolution and energetic content, providing insight into the underlying fracture mechanisms:

- Amplitude (A): the maximum voltage of the waveform, proportional to the energy released by the source.
- Rise Time (RT): the time interval between the first threshold crossing and the maximum amplitude; related to the kinetics of crack development.
- Duration (D): the total time between the first and last threshold crossings; differentiates impulsive from continuous signals.
- Counts (C): the number of threshold crossings within one hit; a measure of AE activity persistence.
- Signal Strength (S): the integral of the rectified signal envelope; corresponds to the total energy emitted during an event.

These quantities form the dataset from which higher-level parameters are derived to interpret the evolution of damage throughout the loading process.

B. Kaiser Effect and Felicity Ratio

The Kaiser effect, first described in [10], expresses the stress memory of a material subjected to cyclic loading. It manifests as the absence of AE activity until the applied stress surpasses the maximum stress reached in the previous loading cycle, typical of stable and undamaged materials. When existing defects become unstable or coalesce into larger cracks, AE signals can appear at lower stress levels than before. This phenomenon indicates the loss of the Kaiser effect, a clear sign of progressive internal deterioration [20].

To quantify this, the Felicity Ratio (FR) is defined as:

$$FR = \frac{\sigma_{AE}}{\sigma_{MAX}} \quad (1)$$

where σ_{AE} is the stress level at which AE activity recommences and σ_{MAX} is the previous maximum stress. Values close to unity indicate undamaged conditions, while smaller values imply the accumulation of damage or microcrack reactivation [21]. This combined interpretation of AE activity and Felicity Ratio is widely used in the structural monitoring of reinforced concrete components and bridge structures [1], [22].

C. Intensity Analysis

To complement the qualitative interpretation provided by the Kaiser effect, Intensity Analysis (IA) offers a semi-quantitative framework based on the evolution and energetic content of AE signals [12], [13].

The method introduces two parameters: the Historic Index ($H(I)$), which represents the rate of AE activity growth, and the Severity Index (S_r), which denotes the mean energy of the most intense events. Their expressions are given as:

$$H(I) = \frac{N}{N\text{-}K}\left(\frac{\sum_{i=K+1}^{N} S_{oi}}{\sum_{i=1}^{N} S_{oi}}\right) \quad (2)$$

$$S_r = \frac{1}{J}\left(\sum_{m=1}^{J} S_{om}\right) \quad (3)$$

Where S_{oi} is the signal strength of the i-th event, N is the total number of events, S_{om} is the signal strength of the m-th event and K, J are constants depending on material type [2].

The Intensity Chart obtained by plotting $H(I)$ versus S_r (Fig. 1) classifies the structure's condition into five zones (Fig. 1) [13]:

- A – insignificant activity;
- B – minor surface damage;
- C – damage requiring follow-up;
- D – significant damage requiring inspection;
- E – severe damage requiring immediate intervention.

The Intensity Analysis therefore provides a rational and repeatable procedure for interpreting AE datasets, and is implemented in this study according to the framework proposed by the Committee on Acoustic Emission of Reinforced Plastics (CARP), which formalises the Severity–Historic chart into diagnostic Zones A–E and defines minimum statistical requirements for the computation of the Historic Index. [15].

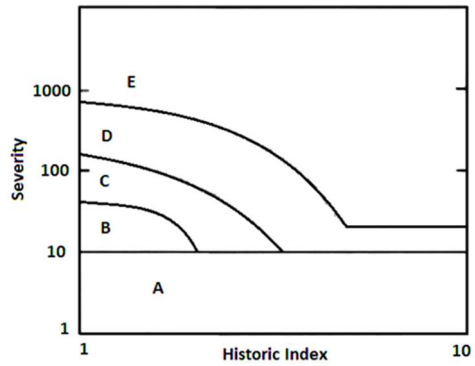


Fig. 1. Severity-Historic index chart for reinforced concrete bridges [13].

III. CASE STUDY: GEIGER KEY BRIDGE

The Geiger Key Bridge is a reinforced and prestressed concrete bridge located within the Florida Keys archipelago. Constructed in 1955, it forms part of the historical series of bridges built during the post-war expansion of the Florida Overseas Highway. The bridge has an overall length of approximately 40 m and consists of five simply supported spans, each 7.6 m long (Fig. 2).

The superstructure is composed of precast girder-beam elements, connected in situ and completed with a cast-in-place concrete deck slab (Fig. 3).

Each span is supported by a series of twenty-four piers with variable height ranging from 2.5 to 6 m, depending on tidal conditions and seabed profile.



Fig. 2. Geiger Key Bridge

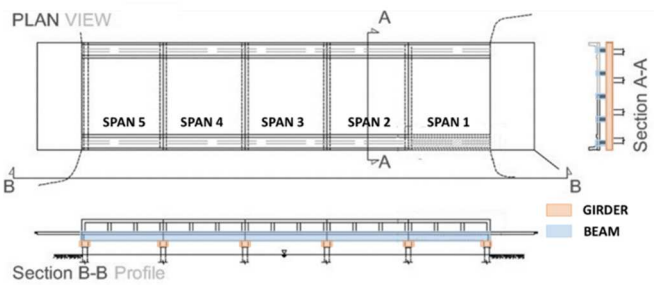


Fig. 3. Geiger Key Bridge

The bridge was designed following the construction standards typical of the 1950s, with limited durability considerations compared to modern criteria.

Over time, the structure has been exposed to a highly aggressive marine and subtropical environment, characterised by high humidity, salt-laden winds, and frequent thermal fluctuations. These conditions have accelerated the corrosion of reinforcing steel and the deterioration of concrete cover.

Prior to testing, a detailed visual inspection identified widespread cracking, spalling, and exposed reinforcement bars along the main girders and the deck slab. Such manifestations of deterioration led the local authorities to subject the structure to a detailed structural health assessment, as part of a broader experimental campaign aimed at validating Acoustic Emission (AE) monitoring for ageing concrete bridges under real environmental conditions.

The Geiger Key Bridge was selected as a representative case study due to its typical configuration, material composition, and degradation pattern, which are shared by several other bridges built in the same period throughout the Florida Keys. This made it a valuable testbed for evaluating the effectiveness of AE-based Structural Health Monitoring (SHM) techniques for infrastructure preservation in marine climates.

A. Load test procedure

The monitoring campaign consisted of a controlled load test combined with Acoustic Emission (AE) data acquisition to evaluate the bridge's structural response and level of deterioration. The load test was designed to reproduce service conditions and to induce a moderate stress range without compromising the structure's residual capacity.

The loading protocol involved two phases using a 23.5-ton fire truck. The truck was equipped with a single front axle (9.5 tons) and a rear axle (14 tons). The procedure included:

- Phase 1 – Full Load (100% X): The truck, fully loaded, was positioned at midspan of the instrumented girders for 10 minutes to generate a stable stress field.

- Rest Period: The load was removed for one hour to allow structural relaxation and stabilisation of residual micro-strains.
- Phase 2 – Reduced Load (95% X): The truck, with a load reduced to 95% of the previous one, was repositioned at midspan for an additional 10-minute interval.

The following Figure 4 shows the positioning of the load for the two instrumented spans.

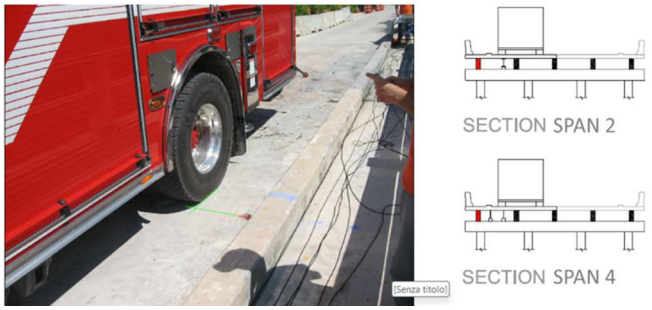


Fig. 4. Positioning of the load for the two instrumented spans.

According to the Kaiser effect, no AE activity should occur during the second phase unless the structure exhibits internal damage or memory loss of previous stress levels. Detecting AE signals during the 95% load phase would therefore provide evidence of degradation.

B. *Instrumentation and Setup*

Twelve R6I piezoelectric AE sensors (Mistras™) were installed on two of the bridge's spans, Span 2 and Span 4, each instrumented on the outer beam. The sensors were connected to a Sensor Highway II acquisition unit, capable of high-speed, 16-channel data recording.

Each sensor was fixed to the concrete surface with epoxy adhesive, ensuring acoustic coupling through manual pressure during the curing phase.

A pencil lead break test (Hsu–Nielsen source simulation [23]) was conducted for sensor calibration, following ASTM E976 recommendations. The detection threshold was set at 42 dB, based on preliminary background noise measurements. Calibration was repeated after the test to confirm the stability and sensitivity of all channels.

The sensors were grouped into two sets per beam, each including three R6I sensors and one broadband sensor, to ensure redundancy and detect possible signal attenuation (Figure 5). The arrangement was designed to capture AE events within the midspan region, corresponding to the maximum bending moment.

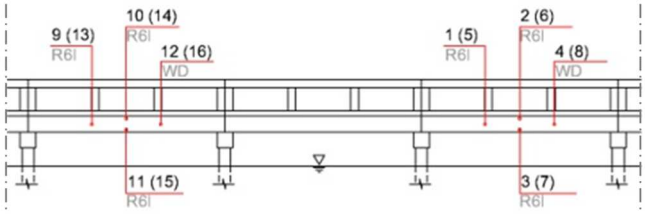


Fig. 5. Positioning of the sensors.

The acquisition settings of the Sensor Highway II unit were kept at the default sampling rate of the system, which is appropriate for the broadband frequency content of the R6I sensors. Acoustic events were identified according to the standard hit-based logic implemented in the software, whereby each hit corresponds to a threshold crossing and a sequence of hits detected across multiple channels forms an event. This information, together with the 42 dB detection threshold and the Hsu–Nielsen calibration procedure, provides a complete definition of the acquisition parameters used during the load test.

Data were collected synchronously during both loading phases, and the AE waveforms were processed to evaluate amplitude, rise time, counts, and signal strength. These parameters formed the basis for the Intensity Analysis and Kaiser effect evaluations discussed in the following section.

IV. Results and Discussion

The Acoustic Emission (AE) data collected during the two loading phases provide a coherent set of qualitative and quantitative indicators of the structural condition of the Geiger Key Bridge. The results include a comparison of AE activity under different load levels, an evaluation of the stress-memory behaviour through the Kaiser effect, and a quantitative assessment based on the Intensity Analysis framework. Together, these findings enable a comprehensive interpretation of the damage state of the instrumented spans and support the identification of critical structural deterioration.

A. *Qualitative Evaluation: Kaiser Effect Response*

The cumulative number of hits recorded during the two loading phases revealed a significant increase in AE activity under the 95% load compared with the full-load condition. According to the classical Kaiser effect, no substantial AE activity should occur until the previous maximum stress level is exceeded. However, the bridge exhibited a marked growth in hit rate, signal strength and counts during the second loading phase, despite the intentional reduction of load to 95% of the previous maximum (Figure 6).

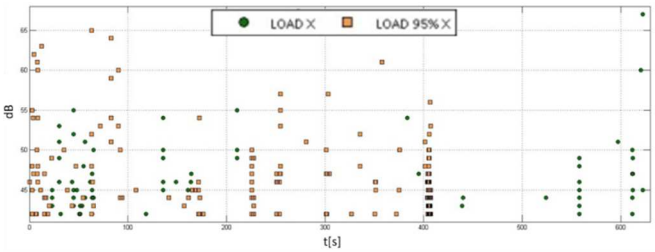


Fig. 6. Amplitude–time plot under the X load (green) and the 95% X load (orange).

Most AE amplitudes ranged between 60 and 70 dB, suggesting the presence of moderate cracking without evidence of sudden macro-fracture. The spatial distribution of hits confirmed that the highest activity developed near the midspan, consistent with the regions of maximum bending moment. A total of several hundred hits were recorded across the instrumented spans, showing clear stress-memory loss and progressive activation of pre-existing defects. This deviation from the expected Kaiser effect behaviour indicates advanced deterioration of the concrete members.

B. *Semiquantitative Evaluation: Intensity Analysis*

To complement the qualitative interpretation, a quantitative evaluation of the AE signals was carried out following the Intensity Analysis methodology described in Section II. This approach requires the computation of both the Historic Index and the Severity Index, as defined in Eqs. (2) and (3), evaluated separately for each beam and for each loading condition. According to the CARP recommendations, the calculation of the Historic Index requires a minimum of 20 valid hits per sensor to ensure statistical reliability. Owing to sensor malfunctioning and/or high attenuation associated with internal material discontinuities, several channels did not record a sufficient number of hits to allow a meaningful estimation of the Historic Index. As a result, a reliable computation of the Historic Index was not possible for most sensors, and only the Severity Index could be adequately evaluated for all spans.

Despite the limitations in computing the Historic Index, the Severity Index (based on the most energetic events) consistently positioned the data within Zone E of the chart (Figures 6 and 7). Zone E corresponds to the most severe condition in the CARP classification, indicating extensive cracking, unstable crack growth, and a high likelihood of rapid deterioration.

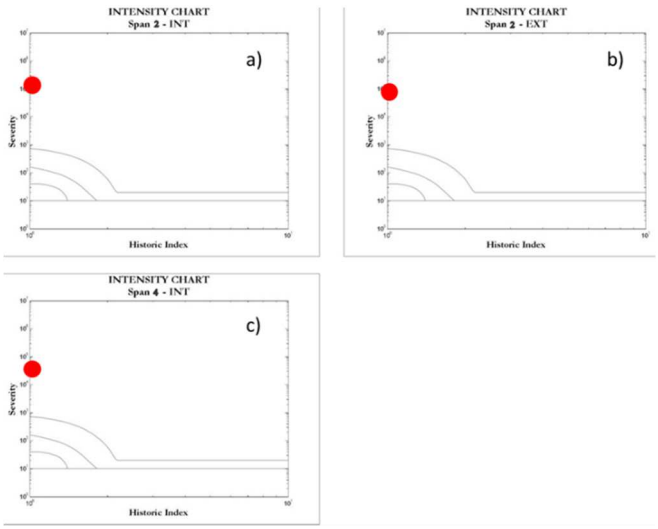


Fig. 7. Intensity chart at X load: (a) Span 2 (internal), (b) Span 2 (external), (c) Span 4 (internal).

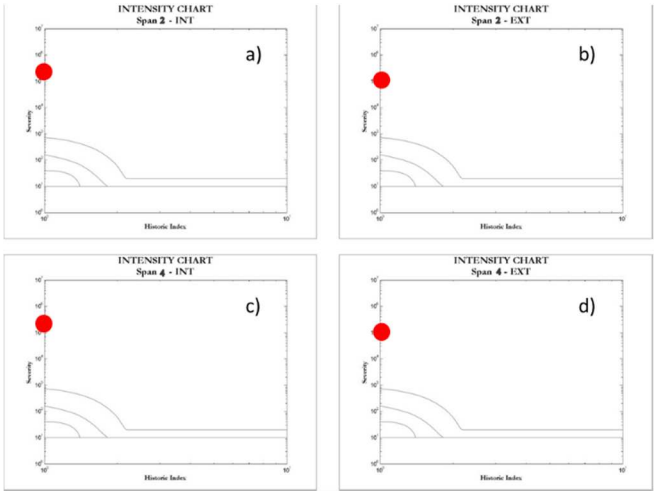


Fig. 8. Intensity chart at 95% X load: (a) Span 2 (internal), (b) Span 2 (external), (c) Span 4 (internal), (d) Span 4 (external)

The placement of the data within this region, together with the observed violation of the Kaiser effect and the field evidence of corrosion-induced damage, confirms the advanced structural degradation of the monitored spans. The Severity Index therefore provides a robust indication of the structural condition even in cases where the Historic Index cannot be reliably computed.

C. *Integrated Interpretation of Results*

The consistency of these results across multiple sensors and both spans reinforces the conclusion that the monitored sections of the Geiger Key Bridge are significantly compromised. The simultaneous occurrence of Kaiser effect violation, high hit rates under reduced load, increased signal strength, and a Zone E classification in the Intensity Chart demonstrates an advanced state of structural degradation. These combined findings confirm the reliability of AE monitoring as a diagnostic tool for detecting severe deterioration in reinforced concrete elements under real service conditions.

V. Conclusion

The research confirms the effectiveness of Acoustic Emission (AE) monitoring as a non-destructive and real-time diagnostic tool for the structural health assessment of ageing reinforced concrete infrastructure. The technique proved capable of capturing both qualitative indicators—such as the violation of the Kaiser effect—and quantitative severity measures derived from Intensity Analysis, thus enabling the identification of damage initiation, crack propagation and advanced deterioration phenomena without interrupting the serviceability of the structure.

The experimental application on the Geiger Key Bridge demonstrated the sensitivity of AE monitoring to deterioration processes commonly associated with marine-exposed concrete structures, including corrosion-induced cracking and localised material degradation. Despite the limitations encountered in computing the Historic Index due to insufficient hit counts on some sensors, the Severity Index consistently indicated a critical damage state (Zone E), corroborating the qualitative evidence and confirming the advanced structural degradation of the monitored spans.

The study also highlighted the importance of integrating AE monitoring with complementary diagnostic approaches—such as visual inspection, corrosion mapping, or vibration-based assessment—to obtain a comprehensive and reliable structural diagnosis. Moreover, environmental factors typical of marine settings (background noise, wave-induced vibrations, variable coupling conditions, and long-term sensor durability) should be carefully considered when designing and interpreting AE monitoring campaigns.

In light of these findings, AE techniques emerge as a sustainable and forward-looking strategy for extending the operational life of existing infrastructure. By facilitating early detection of deterioration and supporting evidence-based maintenance planning, AE monitoring can contribute to reducing lifecycle costs, improving structural resilience, and promoting responsible stewardship of civil infrastructure assets.

Beyond the specific case examined, the results offer broader insight into the practical use of AE-based Structural Health Monitoring for ageing reinforced concrete bridges. The combined evidence of Kaiser effect violation, increased AE activity under reduced loading, and Zone E classification confirms that AE can effectively identify members in advanced stages of deterioration, supporting decisions on prioritisation of maintenance and the need for detailed follow-up inspections.

The difficulty in reliably computing the Historic Index for some sensors also emphasises the importance of careful monitoring design, considering signal attenuation, environmental noise and coupling conditions—particularly in marine environments—to ensure data quality.

As part of a multi-level diagnostic framework, AE should be used in combination with complementary NDT and visual inspection techniques. Its ability to capture ongoing fracture processes provides infrastructure owners with valuable information for risk-informed decision-making and for optimising maintenance strategies across large bridge networks.

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A Low-Cost Vision-based monitoring system for dynamic testing of a cantilever beam

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***Abstract*— This paper deals with the development of a vision-based monitoring system for the dynamic testing of a cantilever beam using a low-cost marker-based approach. The method employs ArUco markers detected through the DeepTag algorithm and a high-resolution camera to track the motion of a vertical aluminum cantilever beam subjected to controlled harmonic excitation. Preliminary dynamic tests were carried out at 2 Hz and 3 Hz, and the measured displacements were filtered and compared with theoretical predictions, showing root mean square errors below 0.3 mm. These preliminary results confirm the capability of the proposed vision-based system to monitor the dynamic response of simple structural elements at low frequencies.**

Keywords — Marker tracking, dynamic tests, image processing, uncertainty assessment

I. Introduction

Assessing the actual condition of civil structures and infrastructures (i.e. Structural Health Monitoring, SHM) involves a complex process in which the role of the experimental tests is key [1,2]. Management of infrastructures involves in fact a complex network of technological, operational, and organizational strategies aimed at enhancing the resilience of the infrastructural system. Foundations and superstructures of buildings, bridges and other elements of infrastructural networks should be monitored to evaluate their capability to face extreme situations or events that can be envisaged during the structures' lifetime [3-6].

Effective predictive maintenance is based on large experimental datasets whose detection, in several cases, is largely expensive, due not only to the cost of the experimental setup, but also to the necessity of high technical skills [7-9]. A low-cost experimental monitoring system will allow local authorities in low-income regions, in charge of infrastructure management, to perform extensive SHM, with social, economic, and sustainability advantages [10].

In particular, dynamic tests offer the possibility, by means of identification procedures, to detect structural defects that are not observable after a visual inspection [1]. Standard accelerometric measurements to obtain time histories present several limitations: (i) the possibility of obtaining measurements at a limited number of points in the structure being examined; (ii) potential drifts when displacements are derived from acceleration measurements. [11].

The proposed measuring system has been successfully employed to detect the displacement of a 3D-scaled masonry model in quasi-static tests [12,13]. The good accuracy and the ease of use have driven the use of the system in a dynamic application on a real-scale aluminum element. The industrial controlled element and its simple structural model allow the assessment of the reliability of the measuring system in a dynamic test, so as to foresee applications in a real environment for monitoring of civil infrastructures.

This paper describes the proposed vision-based monitoring system and reports a preliminary assessment of its measurement performance in the context of dynamic tests. The paper is organized as follows. Section II outlines the deep-learning-based algorithm used for marker tracking, along with the post-processing methods employed to obtain displacement measurements. Section III details the case study, including the theoretical model of the element under test, the experimental setup, and the preliminary results obtained. The final section concludes the paper.

II. Methodology

A. Marker tracking via DeepTag

In this work, the algorithm used for recognizing the markers placed on the object whose dynamic mechanical response is to be analyzed is DeepTag. This algorithm was proposed in [14]. DeepTag represents the evolution of traditional marker detection algorithms, such as those based on ArUco libraries, by integrating deep learning techniques that enhance robustness, accuracy, and reliability even under challenging imaging conditions. In summary, it operates according to a structured pipeline comprising the following sequential steps (see Fig. 1): Keypoint Detection, Region of Interest Estimation, Homography Estimation, Marker Decoding, Inverse Homography Projection, and Pose Estimation.

The first step of the algorithm is Keypoint Detection, where convolutional neural networks (CNNs) are employed to identify distinctive points in the input image that may correspond to potential marker corners. Unlike classical ArUco detection, which relies on thresholding and contour analysis, DeepTag learns visual features directly from the data, allowing it to detect markers even under poor lighting conditions, motion blur, or partial occlusions. The network outputs candidate keypoints that are then grouped according to spatial and geometric constraints. Once the keypoints are located, the algorithm proceeds to the Region of Interest Estimation step. Here, DeepTag aggregates sets of four non-collinear keypoints arranged in a clockwise order to form a potential marker region. This geometric configuration ensures that each detected group corresponds to a quadrilateral area, consistent with the square shape of the ArUco marker. The algorithm then computes the Region of Interest (ROI) for each candidate, which defines the portion of the image that will undergo further processing.

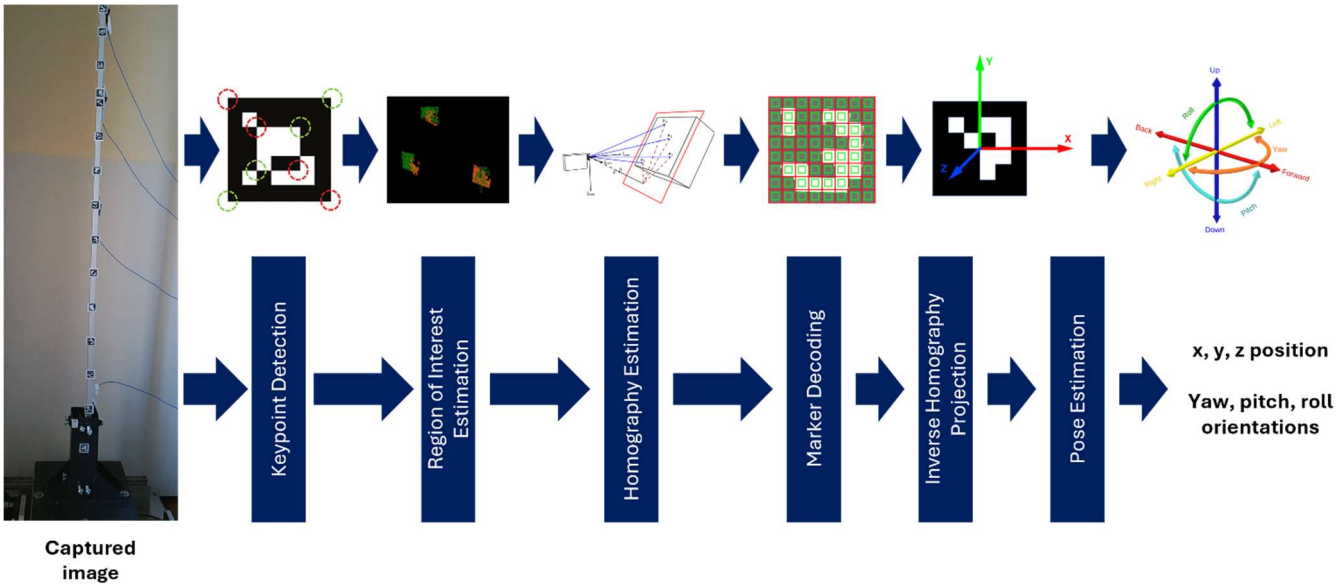


Fig. 1. DeepTag pipeline [14].

The next phase, Homography Estimation, establishes a projective transformation between the detected ROI and a normalized coordinate system representing an ideal square marker. By computing the homography matrix, DeepTag can generate a rectified image patch that removes perspective distortion, making the marker appear frontally viewed. This rectification is crucial for accurately decoding the binary pattern. After rectification, the algorithm performs Marker Decoding. In this step, DeepTag analyzes the rectified patch to extract and interpret the digital symbols that encode the marker's unique identifier. For ArUco markers, these binary patterns are compared with a predefined dictionary to determine the corresponding ID. The deep learning model used by DeepTag improves this process by being capable of distinguishing between valid marker patterns and noise, thus maintaining reliability even when markers are partially occluded or degraded. Following decoding, DeepTag performs the Inverse Homography Back-Projection, where the keypoints identified in the rectified patch are projected back to their original coordinates in the camera frame. This process restores the correct spatial relationship between the detected marker and the surrounding scene, enabling accurate geometrical interpretation of the marker's location within the image.

With these spatial relationships established, the algorithm proceeds to the Pose Estimation step. Using the known physical dimensions of the ArUco marker, DeepTag computes the six degrees of freedom (6-DoF) of the marker, three translational and three rotational components, by applying the Perspective-n-Point (PnP) algorithm. This provides the marker's exact position and orientation relative to the camera. Camera lens distortions are corrected through a calibration process based on a chessboard pattern, where the distortion coefficients are estimated to compensate for both radial and tangential effects. These corrections ensure that the computed poses remain accurate even at the edges of the image, where distortion is more significant.

At the core of DeepTag lies its neural-based architecture, composed of convolutional layers for feature extraction and fully connected layers for both classification (marker ID recognition) and regression (pose estimation). The system is trained on a large synthetic dataset of various marker types, shapes, at different orientations, and lighting conditions, allowing it to generalize effectively to real-world scenarios. Training data are augmented with random noise, blurring, and illumination variations to further improve robustness against unpredictable imaging conditions. When used with ArUco markers placed along a controlled mechanical structure, DeepTag achieved a reduction in orientation uncertainty to approximately 0.29° [13], nearly half the uncertainty of a standard ArUco-based tracking system. Similarly, distance measurement repeatability improved by an order of magnitude, reaching sub-millimeter precision.

The proposed measuring system has been successfully employed to detect the displacement of a 3D-scaled masonry model in quasi-static tests [12,13]. However, in quasi-static experiments, due to the slow dynamics of the structure, it is possible to apply stronger filtering to the position measurements of the markers without compromising the accuracy of the results. In the present work, instead, the goal is to evaluate whether the same algorithm can be effectively used in dynamic tests, where higher-frequency components, i.e., on the order of a few hertz, cannot be neglected. This requires verifying the system's capability to accurately track marker displacements and orientations in real time, even in the presence of rapid motion and vibration phenomena that introduce additional challenges in image acquisition and processing.

B. Post-processing

The dynamic test consists of a setup in which a shaker table imposes an oscillation on the object under test, which is rigidly fixed at its base to the shaker itself. During the test, several fiducial markers are placed along the surface of the object and are continuously monitored by a camera positioned to capture their motion.

In the post-processing phase, the position measurements provided by DeepTag are analyzed, focusing specifically on the motion in the x–y plane. During the dynamic tests, the displacement occurred only along the y-axis of the camera reference frame. For this reason, the x-positions of the markers placed along the monitored element were calculated as the

average of their x-values over the entire test duration. In this case, it is assumed that the camera plane is parallel to the surface plane of the monitored object. This assumption is validated by verifying the absence of noticeable oscillations in the x-axis data, indicating that lateral movement was negligible.

The x-axis measurements are referenced to a fixed marker located at the base of the shaker used during the test. Subsequently, for the y-axis measurements, the mean position was computed under static conditions, when no oscillation was applied to the object under examination. The dynamic displacements along the y-axis for each marker were then determined as the difference between the instantaneous position measured in a specific frame and the mean static position. This procedure enables the determination of the displacement of each marker along the y-axis during the vibration test. In cases where displacement data were missing due to marker misdetection in a specific frame, the corresponding values were estimated through third-order polynomial interpolation. The reconstructed displacements were then filtered according to the excitation frequency imposed by the shaker using a 4th-order Butterworth bandpass filter centered at the excitation frequency with a bandwidth of 0.2 Hz. Finally, displacement measurements at the excitation frequency are obtained for the entire test duration for each marker.

The main sources of uncertainty affecting the proposed approach are: (i) the intrinsic camera parameters and lens distortion coefficients, (ii) the reference measurement of the ArUco marker side length, and (iii) the variability of environmental lighting conditions. The accuracy related to the intrinsic parameters and lens distortion coefficients was assessed through a chessboard-based calibration procedure, which yielded a reprojection error lower than 0.5 pixels. The reference measurement of the ArUco marker side length was performed using a caliper with a resolution of 0.1 mm. Future work will focus on investigating the effects of environmental lighting conditions.

III. The Case Study

The case study is a vertical aluminum cantilever beam subjected to harmonic base shaking.

A. Geometry of the structural model

A cantilever aluminum beam with hollow rectangular section has been placed on an unidirectional shaking table, able to perform harmonic shaking, according to the minimum second moment of area of the cross section, see Figure 2.

The initial section at $x = 0$ is considered fully supported on the shaking table.

B. Analytical solution of the problem

The vibrations of a cantilever beam with harmonic base motion $\eta(0,t) = a \sin(\omega t)$ is a problem with a closed solution. Let $\eta(x,t)$ be the horizontal displacement of the section at a distance x from the fully supported cross section. At time t, a classical decomposition in the case of stationarity gives:

$$\eta(x,t) = f_x(x) \cdot f_t(t) \qquad (1)$$

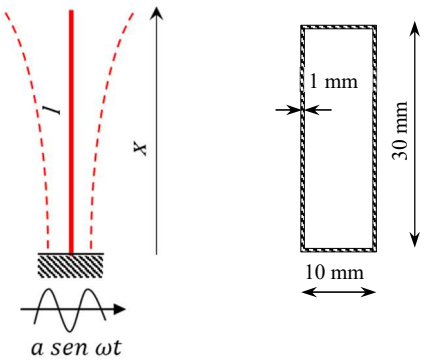


Fig. 2. Geometry of the test and scheme of the cross-section.

where:

$$f_x(x) = C_1 \sin(kx) + C_2 \cos(kx) + C_3 sinh(kx) + C_4 \cosh(kx)$$

with:

$$C_1 = \frac{a}{2} \frac{\sin kl \cos kl + \cos kl \operatorname{senh} kl}{(1+\cosh kl \cos kl)} \qquad C_3 = -C_1$$

$$C_2 = \frac{a}{2} \frac{\sin kl \sinh kl - \cos kl \cosh kl - 1}{(1+\cosh kl \cos kl)} \qquad C_4 = a - C_2$$

and:

$$k^4 = \frac{\omega^2 A \gamma}{EJg}$$

Values of the mechanical parameters are reported in Table I.

C. Experimental setup

The experimental setup consists of a shaker system used to impose a controlled oscillation on the vertical aluminum cantilever beam. The shaker employed for this purpose is the TRIO-TSD-01-22, manufactured by Trio Sistemi e Misure, and it is driven by a brushless motor model R88M-K1K020T-S2 produced by Omron. The vertical aluminum cantilever beam is rigidly fixed at its base to the shaker platform, allowing the oscillatory motion generated by the shaker to be transmitted directly to the beam.

Along the length of the cantilever, thirteen ArUco markers were placed at almost regular intervals to track the beam's motion during the dynamic tests, while an additional reference marker was positioned at the base of the shaker. This configuration allows the measurement of the beam's deformation under oscillatory excitation at each marker position.

TABLE I. CANTILEVER BEAM MECHANICAL CHARACTERISTICS

Geometry and mechanical parameters		
Characteristic	***Dimensions***	***Value***
Young modulus E	N/mm^2	70,000.00
Second moment of area J	mm^4	7,865.33
Aluminum density γ	N/mm^3	2.70*10^{-5}
Cross-sectional area A	mm^2	76.00
Gravity acceleration g	mm/s^2	9,810.00
Length of the beam	mm	1,400.00

The camera used for image acquisition is the EMEET SmartCam C60E, which features a 4 K resolution and a frame rate of 60.1 Hz. Prior to the experiments, a compensation procedure was carried out using a chessboard pattern to estimate the optical distortion parameters. These compensation parameters were subsequently applied to correct for radial and tangential lens distortions.

Two dynamic tests were performed, in which the shaker imposed sinusoidal oscillations at 2 Hz and 3 Hz, respectively. These excitation frequencies were selected to evaluate the system's capability to accurately track the cantilever's motion under different dynamic conditions and to assess the robustness of the DeepTag-based measurement approach at varying oscillation rates.

D. Results

The measurements provided by the camera–marker-based system were compared with the displacement values predicted by the theoretical model of the vibrating cantilever beam. After filtering the displacement data obtained for each marker, the amplitude of the oscillation imposed by the shaker was estimated using the displacement signal of the reference marker positioned at the base of the shaker itself. This amplitude was then used as an input parameter for the theoretical model to compute the expected displacements at the same locations where the ArUco markers were placed along the beam.

In Fig. 3, the Fourier Transform of the displacement measurements for the base marker is shown. A clear peak at 1.99 Hz can be observed, corresponding to the nominal excitation frequency of 2 Hz. Additionally, smaller harmonic components appear at higher frequencies, mainly due to mechanical imperfections in the shaker's actuation system.

After filtering the displacement signal around the 1.99 Hz component, the measured and theoretical displacement signals were compared over time, excluding the initial transient phase caused by the start-up of the shaker. In Fig. 4, the measured and theoretical displacement signals are presented for the marker located 918.75 mm from the base. The comparison shows a close agreement between the two signals. The difference between the signals was also computed, and the root mean square error (RMSE) was evaluated to quantify the deviation between the experimental and theoretical data. This analysis was repeated for each marker placed along the beam, as well as for the reference marker at the shaker base.

The obtained RMSE values for the different marker positions are illustrated in Fig. 5. The results show RMSE values below 0.3 mm, confirming the high accuracy of the DeepTag-based tracking system and aligning well with the findings reported in [13] for static tests. A gradual increase in the RMSE can be observed as the distance from the beam's base increases. This may be due to optical distortions that affect the outer regions of the image or inaccuracies in the model's approximation. Further investigation is necessary to pinpoint the source of these discrepancies between the measured values and the theoretical ones.

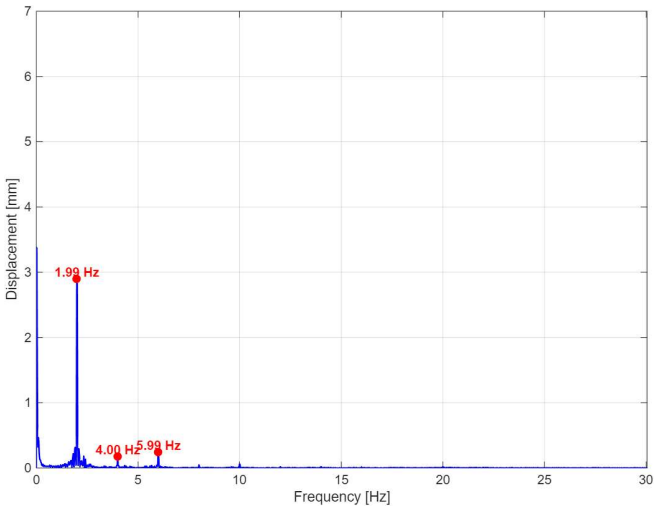


Fig. 3. Fourier transform of the measured displacements of the marker on the shaker base at 2 Hz.

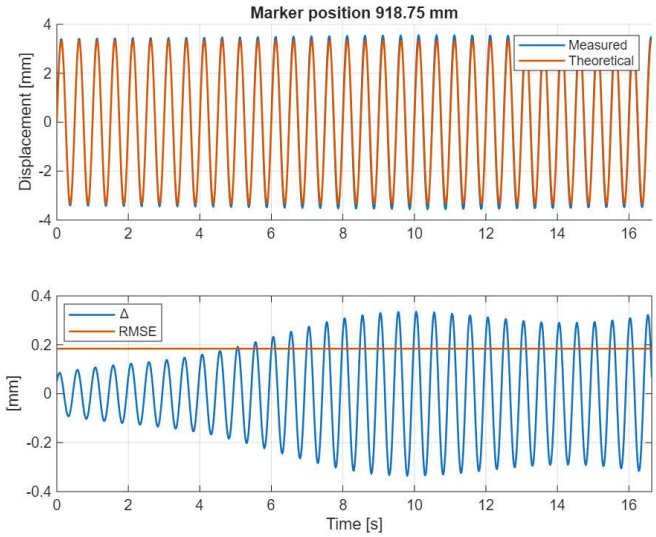


Fig. 4. Measured vs. theoretical displacements for the marker placed at 918.75 mm from the basis, and the difference Δ between the two values in time at 2 Hz of excitation.

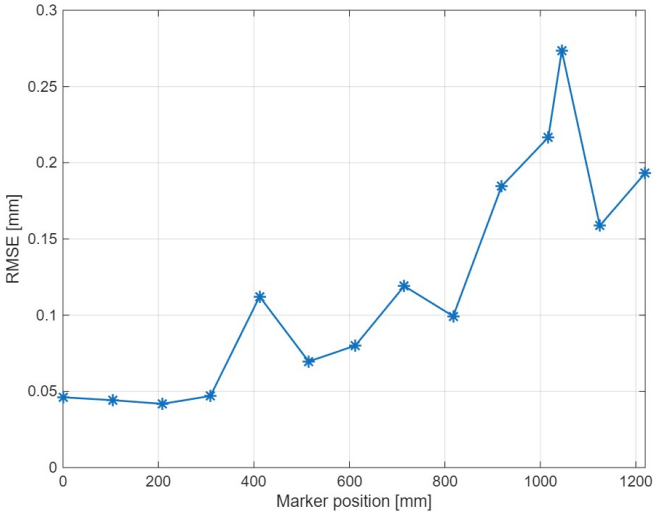


Fig. 5. RMSE at the different marker locations at 2Hz.

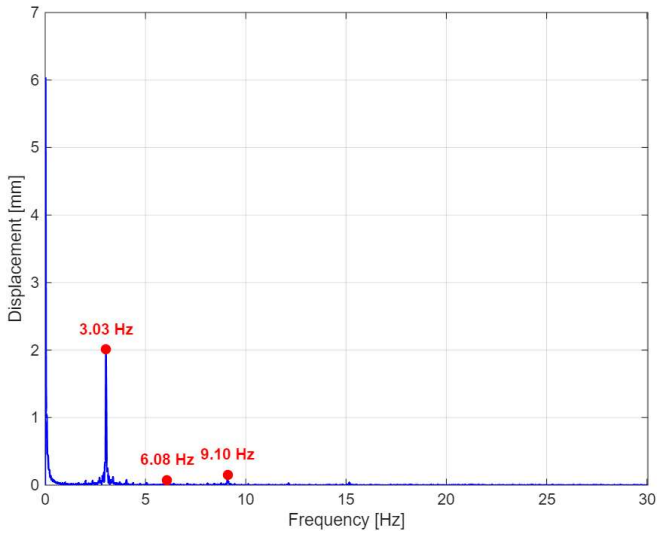


Fig. 6. Fourier transform of the measured displacements of the marker on the shaker base at 3 Hz.

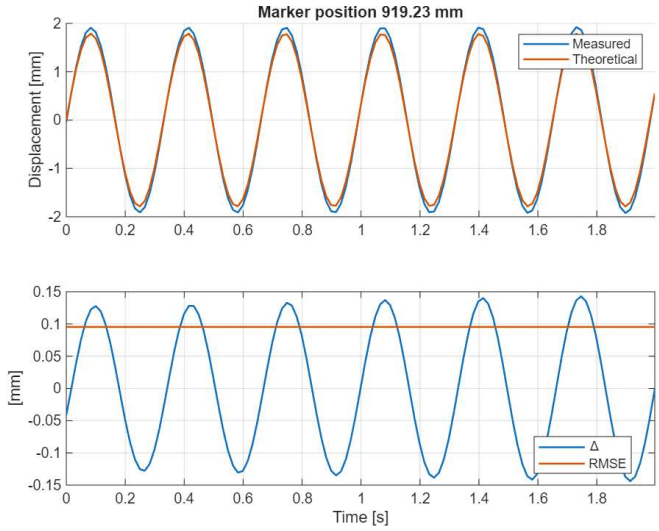


Fig. 7. Measured vs. theoretical displacements for the marker placed at 919.23 mm from the basis, and the difference Δ between the two values in time at 3 Hz of excitation.

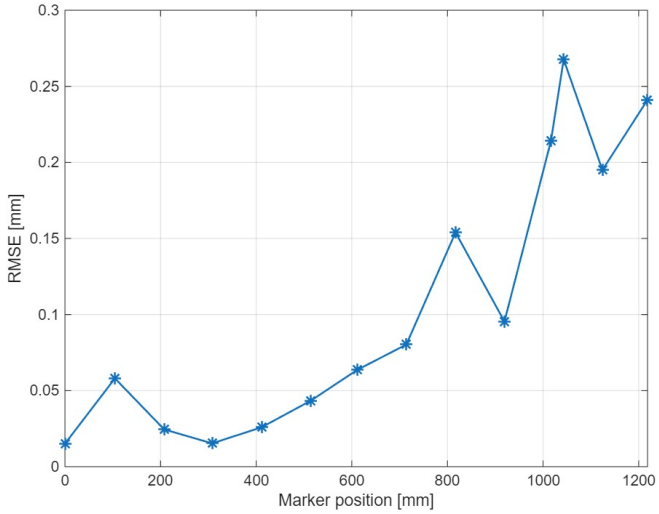


Fig. 8. RMSE at the different marker locations at 3Hz.

The same analysis was performed for the 3 Hz excitation frequency. The Fourier Transform of the base marker displacement, shown in Fig. 6, reveals a lower level of harmonic distortion compared to the 2 Hz case, indicating more stable mechanical behavior of the shaker at higher frequencies. The displacement measurements obtained for the marker placed at 919.23 mm from the base are depicted in Fig. 7. The corresponding RMSE values obtained for the tracking of all markers at 3 Hz confirmed the consistency of the results observed in the 2 Hz tests (see Fig. 8), demonstrating that the DeepTag-based measurement system maintains reliable performance even under faster oscillatory conditions.

The preliminary results obtained from the proposed system during the dynamic test show RMSE values lower than 0.3 mm, demonstrating lower errors compared to other marker-based approaches reported in the literature, which achieved errors in the range of 1–2 mm [15], [16].

IV. Conclusions and Future Developments

The study presented in this paper demonstrated the good performance and efficiency of a low-cost marker-based vision system for displacement detection in dynamic laboratory tests. The proposed method, which utilizes ArUco markers detected by the DeepTag algorithm and a high-resolution, low-cost camera, was successfully applied to the monitoring of a vertical aluminum cantilever beam subjected to controlled harmonic excitation.

The preliminary dynamic tests, carried out at 2 Hz and 3 Hz, showed a strong agreement between the measured displacements and theoretical predictions, with root mean square errors consistently below 0.3 mm. These results confirm the capability of the developed vision-based system to accurately track the dynamic response of simple structural elements at low frequencies, even when using low-cost hardware and open-source software tools.

The outcomes of the experimental campaign, conducted in a controlled laboratory environment, provide a solid foundation for the reliable application of this system to real-world monitoring tasks. In particular, the results highlight the potential of marker-based vision techniques as a viable and affordable alternative to traditional displacement sensors in SHM of civil infrastructures. This is especially relevant for infrastructures located in low-income regions, where the availability of low-cost yet accurate measurement solutions can support decision-makers in timely maintenance and safety assessments.

Future work will focus on extending the application of the proposed system to uncontrolled environments, such as full-scale infrastructures, where varying illumination and environmental conditions may affect marker detection and tracking accuracy. A more extensive metrological characterization will also be carried out, employing a reference measurement system capable of ensuring the traceability of the results and enabling a comprehensive assessment of the measurement uncertainty under different operating and environmental conditions. In parallel, further improvements in data analytics, filtering techniques, and machine learning algorithms will be pursued to enhance the robustness, automation, and overall reliability of the measurement process. These developments aim to enable continuous and real-time monitoring of structural systems, promoting the broader use of low-cost vision-based SHM technologies in both research and real applications.

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Structural damage identification through PCA and subspace comparison

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***Abstract*— A numerical study is presented to assess the sensitivity of a PCA-based subspace comparison method for structural damage detection. Results demonstrate that principal angles between subspaces reliably quantify damage severity, confirming the robustness of the approach under controlled conditions.**

Keywords*— *Structural Health Monitoring, Structural diagnostics.

I. INTRODUCTION

Structural Health Monitoring (SHM) represents one of the most active and challenging research areas in civil engineering, since it directly concerns the preservation, safety, and functionality of infrastructures that are inevitably affected by material degradation and aging. In particular, motorway viaducts and prestressed concrete bridge decks are highly exposed to environmental actions, traffic loading, and long-term deterioration processes, which can progressively compromise their serviceability and structural integrity. The need for reliable diagnostic tools, capable of detecting anomalies before they evolve into severe damage, is therefore widely recognized in both the scientific community and professional practice.

Within this broad field, a variety of statistical and data-driven approaches have been explored to process the large amount of information provided by experimental monitoring systems. Among them, methodologies based on Principal Component Analysis (PCA) combined with subspace comparison through principal angles have proven to be especially effective. The strength of this approach lies in its ability to condense the high-dimensional information contained in ambient vibration data into a reduced representation that captures the essential features of the structural response. Such a reduction is crucial because vibration measurements collected under operational conditions are inherently affected by environmental variability and noise, which may mask or distort the signatures of damage. By exploiting the properties of PCA, it becomes possible to filter out much of this variability and to focus on the structural characteristics that are most informative for diagnostics (Agrò 2022; 2025).

In previous investigations, this methodology was applied to real motorway viaducts, where it was tested under true operational scenarios. The results demonstrated its capability to reveal anomalies in the dynamic response of the structures, even when only ambient vibrations were available as input data (Agrò 2022). To further strengthen the reliability of the diagnostic indicators, the approach was subsequently enhanced through the integration of bootstrap resampling procedures for time series. This extension made it possible to assess the statistical significance of the results, thereby providing a quantitative measure of confidence and reducing the risk of misinterpretation due to random fluctuations. The combination of PCA and bootstrap-based validation thus offered a robust framework that could effectively operate in the presence of real-world variability.

However, the use of experimental data, while essential to validate the method under practical conditions, also introduces a limitation: the intrinsic complexity of field measurements prevents a systematic and controlled assessment of the sensitivity of PCA with respect to different levels of structural damage. In other words, when dealing with real infrastructures, the damage scenarios cannot be finely tuned or precisely isolated, making it difficult to quantify how the method responds to incremental or localized deteriorations.

To overcome this limitation, the present work introduces a numerical study specifically conceived to reproduce controlled scenarios and to isolate the effects of damage from other sources of variability. The objective is to create an artificial yet representative environment where the detectability of damage can be investigated in a systematic and reproducible manner. In this framework, PCA is employed not as a direct damage index, but as a fundamental tool for dimensionality reduction, enabling the construction of a compact representation of the structural response space. Damage detection is then formulated as a problem of subspace comparison, in which the response of the intact structure defines the reference configuration, while the response of the damaged structure is projected onto a different subspace. The divergence between these subspaces, measured in terms of principal angles, provides the diagnostic evidence needed to identify and evaluate damage.

II. METHODOLOGY

A. Numerical model

The objective of this study, pursued through a numerical approach, is the development of a diagnostic tool capable of providing a quantitative and statistically supported assessment of structural damage, while also expressing its severity through a numerical parameter. The procedure relies on the analysis of the structural dynamic response, expressed in terms of acceleration time histories, which represent the most direct and informative signal for vibration-based diagnostics.

To establish a rigorous benchmark, the method was first calibrated on a controlled reference system, whose mechanical properties are well defined and unaffected by environmental disturbances. It is worth noting that the numerical signals used in this study do not include any additive measurement noise.

While this choice isolates the effect of stiffness degradation and allows the subspace-based indicator to be evaluated under idealized conditions, it also represents a limitation of the present simulation framework.

For this purpose, a finite element (FE) model of a simple yet spatially representative structural configuration was implemented. The model was subjected to excitation by means of an accelerogram characterized by variable amplitude and frequency content, and the resulting acceleration responses at selected nodes were extracted and organized for subsequent statistical processing.

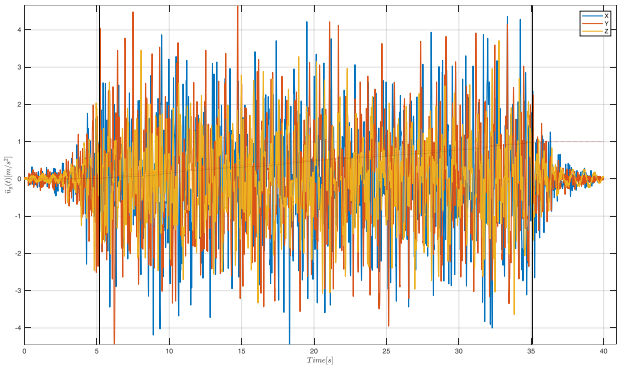


Fig. 1 - Input accelerogram - earthquake record

The numerical model consists of a slender vertical structure resting on a rigid base. This configuration was selected as a representative and simplified case study, suitable for reproducing the fundamental vibration modes in the two principal directions, x and y. The structural member was assigned inertial properties equivalent to those of a standard steel profile commonly available on the market. The discretization was performed using four beam-type finite elements and five nodes, each characterized by six degrees of freedom. This simplified configuration serves as a preliminary reference model, conceived to test and validate the proposed diagnostic procedure under controlled conditions.

The base node of the vertical structure was connected to a three-dimensional truss support system. This secondary structure did not influence the analysis results, as the focus was placed on the acceleration response matrices corresponding to the five nodes of the slender column. Although the support could have been simplified as a single rigid vertical member fixed at the base, a trussed configuration—commonly employed in the electromechanical field—was preferred to provide the overall model with a realistic geometrical representation.

The numerical investigation was conducted through four consecutive stages, each designed to simulate a progressive damage scenario under controlled conditions. In the first stage, the elastic modulus of steel (E=210,000 MPa) was adopted, representing the undamaged reference state of the structure. This configuration established the baseline dynamic behaviour and served to calibrate the PCA-based diagnostic framework on a healthy system, free of stiffness degradation.

In the subsequent stages, the elastic modulus of the second element of the slender portion—counting from the base—was systematically reduced in order to reproduce a localized loss of stiffness, corresponding to a gradual evolution of damage. The choice of the second element as the damaged component was intentional: its position ensures that the effects of stiffness reduction are transmitted through the structure without directly involving the boundary conditions, thus allowing a more realistic propagation of local damage to the global dynamic response.

The adopted sequence of stiffness reductions was defined as follows:

- **Stage 2:** E=100,000 MPa
- **Stage 3:** E=50,000 MPa
- **Stage 4:** E=25,000 Mpa

These values were selected to represent increasing levels of mechanical degradation—from moderate to severe—while still preserving the overall stability of the system. This progressive reduction provides a systematic framework for assessing the sensitivity of the diagnostic method to different degrees of damage severity. The induced stiffness losses modify the modal properties of the structure, producing measurable variations in the acceleration response, which are subsequently captured and quantified through the PCA and subspace comparison procedure.

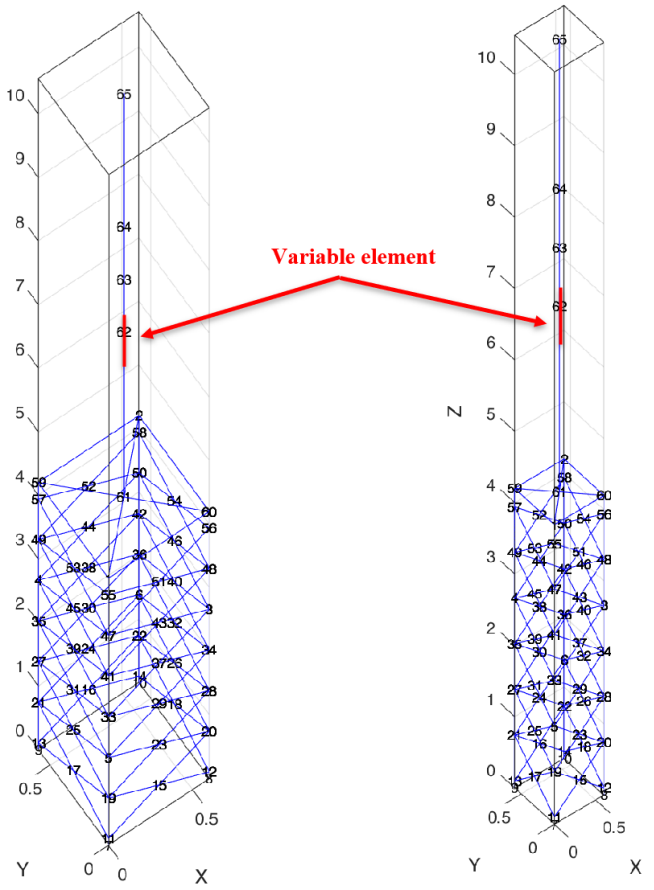


Fig. 2 - Finite Element Model (general view and mesh)

From the FE solver, acceleration responses in the x and y directions were extracted for all five nodes. The acceleration time histories consist of $n = 40\,000$ samples acquired at a sampling frequency of $f_s = 100$Hz, resulting in a total record

length of 400 s. The corresponding FFT frequency resolution is

$$\Delta f = \frac{f_s}{n} = 0.0025 \text{ Hz}.$$

These data were subsequently organized into two matrices, respectively X and Y, each containing five columns corresponding to the acceleration time histories of the five nodes.

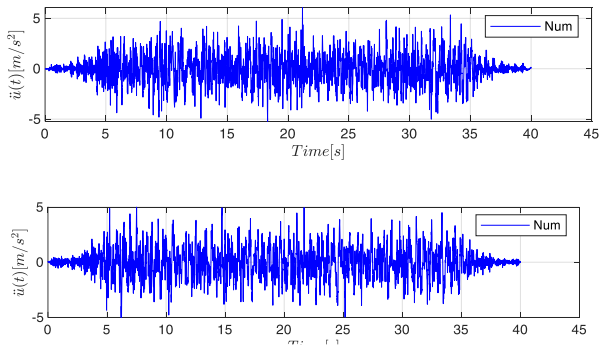


Fig. 3 – Typical accelerometric response of the points of the slender structure

Finally, the system was described by the matrix:

$$Z = X^2 + Y^2 \quad (1)$$

The adoption of configuration Z was motivated by the need to analyze a structural system whose dynamic behaviour is not governed by a single direction. This choice ensures a spatial response, closer to real structural conditions, and allows the proposed method to be tested under multidirectional dynamics, where modal interactions make damage detection more challenging and therefore more significant.

Indeed, many real structures, even when geometrically simple, do not exhibit a purely uniaxial dynamic response. The interaction between mass distribution, stiffness, and boundary conditions often produces coupled vibration modes that dominate the global behavior. For this reason, the numerical model was conceived with a simple geometry but designed to reproduce a spatially coupled dynamic response. Investigating an overly idealized structure vibrating in a single direction would have provided only limited insight, reducing both the generality and the practical relevance of the proposed diagnostic method.

For the intact configuration, the response data were arranged into the matrix $ZI=XI^2+YI^2$ with dimensions $(n\times p)=40{,}000\times 5$. The application of PCA to this matrix revealed that the first principal component accounts for approximately 90% of the system's total energy. On this basis, the optimal dimensionality reduction is achieved with k=1, leading to a one-dimensional subspace sZI that effectively represents the intact state of the structure.

B. Bootstrap distribution of the angle

To evaluate whether the observed differences between subspaces are statistically significant, a hypothesis test is formulated. The null hypothesis H_0 assumes that the subspaces represent the same dynamic behavior, implying that the maximum principal angle between them is zero. Since the sample distribution of principal angles under H_0 is not analytically known, we estimate it empirically using the Bootstrap method (Efron & Tibshirani, 1994), specifically employing a Moving Block Bootstrap (MBB) approach. This method accounts for temporal dependence within the vibration time series by resampling contiguous blocks rather than individual observations (Lahiri, 2003).

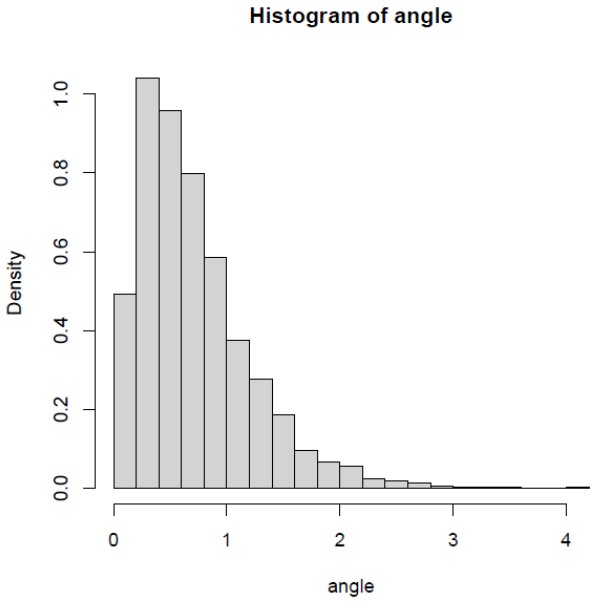


Fig. 4 - Sampling distribution of the angle θ

The figure shows the histogram of the sampling distribution of the angle θ, the corresponding to the maximum principal cosine, between sZI and the analogous samples generated, through moving-block bootstrap applied to time-series matrices of ZI.

III. RESULTS

The model is first modified by introducing a first level of damage (e.g., a localized stiffness reduction). The new matrix is:

$$Z1 = X1^2 + Y1^2 \quad (2)$$

with the same dimensions (nxp) = 40000 × 5. PCA shows that the first principal component explains about 96% of the energy. The comparison between sZI and sZ1 yields an angle of about 6°, significantly different from zero with confidence level 0.001.

With a second level of damage, more severe than the first, the resulting matrix is:

$$Z2 = X2^2 + Y2^2 \quad (3)$$

The comparison between sZI and sZ2 gives an angle of about 10°, also significantly different from zero.

Finally, introducing a third and more severe level of damage:

$$Z3 = X3^2 + Y3^2 \quad (4)$$

the PCA reduction (k = 1) and comparison with sZI return an angle of about 16°, again statistically significant.

Structural state	*Variance explained by 1st component*	*Principal angle vs. intact system*	*Statistical significance*
Intact (ZI)	~90%	-	-
Damage 1 (Z1)	~96%	~6°	$p < 0.001$
Damage 2 (Z2)	~95%	~10°	$p < 0.001$
Damage 3 (Z3)	~94%	~16°	$p < 0.001$

IV. DISCUSSION

The progressive increase in principal angles with damage severity (from 6° to 10° and then to 16°) highlights the capability of the proposed method not only to detect structural damage but also to quantify its extent. Within this framework, PCA serves as a tool for dimensionality reduction and information condensation, whereas the actual damage diagnosis is carried out by comparing the subspaces associated with the intact and the altered structural states. This strategy thus combines the efficiency of a compact representation with the discriminative power of subspace angles.

In practical applications, measurement noise would introduce additional variability in the acceleration time histories and could reduce the separation between the PCA subspaces associated with the intact and damaged states. In particular, noise tends to increase the variance explained by higher-order components and may partially obscure the changes induced by low-severity damage. However, the bootstrap-based statistical assessment adopted here can mitigate this effect by quantifying the confidence level associated with the observed subspace divergence. A future extension of this work will include controlled noise injection into the numerical model to evaluate the robustness of the proposed indicator under realistic ambient-vibration conditions.

V. ANALYSIS IN THE FREQUENCY DOMAIN

To further validate the sensitivity of the PCA-based diagnostic method, an additional investigation was carried out in the frequency domain, with the aim of correlating the statistical indicator obtained from subspace comparison with the physical variation of the dynamic properties of the structure. Indeed, any reduction in the stiffness of a structural element — simulated in this study by the progressive decrease of the Young's modulus in a single finite element — is expected to produce a corresponding decrease in the natural frequencies. By evaluating these changes alongside the PCA results, it is possible to establish a coherent relationship between the two diagnostic indicators.

The acceleration time histories of the four structural configurations (intact, first, second, and third damage) were processed through the Fast Fourier Transform (FFT) to identify the predominant frequency peaks associated with the fundamental vibration modes. As expected, the first two natural frequencies exhibited a clear and monotonic decrease as the damage severity increased. This trend directly reflects the loss of global stiffness resulting from the localized degradation introduced in the numerical model. The computed frequencies for the four damage scenarios are summarized in table below, together with their percentage reduction with respect to the intact configuration.

Structural state	*f_1 (Hz)*	*Δf_1 [%]*	*f_2 (Hz)*	*Δf_2 [%]*
Intact (ZI)	0.262	-	0.895	-
Damage 1 (Z1)	0.232	−11.4 %	0.850	−5.0 %
Damage 2 (Z2)	0.192	−26.7 %	0.800	−10.6 %
Damage 3 (Z3)	0.165	−37.1 %	0.737	−17.6 %

The progressive reduction of the natural frequencies provides an objective confirmation of the degradation simulated in the finite element model. When these variations are compared with the principal angles obtained from PCA subspace analysis (6°, 10°, and 16° for the three damaged states, respectively), a consistent and proportional trend emerges: the larger the reduction in stiffness (and thus in frequency), the greater the divergence between the subspaces representing the intact and damaged dynamic responses.

This dual evidence—statistical and physical—reinforces the robustness of the proposed diagnostic approach. PCA captures the structural changes through a geometric indicator in the feature space (the principal angle), while the FFT analysis links those changes to a measurable physical parameter, namely the shift in modal frequencies. Figure 5 illustrates this comparison by jointly plotting the evolution of the principal angle θ and the percentage reduction of the first two natural frequencies as functions of the damage level. To emphasize their common increasing trend, the frequency variation is represented on an inverted secondary axis, ensuring that all three curves consistently exhibit an upward trajectory with increasing damage severity.

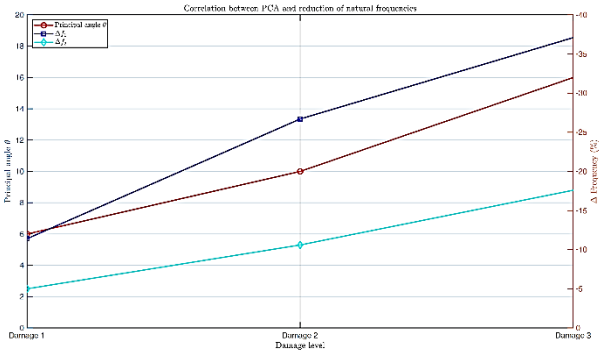


Fig. 5 - Comparison between the principal angle θ from PCA and the percentage reduction of the first two natural frequencies.

VI. CONCLUSIONS

This study has assessed, through a controlled numerical model, the capability of a PCA-based subspace comparison approach to detect and grade structural damage. The adoption of a moving-block bootstrap scheme provides a statistically robust basis for evaluating the significance of the observed subspace deviations. The numerical investigation complements earlier applications to real structures, offering a clearer perspective on the diagnostic potential of PCA and outlining several directions for future developments. Future work will incorporate simulated random noise to evaluate the reliability of the proposed indicator under operational conditions and to quantify its sensitivity in the presence of

realistic disturbances. Additional extensions will include extending the analysis beyond the first principal component and integrating the approach with more advanced subspace-based techniques to further examine the robustness and applicability of the method.

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Automatic Mapping Of Vegetated Areas In Benevento (Italy) From Sentinel-2 Images

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***Abstract*— Mapping vegetated areas provides essential data for multiple purposes, from sustainable management of natural resources to precision agriculture, from urban planning to environmental protection. Indeed, the precise location, perimeter, and consistency of vegetated areas are crucial for monitoring plant health, optimizing water and fertilizer use, identifying at-risk areas, preventing health problems, and assessing the impact of climate change, contributing to biodiversity conservation and ecosystem resilience. Multispectral remote sensing images appropriately processed using algorithms capable of emphasizing the presence of living organisms where chlorophyll synthesis is occurring, and others capable of classifying "green areas" as such, provide valuable support for mapping vegetated areas. This process is typically assisted by an operator who provides the machine with statistical data to support the process of recognizing and classifying vegetated areas. This article aims to demonstrate that the process of mapping green areas can be completely automated and eliminate training phases. The study area is Benevento city and surrounding territory in the Campania Region (Italy), particularly rich in natural vegetation, cultivated fields, and urban parks. Sentinel-2 imagery at a resolution of 10 m is used for this purpose: the construction of the Normalized Difference Vegetation Index (NDVI) allows us to emphasize the presence of green areas, and the unsupervised K-means classifier provides automatic pixel recognition, distinguishing vegetation from non-vegetation. The use of test sites for the two classes involved, the construction of the confusion matrix, and the calculation of the accuracy parameters—producer accuracy (PA), user accuracy (UA), and overall accuracy (OA)—highlight the excellent level of the results achieved. For the entire study area, an OA value of 0.989 is recorded.**

Keywords—Vegetated area automatic mapping, Normalized Difference Vegetation Index (NDVI), unsupervised classification, k-means, accuracy test sites.

I. Introduction

Vegetation can be defined as an assemblage of plants of one to many species growing in areas of different sizes [1]. A vegetated area is a geographic space predominantly covered by plant life, such as trees, shrubs, grasses, and other flora, which can include both live plants and residual plant matter like litter or residues. These areas can range from naturally occurring ecosystems like forests and grasslands to cultivated areas like gardens and agricultural fields, all characterized by the significant presence of vegetation.

Population growth and urban development are leading to the conversion of land into less vegetated areas; information on land cover changes is essential to facilitate strategic decisions, primarily to support regional urban planning [2]. Mapping vegetated areas facilitates land-use planning because it provides a detailed and visual knowledge base for defining interventions that ensure environmental sustainability and land quality. By identifying the distribution, type, and health of vegetation, strategies can be developed for managing natural resources [3], protecting biodiversity [4], creating ecological corridors [5], and preventing environmental risks [6].

Mapping vegetated areas is the first step in assessing environmental status: it allows us to understand the extent and state of conservation of green spaces, including woodlands, forests, and parks, providing a clear picture of an area's "natural capital". In addition, mapping vegetated areas is useful for identifying critical areas, such as those subject to hydrogeological instability, for which vegetation plays a protective role.

The use of digital mapping tools provides objective data that improves the transparency and effectiveness of decisions made by competent authorities [7]. Integration with other plans is also possible: the mapping of vegetated areas can be combined with water resources management plans, energy planning and sustainable mobility strategies, promoting harmonious territorial development.

Remote sensing is essential for mapping vegetated areas because it analyzes the radiation reflected by vegetation, allowing the creation of vegetation indices that correlate with the health, biomass, and phenology of the vegetation itself [8]. It also offers the advantage of collecting data over large, inaccessible areas quickly and cost-effectively, providing continuous monitoring and frequent updates [9].

Multispectral optical sensors on board of satellites, manned aircrafts or drones allow us to acquire images at

different resolutions from which it is possible to extract the vegetated areas automatically. Each acquisition platform is subject to distinct sources of uncertainty — the most common being atmospheric conditions, which can significantly affect remote sensing measurements, especially in satellite imagery [10]. The errors present therefore require a preliminary correction to remove them. Indeed, by selecting the bands that emphasize the different reflectance between vegetation and other types of land cover, such as water and bare soil, it is sufficient to classify the pixels as vegetation or non-vegetation. This result can also be achieved with unsupervised classification, based exclusively on the spectral characteristics of the pixels themselves, that is, on their radiance values, without training sites and the assistance of an operator [11] [12].

To contain the costs of the entire process of mapping and monitoring vegetated areas, aimed at promptly capturing temporal variations in both their size and health, it is necessary to act on two fronts: on the one hand, using freely available satellite imagery, on the other, automating the entire process or at least minimizing operator intervention. This article focuses on the use of freely available satellite images such as Sentinel-2, appropriate index application and unsupervised classification for automatic mapping of vegetated area. Using the highest resolution bands of Sentinel-2 imagery (cell size: 10 m x 10 m), Normalized Difference Vegetation Index (NDVI) [13] is used for then submit the resulting layer to unsupervised classification algorithm named K-means. Test sites are introduced to evaluate the accuracy of the two classes. i.e. vegetation and no-vegetation. The entire process is carried out using Geographic Information System (GIS) tools available in Quantum GIS software, version 3.40 [14].

The article is structured as follows. After section I that introduces the topics covered, Section II describes the study area, i.e. Benevento city and surrounding territory, in Campania (Italy), and the dataset used concerning the Sentinel-2 images with a resolution of 10 m. Section 3 presents the adopted methodological approach based on the use of NDVI for emphasizing the presence of vegetation and K-means for unsupervised classification. Section IV shows and comments the results achieved. Finally, Section V concludes the article remarking the principal results and highlighting the possibility of extending the approach to other situations.

II. Study Area and Datasets

A. Study area

The applications have as their geographical reference area Benevento city and surrounding territory, in Campania (Italy).

Benevento is an Italian municipality with 55,319 inhabitants, the capital of the province of the same name in Campania. The city is located in the Apennine hinterland of this region, in a basin surrounded by hills and highlands at the confluence of two rivers: the Calore, a tributary of the Volturno, and the Sabato, which flows into the Calore in the Pantano district, just west of the city center. A third river, the Tammaro, flows into the Calore near Ponte Valentino, near the eponymous industrial area.

The city's terrain is quite undulating: the center rises on a modest hill in the middle of the valley, while some districts are located on other surrounding hills. The municipal seat is 135 meters above sea level, with a minimum of 80 meters and a maximum of 495 meters, equal to a range of 415 meters. The geological base on which the urban area rests is made up of the Ariano unit (detrital formation of Pliocene origin), on which alluvial and pyroclastic deposits are superimposed (the latter linked to the eruptions of volcanoes in the Campania area). The climate is typically Mediterranean, with more continental influences than the coast, and the area is subject to high seismic risk and occasional flooding. The vegetation of Benevento and its surrounding area is diverse, encompassing both typical Mediterranean scrub and broadleaf forests, with a transition to beech forests at higher altitudes. In the lower areas, cultivated fields and Mediterranean scrub are found, while higher up, oak trees such as holm oak and downy oak appear, followed by chestnut trees and beech forests. Along the waterways, riparian vegetation includes willows and poplars [15]. Fig. 1 shows the study area.

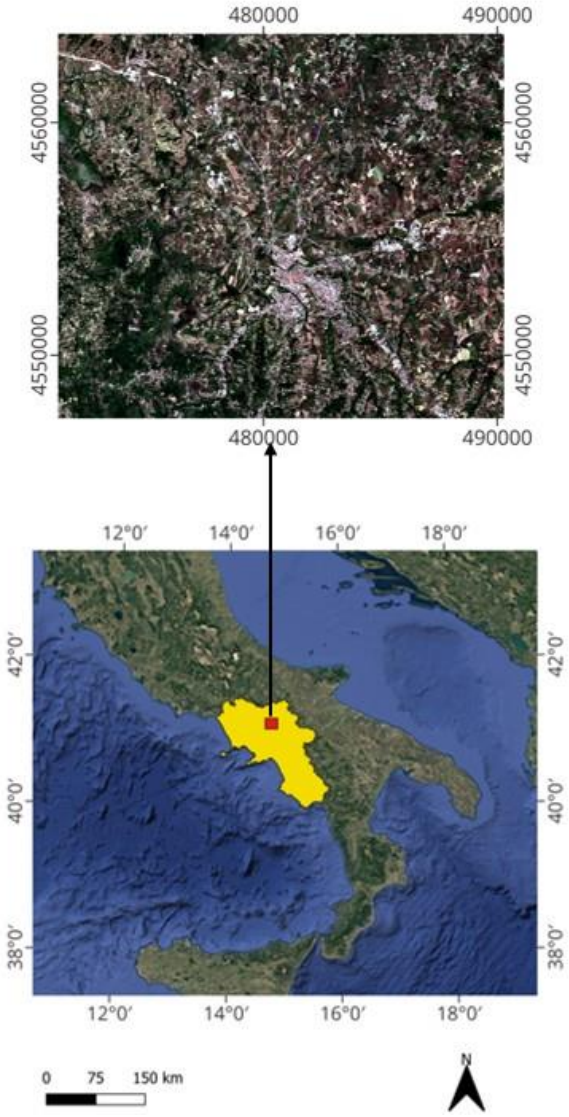


Fig. 1. Geolocalization of the study area: Benevento city and surrounding territory in Campania Region. The coordinates referred to World Geodetic System -WGS84: Universal Transverse Mercator (UTM) Zone 33 N plane coordinates for the detailed view (in the upper part) and ellipsoidal coordinates for the South Italy (in the lower part).

B. Datasets *Universal Transverse Mercator -*

The Copernicus Sentinel-2 mission is an Earth-observing satellite mission by the European Space Agency (ESA) that

provides high-resolution, multi-spectral optical imagery of Earth's land surface and coastal areas. It monitors land cover, vegetation health, soil, and water, providing data crucial for agriculture, forestry, land management, and disaster relief efforts like mapping floods and burned areas. The mission uses a constellation of twin satellites, with Sentinel-2A, Sentinel-2B, and Sentinel-2C currently in orbit, offering frequent revisits and high-detail images [16]. The Sentinel-2 dataset includes images acquired in 13 different bands with varying geometric resolutions: 4 at 10 meters, 6 at 20 meters, and 3 at 60 meters. Sentinel-2 imagery features different levels of correction, which are applied to the raw data to remove the effects of external factors and prepare the data for specific analyses. The main levels are identified as Level 1 (raw data, with few corrections, mainly geometric) and Level 2 (geometrically and radiometrically corrected data). This study uses Level 2A imagery, which is also atmospherically corrected, making it "analysis-ready" for quantitative land-based applications, such as vegetation or inland water monitoring. Therefore, given the objectives pursued, images are not further corrected for this study.

The main characteristics of Sentinel-2 images are shown in Table I. The highest-resolution images, i.e. B2, B3, B4 and B8, are used for the applications developed in this work.

TABLE I. MAIN CHARACTERISTICS OF SENTINEL-2 IMAGES

Sentinel-2		
Bands	**Central Wavelength (µm)**	**Resolution (m)**
B2—Blue	0.490	10
B3—Green	0.560	10
B4—Red	0.665	10
B8—NIR	0.842	10
B5 - Red Edge 1	0.705	20
B6 - Red Edge 2	0.740	20
B7 - Red Edge 3	0.783	20
B8 - NIR	0.842	10
B8A - Narrow NIR	0.865	20
B9 - Water Vapor	0.945	60
B10 - SWIR - Cirrus	1.375	60
B11 - SWIR 1	1.610	20
B12 - SWIR 2	2.190	20

III. METHODS

Several scientific articles and research studies demonstrate relevant progress and the widespread use of automated vegetated area mapping techniques based on satellite imagery. Research has made significant strides, particularly with the advent of artificial intelligence (AI), machine learning [17], and, more recently, deep learning [18]. These methods enable the efficient processing of large volumes of satellite data (such as those from the Copernicus Sentinel or Landsat missions) to classify land use and identify vegetation with a significant reduction in human intervention.

Although good levels of automation have been achieved, certain operations such as calibration, training sites definition, field validation, and human interpretation often remain crucial to ensuring the accuracy of results. This research aims to reduce the need for these interventions and achieve a higher degree of automation in the mapping of vegetated areas, at least when the goal is not to distinguish within them (trees, crops, meadows, etc.) but simply to detect their presence or absence.

The approach followed for the automatic mapping of vegetated area from Sentinel-2 images at 10 m resolution is based on four fundamental steps as shown in the workflow in Fig. 2.

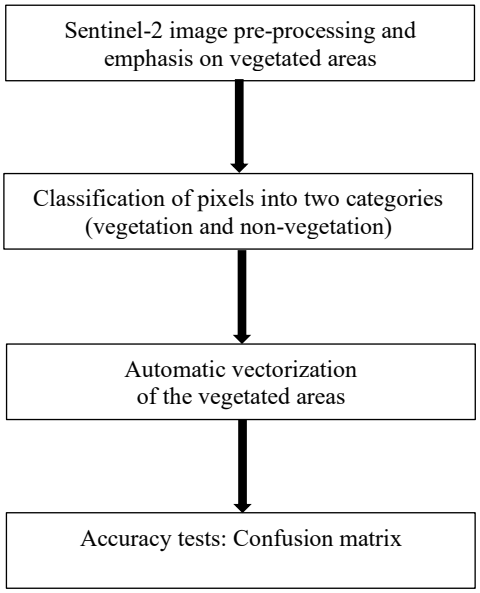


Fig. 2. Workflow of the methodological approach adopted in this study.

The first step involves image preprocessing, i.e., geometric and radiometric corrections and vegetation index application. However, corrections are not necessary for this study, as Sentinel-2 level 2A was chosen. Vegetated areas are emphasized using NDVI. The second step involves classifying the NDVI layer to distinguish vegetated areas from their context. The third step involves automatically vectorizing the vegetated areas, an operation usually provided by GIS software. The fourth step is the final verification of the accuracy of the generated map.

The above-mentioned steps are described in details in the following subsections.

A. Vegetation area enphasis

Near Infrared (NIR) and red light are the most suitable frequency region of electromagnetic spectrum for detecting vegetation. In fact, healthy plants reflect strongly in NIR region while absorbing most red light for photosynthesis. This significant contrast between high NIR reflectance and low red light absorption creates a distinct spectral signature for vegetation that multispectral sensors can detect, enabling the differentiation of healthy plant-covered areas from other surfaces and even indicating plant health and stress.

Vegetation indices are mathematical combinations of spectral bands from imagery, like satellite images, that are used to quantify and analyze vegetation properties such as

plant health, biomass, vigor, and water content. These indices work by processing the reflected light from vegetation, especially in the NIR and red portions of the electromagnetic spectrum, to create a single number that highlights vegetation characteristics in a specific area. The most common example is NDVI.

Introduced by Rouse et al [13], the NDVI is provided by the following formula:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

NDVI values are mathematically limited to a range between -1 and +1 due to the way the index is calculated. In fact, normalization ensures that the resulting value always falls within this range, regardless of the total sunlight intensity or the sensor used. Healthy vegetation returns high NDVI values because it has a unique spectral signature: it absorbs a lot of red light for photosynthesis and reflects near-infrared (NIR) light intensely due to its cellular structure. In fact, chlorophyll, the key pigment for photosynthesis, absorbs most visible light, particularly in the red range. Therefore, an area with dense, healthy vegetation will have a very low reflectance (RED) value. The internal structure of healthy plant leaves reflects near-infrared light very efficiently, scattering it to prevent overheating. Therefore, an area with healthy vegetation will have a very high reflectance value (NIR). Low positive values (around 0.2-0.5) indicate sparse vegetation, such as shrubs, grasslands, or early crops. High positive values (around 0.6-0.9) correspond to dense and lush vegetation, such as rainforest forests and temperate forests, which reflect a lot of near-infrared light. Values close to zero (-0.1 to 0.1) indicate a near-total absence of vegetation (barren areas, rocks, sand, and bare soil). Lower negative values usually indicate the presence of bodies of water.

NDVI is applied in this study using B4 and B8 bands of the selected image. Actually, it is not recommended to use a single satellite image for accurate identification of vegetated areas. While a single image can provide a basic indication, the use of time series or multiple images is essential to obtain reliable results and overcome several limitations [19]. However, this phase of our study is testing the ability of the procedures examined to automatically identify vegetated areas present in the examined images, rather than accurately mapping the actual conditions present in the study area. In other words, the aim is to test the accuracy achievable with the proposed method for processing remotely sensed images, with reference to the contents of the dataset used and not to the actual situation in the study area.

The application is implemented using Raster calculator, a tool employed to perform calculations on the pixel values of raster layers, creating a new raster layer with the results.

B. Unsupervised Classification: K-means application

K-Means clustering is an unsupervised algorithm that segments remote sensing images into a pre-defined number of groups (clusters). It iteratively assigns pixels to the nearest cluster center (centroid) and recalculates the centroid's position based on the assigned pixels' features (e.g., spectral values) [20] [21]. In short, it starts by choosing K clusters and randomly initializing their centroids. Then, each data point is assigned to the closest centroid, the centroids are recalculated as the average of the points in their cluster, and this process repeats until the cluster assignments no longer change.

The principal steps can be summarized as follows.

1. Initialization: Define the number of clusters, K, and Randomly place K centroids in the data space.
2. Assignment: For each data point, calculate the distance from each centroid (for example, using Euclidean distance) and assign each point to the cluster with the closest centroid.
3. Update: Recalculate the position of each centroid as the average of all data points assigned to its cluster.
4. Iteration: Repeat steps 2 and 3 until the centroids no longer change between iterations, or until a maximum number of iterations is reached. This indicates that the algorithm has converged.

This basic method provides an overview of objects, useful for tasks like land cover classification, and is often implemented in GIS and remote sensing software. The Unsupervised Classification Plugin available in QGIS allows us to classify satellite images using unsupervised methods. This plugin provides an easy-to-use interface for loading satellite images and selecting from a variety of unsupervised classification algorithms, including K-means.

K-means is applied to NDVI layer. This algorithm achieves good results when applied to segment a raster layer into a few clusters with very distinct statistical characteristics. Therefore, the algorithm is useful for the purposes pursued in this study since water, bare soil and vegetation pixels present different values in NDVI.

C. Automatic vectorization

Through the classification by K-means, the NDVI layer is clustered into two parts: vegetation and non-vegetation.

Polygonization tool available in QGIS provides to convert raster data into vector polygons. This tool generates polygons from contiguous raster cells of the same value.

D. Accuracy tests

To evaluate the results obtained by integrating NDVI and unsupervised classification, accuracy tests are executed. Specifically, confusion matrix and related indicators are used to establish the quality of the classification.

Confusion matrix is a table used to evaluate the performance of a classification model, showing the counts of correct and incorrect predictions for each class. It breaks down predictions into True Positives, True Negatives, False Positives, and False Negatives, providing a detailed view of a model's accuracy and revealing specific types of errors it makes, which is crucial for understanding its strengths and weaknesses.

Three indices are used: Producer Accuracy (PA), User Accuracy (UA), and Overall Accuracy (OA).

The PA represents the probability that a real-world feature (ground truth) has been correctly classified in the map. This value is obtained by dividing the number of correctly classified pixels or samples (elements on the main diagonal of the confusion matrix) by the actual total for that class in reality (sum of the corresponding column in the confusion matrix) [22]. The UA indicates the probability that an element (for example, a pixel on a thematic map) classified in a given

category belongs to that category in the real world (ground truth). It is calculated as the proportion of correctly classified pixels compared to the total number of features the model has labelled as belonging to that class [23]. OA represents the total proportion of correct predictions or classifications made by a model compared to the total number of cases examined. Overall accuracy is calculated by dividing the total number of correctly classified pixels by the total number of pixels in the dataset [24].

IV. Results and Discussion

Fig. 3 shows the NDVI layer resulting from bands B4 and B8 of the Sentinel-2 dataset concerning the study area.

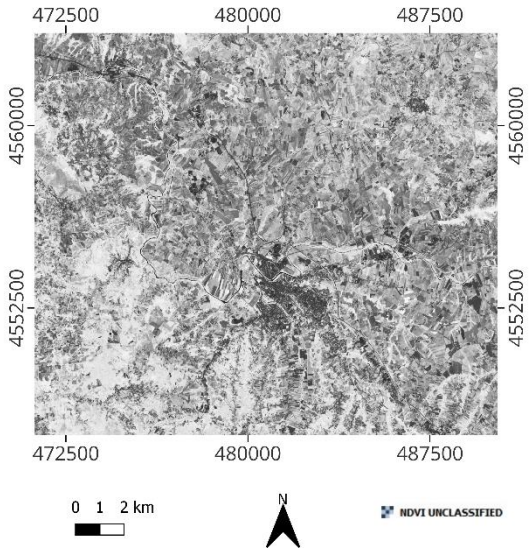


Fig. 3. The NDVI layer resulting from band 4 and band 8 of Sentinel-2 imagery (reference system: WGS84 – UTM Zone 33N)

Fig. 4 shows the results of K-means unsupervised classification algorithm applied to the NDVI.

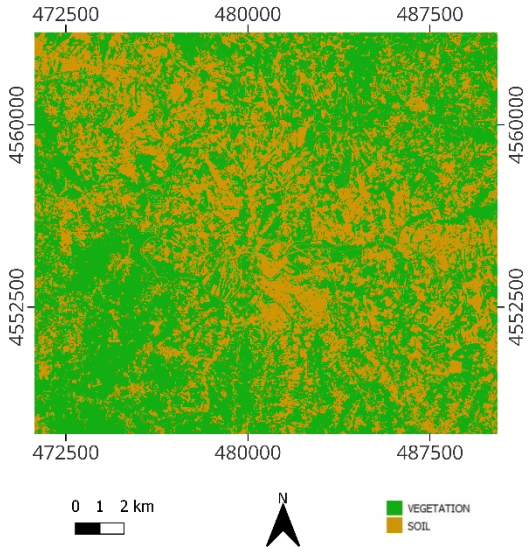


Fig. 4. The map resulting from K-means unsupervised classification algorithm applied to the NDVI layer (reference system: WGS84 – UTM Zone 33N).

Fig. 5 and fig. 6 show examples of test sites for vegetation and non-vegetation respectively.

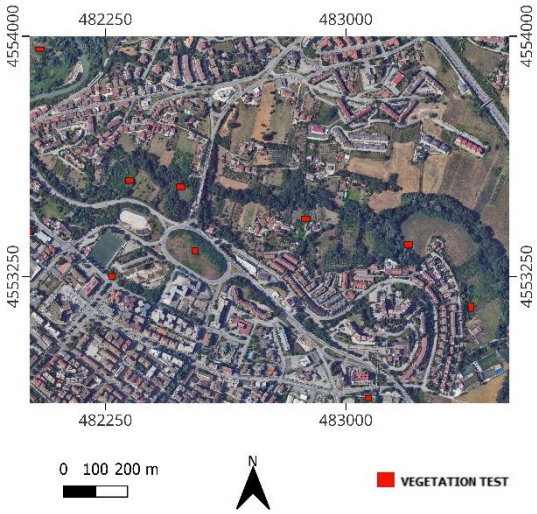


Fig. 5. Examples of test sites for vegetation (reference system: WGS84 – UTM Zone 33N).

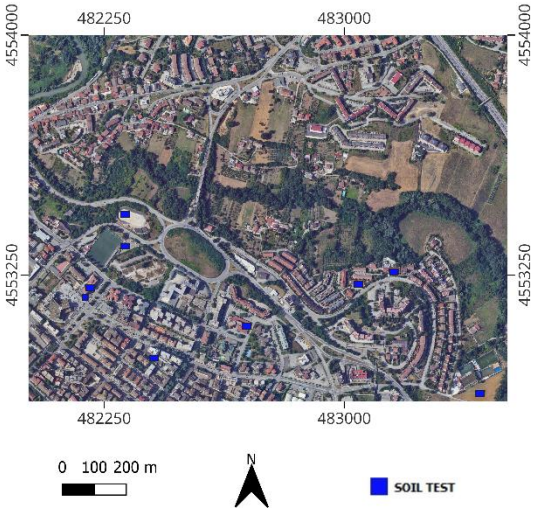


Fig. 6. Examples of test sites for non-vegetation (reference system: WGS84 – UTM Zone 33N).

Table II shows the results of the accuracy tests conducted with the confusion matrix applied to the classification operated by k-means applied to NDVI layer. The high values of the indicators used highlight the high capacity of the approach followed to distinguish pixels as vegetation and non-vegetation. A higher performance of the adopted approach is evident since OA is equal to 0.989, with an optimal classification for each class: 98.1% of vegetation pixels and 99.8% of non-vegetation pixels are correctly classified.

TABLE II. Thematic accuracy values: PA,UA and OA for NDVI layer

Layer	*Class*	*PA*	*UA*	*OA*
NDVI	Vegetation	0.981	0.997	0.989
	Non-vegetation	0.998	0.981	

V. Conclusions

The paper demonstrates that the automatic mapping of the vegetated areas from Sentinel-2 images at 10 m resolution is possible using GIS tools.

The procedure followed is based on the application of the NDVI which permits to emphasize the different spectral responses of bare soil and vegetation. The K-means classifier applied to the NDVI layer allows the differentiation of the image into two clusters associated with vegetation and non-vegetation. This algorithm works in an unsupervised manner, therefore without the operator having to provide training sites or do anything more than establish the number of classes.

The accuracy of the results is tested using confusion matrix and related indices PA, UA and OA. All results are no less than 0.98 confirming the high performance of the proposed approach.

The workflow adopted minimizes operator intervention and can be applied repeatedly for temporal monitoring. In fact, the experiment can be carried out for other images of the same area at different dates to reconstruct the changes over time of areas covered by vegetation; in this way it is possible to understand the dynamics underway and support an intervention plan aimed at protecting the environment, natural and artificial green spaces.

Finally, another consideration is necessary. The experiments are performed on a single image from a specific date. To determine whether an area is vegetated, multiple images from different acquisition dates within a year must be considered. An agricultural area, for example, might appear bare on one date, while on another, it might be thriving. As a result, future developments should include: validating the automation and assessing the robustness of the proposed method by applying it to multiple temporal datasets (different seasons or years); the expansion of the classification scheme to include other land cover types, such as water and built-up areas, to enhance comprehensiveness; the inclusion of a more detailed comparison with existing studies in the literature to better contextualize the performance and relevance of the proposed workflow.

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Coastline Automatic Extraction From Sentinel-2 Images: Different Methodological Approaches In Comparison

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Abstract*— Remote sensing techniques are useful for acquiring coastline position because they allow data to be collected in dangerous or inaccessible areas without disturbance, offer frequent updates, and reduce costs and time compared to land-based collection. Data acquired by satellite, aircraft, or drones provide a broad and detailed view, facilitating the monitoring of coastal changes over time. Automating the process of coastline detection in satellite images dramatically reduces processing time compared to manual methods, enabling the analysis of large areas over long periods. Automation facilitates the management and organization of large amounts of data and helps speed up the analysis of time series of images to study phenomena such as erosion or sediment accumulation. The literature describes various methodological approaches for the automated extraction of coastlines from multispectral optical images. However, a common thread is generally found: the use of unsupervised classification algorithms such as K-means or Iterative Self-organizing Data Analysis Techniques (ISODATA). These are applied either directly to the images or after processing them. This paper compares three different methodological approaches for automatically extracting coastlines from Sentinel-2 multispectral images. The study area includes the coastline around the Gulf of Gaeta (Italy). All three methods analyzed use ISODATA to distinguish water from non-water pixels in the scene. Unsupervised classification is performed starting from: the synthetic image obtained via Normalised Difference Water Index (NDWI), the first component provided by the Principal Component Analysis (PCA) application and the three multispectral images selected based on the Optimal Index Factor (OIF) index that certifies the maximum level of decorrelation between the bands. The results are compared taking into account the level of accuracy achieved in the three cases analyzed. Test sites are used to construct the confusion matrix and calculate thematic accuracy indices. A comparison is also made between the position of the line manually vectorized through photointerpretation of the scene true-color Red Green Blue (RGB) composition, and the position of the line obtained as result of each methodological approach. Both tests prove a higher level of accuracy for the PCA-based method.

Keywords—Coastline automatic extraction, Normalized Difference Water Index (NDWI), Principal Component Analysis (PCA), Optimal Index Factor (OIF), unsupervised classification, Iterative Self-organizing Data Analysis Techniques (ISODATA), accuracy tests.

I. INTRODUCTION

Defined as a narrow strip of land that borders the sea along a continent or an island [1], coastline is a dynamic zone constantly shaped by natural processes like waves, tides, currents, erosion, and deposition, and its form depends on the type of land material and geological activity. Knowing the location of the coastline and monitoring its changes is essential for sustainability, as it helps protect ecosystems, manage vulnerable areas, and plan effective interventions to contrast the impacts of phenomena such as erosion [2] and sea level rise [3]. In fact, changes in the coastline can indicate the loss of key ecosystems that serve as natural barriers; the information collected supports land management decisions, allowing us to prioritize restoration efforts in the most at-risk areas, such as degraded wetlands, to reduce the erosion effects.

Remote sensing is a fundamental tool for monitoring coastlines over time [4][5]. By analyzing images or numerical data acquired by satellites, aircraft, drones, or other remote sensors, it is possible to compare coastline positions at different times to identify phenomena such as erosion. Remote sensing technologies collect data on the Earth's surface from remote platforms such as satellites or aircraft. By comparing images or numerical data acquired at different times, it is possible to observe variations in the position of the coastline. This process allows us to detect and quantify coastal retreat (erosion) or advance over time. The results can be used to understand the causes of changes (such as alterations in sedimentary cycles) and for environmental monitoring and land management purposes, as highlighted by the Italian Ministry of the Environment and Energy Security and l'Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), a public research body that conducts technical and

scientific work for the Italian government on environmental protection.

The advantages of remote sensing for coastline acquisition include the ability to acquire data synoptically and repeatedly over time, providing a comprehensive and up-to-date view of the coastline [6]. This technique is efficient for large-scale and multi-temporal monitoring, also offering data generalization and interpolation once the area of interest has been identified, and the possibility of using new technologies such as optical sensors, radar, and Lidar. In addition, using remote sensing to acquire coastlines offers significant economic advantages over other techniques, primarily because it is faster, more extensive, and potentially less expensive on a large scale. It allows for efficient coverage of large areas, reducing the costs associated with traditional field surveys, while maintaining good accuracy and the ability to monitor changes over time.

The coastline visible in a satellite or aerial image is the instantaneous position of the land-water boundary at the exact moment the image was taken (instantaneous coastline) [7]. This position varies continuously due to the tidal cycle (high and low tide). Consequently, the tide level at the time of image acquisition must be taken into account for high and very high resolution images [8]. However, tide consideration becomes irrelevant if the values are low (a few centimeters) in the area considered and the resolution is not high (pixel size over 4-5 meters).

This article focuses on the use of optical multispectral imagery, specifically processed using fully automated procedures to derive coastlines in vector format. The applications are performed on 10-meter-resolution Sentinel-2 imagery of the Gulf of Gaeta (Italy). The software used is Quantum GIS (QGIS) version 3.40.

The article is structured as follows. Section I introduces the topic by providing a summary of the importance of remote sensing for coastline monitoring and the opportunity to automate the coastline extraction process from multispectral optical images. Section II describes the study area that includes the Italian Tyrrhenian coastline around the Gulf of Gaeta, and the dataset used concerning the Sentinel-2 images with a resolution of 10 m. Section 3 presents the three different methodological approaches that applied unsupervised classification on different selection and processing of the satellite data. Section IV shows, compares and comments the results achieved. Finally, Section V concludes the article remarking the performance of each adopted approach and outlining future developments.

II. STUDY AREA AND DATASETS

A. Study area

The coastline examined in this study extends between the Italian regions of Lazio and Campania from point P1 to point P2, with the following ellipsoidal coordinates (longitude and latitude) referred to World Geodetic System 1984 (WGS84):

$\lambda_1 = 12° 36′ 17.55″$ E, $\phi_1 = 41° 28′ 15.85″$ N;

$\lambda_2 = 13° 55′ 20.65″$ E, $\phi_2 = 41° 01′ 40.00″$ N.

Most of the coast analyzed coincides with the Gulf of Gaeta. Fig. 1 shows geolocalization of the analysed coastline. The Gulf of Gaeta extends between the promontory of Mount Circeo (Lazio) to the north and the promontory of Capo Miseno (Campania) to the south, while to the west it is fronted by the Pontine archipelago. From a geomorphological point of view, the gulf is characterized by high coasts and alluvial plains. The high coasts extend mainly between Mount Scauri and Sperlonga, while the low coasts develop between Mount Scauri and Mount Procida. From a lithological point of view, the high coasts are composed of carbonate rocks that do not produce a significant amount of sandy detrital material, while the low coasts are composed of detrital material deriving from the Roccamonfina volcano and sandy-producing arenaceous rocks found on the right bank of the Garigliano River [9].

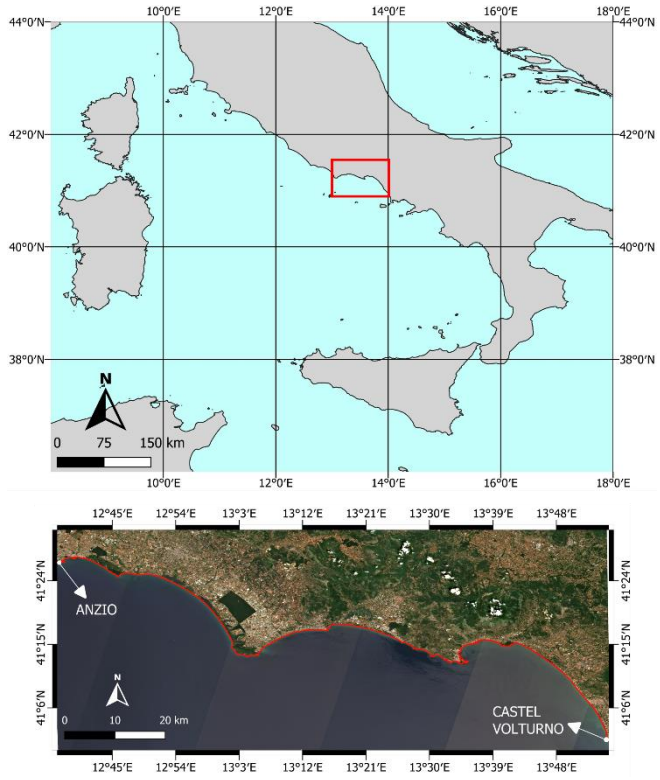


Fig. 1. Geolocalization of the study area: equirectangular projection with ellipsoidal coordinates referred to World Geodetic System 1984 (WGS84).

B. Datasets

Sentinel-2 is a mission developed by the European Space Agency (ESA) [10] as part of the Copernicus program [11] to monitor the planet's green areas and provide support in the management of natural disasters. It consists of two satellites, Sentinel-2A and Sentinel-2B, which will later be replaced by Sentinel-2C, launched in 2024, and Sentinel-2D.

The mission has the following characteristics:

Multispectral image acquisition in 13 visible and infrared bands;

Global coverage of land between 84° S and 84° N, coastal waters, and the entire Mediterranean Sea;

Overflight of the same point on the Earth's surface with the same viewing angle every 5 days (at higher latitudes, surface overflights are more frequent, but with different viewing angles);

Resolution of ground details of 10, 20, and 60 meters depending on the spectral band;

Ground horizon of 290 km;

Freely accessible data.

To ensure a high frequency of overflights and continuous availability, two identical satellites operate simultaneously in

the same sun-synchronous orbit at an altitude of 786 km and offset by 180 degrees.

The applications performed and described in this article use only Sentinel-2A images at 10 meters resolution acquired on June 10, 2025: Blue (B2), Green (B3), Red (B4) and Near Infrared (B8). All data are atmospherically corrected surface reflectance products, meaning they have been processed to remove the effects of the atmosphere to provide more accurate measurements of the Earth's surface. The images present cloud cover of less than 1%. However, appropriate cuts to areas not relevant to the intended purpose (extraction of the coastline of the Gulf of Gaeta) allow us to eliminate clouds from the study scene. This choice is appropriate to avoid any potential interference with the automatic classification [12].

III. METHODS

Automatic coastline extraction from Sentinel-2A images is performed using three different methodological approaches (MAs). The first one (MA1) applies the NDWI (Normalised Difference Water Index) to highlight the presence of water bodies (and therefore the sea) within the scene. The second (MA2) applies Principal Component Analysis (PCA) to reduce the number of variables, transforming potentially correlated ones into a smaller set of uncorrelated variables. Specifically, starting from the four 10-meter resolution images, it determines three new images that are highly decorrelated. The first principal component, which captures the most variance and best highlights the differences between pixels in relation to the nature of what they represent, is used for subsequent applications. The third approach (MA3) relies on the Optimum Index Factor (OIF) to select the three most decorrelated from the four 10-meter resolution images. In this case, too, decorrelation helps better highlight the differences between the areas.

The three methodological approaches adopted all involve the same next step: the application of the unsupervised classification [13], [14]. Obviously, the object of classification changes: in the first approach, it is the NDWI layer, in the second, the first principal component, and in the third, the subset of the three most decorrelated images.

To verify the accuracy of the results, two different types of tests are used: the first based on the confusion matrix and the respective indices, the second aimed at verifying the level of coincidence (and therefore overlap) between the coastline resulting from each method and the assumed true coastline, i.e., the one obtained through photointerpretation and vectorization of the true-color RGB composition. Unlike automated digital analysis, which relies on algorithms to classify pixels, photointerpretation relies primarily on the experience and cognitive skills of the human operator, using visual principles such as: hue and color, shape and size of objects, texture, context and association, etc.

It should be noted that the coastline extracted from the image using the three different methodological approaches represents the instantaneous coastline without any claim to identify the true coastline. Therefore, the tide height at the time of image acquisition is not considered; after all, in the area under consideration, the tide values are just a few centimeters, and the image has a resolution of 10 m.

The following subsections provide theoretical background and descriptions of the methods used.

A. OIF

Optimum Index Factor (OIF) is a quantitative method used to determine the best three-band combination for a color composite image. The OIF value is calculated based on the standard deviation (variance) within each band and the correlation between pairs of bands, with the highest value indicating the most informative and least redundant combination for visual interpretation [15].

The three-band combination with the highest OIF value is considered the best for creating a color composite because it maximizes the information content and minimizes redundancy [16].

This helps users choose the best band combination for visualizing specific features, like distinguishing between oil and water or mapping urban land use. OIF is calculated using the following formula:

$$OIF = \frac{Std_i + Std_j + Std_k}{|Corr_{i,j}| + |Corr_{i,k}| + |Corr_{j,k}|} \quad (1)$$

Where:

Std_i, Std_j, Std_k are the standard deviation of band i, band j and band k respectively;

$Cor_{i,j}$, $Corr_{i,k}$ and $Corr_{j,k}$ are correlation coefficients of band i and band j, band i and band k, band j and band k respectively.

B. Water body enhancement

Water indices in remote sensing are calculated as ratios of spectral bands from satellite or aerial images to highlight and map water bodies [17]. They work by leveraging the different ways water absorbs and reflects light compared to land. This process allows for the identification, monitoring, and analysis of surface water features like sea, lakes, rivers, and flooded areas [18].

The most common is the Normalized Difference Water Index (NDWI), which uses green and near-infrared bands [19].

Defined by McFeeters (1996) [20], the NDWI index is provided by the following formula:

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (2)$$

NDWI is applied in this study using B3 and B8 images.

C. Unsupervised Classification: ISODATA application

Originally proposed by Ball and Hall [21], Iterative Self-organizing Data Analysis Techniques (ISODATA) is an unsupervised clustering algorithm that is recognized as an extension of the classical k-means method [22]. It incorporates additional functions that control the classification process by dynamically merging and splitting clusters.

We use the Unsupervised Classification Plugin available in QGIS for applying ISODATA to NDWI (MA1), First Principal Component (MA2) and the subset of the three decorrelated bands respectively (MA3).

D. Coastline automatic vectorization

Each of the three raster layers obtained from the unsupervised classification is automatically vectorized. The Polygonise command available in QGIS software is used for this purpose. The polygon corresponding to the seawater in the scene is transformed into a polyline, and the portion coinciding with the edges of the scene being investigated is eliminated because it is completely unrelated to the coastline.

E. Accuracy tests

To evaluate the results obtained by each methodological approach, accuracy tests are executed. Specifically, confusion matrix and related indicators are used to establish the quality of the classification.

Confusion matrix is a table that evaluates the accuracy of a classification by comparing a map of classified pixels against a reference map of known ground truth values. It is a cross-tabulation that shows how well a classification model correctly identifies different land cover classes, highlighting both correct classifications (on the diagonal) and misclassifications (off the diagonal).

Producer accuracy (PA), user accuracy (UA), and overall accuracy (OA) are key metrics for evaluating remote sensing classification maps. PA measures how well the resulting classified areas match the ground truth, showing what proportion of the analysed zone was correctly classified [23]. It is calculated by dividing the number of correctly classified pixels for a given class by the total number of reference pixels that actually belong to that class. User accuracy measures how often the resulting classification is correct for a user looking at the map, identifying the probability that a pixel on the map is correct for its real-world location [24]. It is calculated by dividing the number of correctly classified pixels for a given class by the total number of pixels that were classified into that class. OA is the total percentage of correctly classified pixels in the entire map compared to the reference data [12]. It is calculated by summing the correctly classified values on the diagonal of a confusion matrix and dividing by the total number of reference pixels.

Test sites are introduced for water and non-water. Since the aim is to extract the coastline as a separating element between land and sea, the analysis is performed only for the area surrounding the Tyrrhenian sea coastline (the one vectorized by hand and assumed to be true). In particular, a 300-meter buffer is identified around the aforementioned line, distinguishing the sea from the land and verifying the thematic accuracy of each of the three MAs compared.

In addition, the Ratio Index (RI) introduced by Maglione et al. [2] is used to evaluate the accuracy of each extracted coastline. It is given by the following equation:

$$RI = \frac{A}{L} \tag{3}$$

Where: A is the area of the polygons between the two compared coastlines; L is the length of the reference coastline.

This index represents the average deviation between the compared coastlines: the higher the RI value, the worse the accuracy of the result.

IV. Results and Discussion

Fig. 2 shows the NDWI layer resulting from bands B4 and B8 of the Sentinel-2 dataset concerning the study area. Fig. 3 shows the First Principal Component. Fig. 4 shows the RGB false color composition generated by the three most uncorrelated bands (B2B4B8).

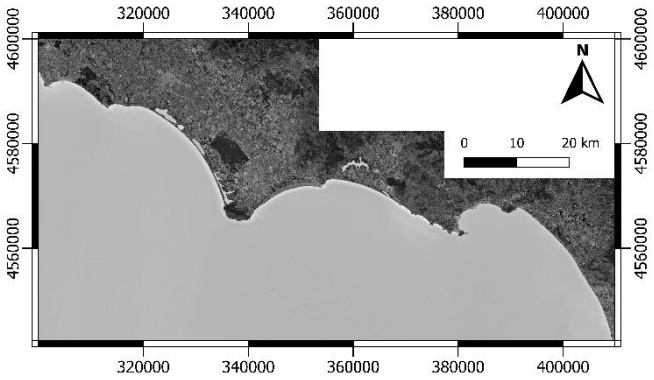


Fig. 2. The NDWI layer resulting from band 4 and band 8 of Sentinel-2 imagery (reference system: WGS84 – UTM Zone 33N).

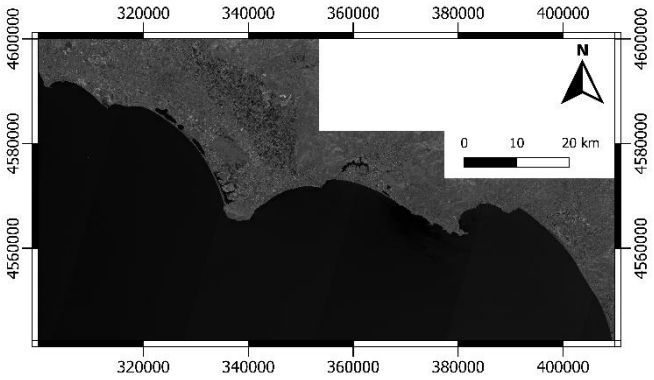


Fig. 3. The First Principal Component (reference system: WGS84 – UTM Zone 33N).

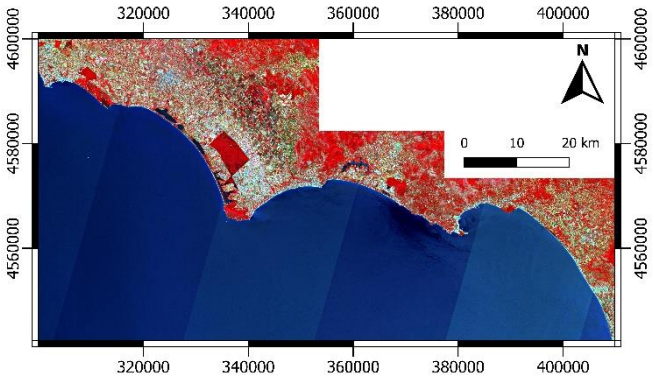


Fig. 4. RGB false color composition generated by the three most uncorrelated bands (B2B4B8) (reference system: WGS84 – UTM Zone 33N).

Fig. 5 shows a portion of the buffer area we choose as a test of classification accuracy: the buffer includes a sea portion that is used as ground truth for water pixels and a land portion as ground truth for non-water pixels.

Table I shows the results of the accuracy tests conducted with the confusion matrix applied to NDWI, First Principal Component and the subset of the three decorrelated bands respectively.

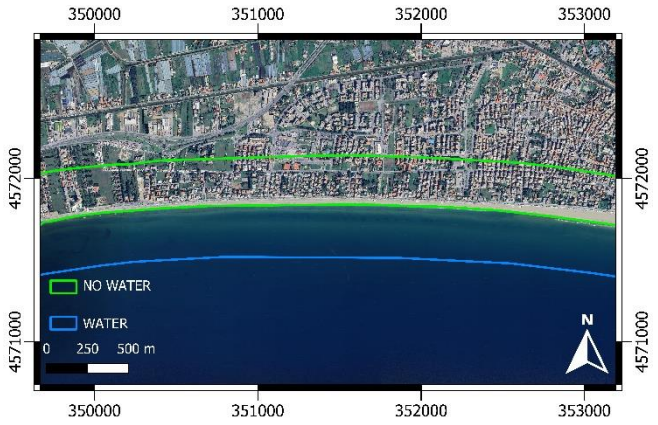


Fig. 5. A detail of the buffer area chosen as a test of classification accuracy: the buffer includes a sea portion used as ground truth for water pixels and a land portion used as ground truth for non-water pixels (reference system: WGS84 – UTM Zone 33N).

TABLE I. THEMATIC ACCURACY VALUES: PA, UA AND OA FOR EACH CLASSIFIED LAYER

Layer	*Class*	*PA*	*UA*	*OA*
NDWI	Water	0.988	0.907	0.941
	Non-water	0.891	0.985	
First Principal Componenent	Water	0.982	0.985	0.983
	Non-water	0.984	0.981	
Subset of the three most decorrelated band combination	Water	0.946	0.989	0.967
	Non-water	0.989	0.945	

The high values of the indicators used highlight the high capacity of each adopted MA to distinguish pixels as water and non-water. The best performance of the MA2 is evident since for this approach OA is equal to 0.983, with an optimal classification for each class (PA equal to 0.982 for water and 0.984 for non-water; UA equal to 0.985 for water and 0.981 for non-water).

Fig. 6 shows a detail of the resulting coastlines and the reference one for the central part of the examined area.

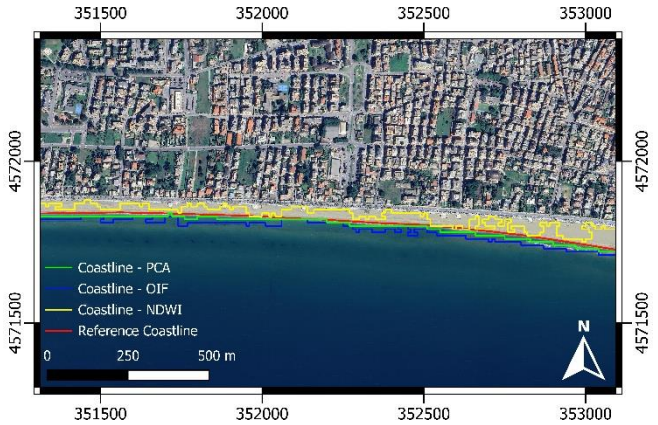


Fig. 6. Comparison between the three coastlines: the zoom on the study area highlights the good performance of the MA2 (reference system: WGS84 – UTM Zone 33N).

Table II shows the RI value for each extracted coastline. Results confirm the good performance of MA2 since the average deviation of the extracted coastline from the reference one is less than the pixel size of the image used.

TABLE II – RI VALUE FOR EACH AUTOMATIC EXRACTED COASTLINE

Layer	*RI*
NDWI	24.66
First Principal Componenent	6.91
Subset of the three most decorrelated band combination	16.08

The results are in line with what is reported in the literature. The experiments carried out by Parente et al. [25] in 2024 on datasets characterized by different geometric resolution, i.e., Landsat 9 Operational Land Imager (OLI) multispectral images, a Sentinel-2 dataset including bands with 10 m pixel size and a Sentinel-2 dataset including bands with 20 m pixel size, demonstrate the high performance of PCA based approach to extract coastline from all the considered satellite optical data. The excellent performance of unsupervised classification approach in distinguishing sea from land and facilitating the identification of the coastline is also confirmed by studies in the literature [26] [27].

V. CONCLUSIONS

This article demonstrates how the automatic extraction of the coastline as a separating element between land and sea is a fully automated process using three different methodological approaches. Although they are all based on unsupervised classification with the ISODATA algorithm, each uses a different processing of the starting dataset.

The tests performed demonstrate that the first principal component subjected to unsupervised classification yields the most accurate results. The highest level of performance is certified both by the confusion matrix and related indices, and by the RI that is the average deviation between the obtained coastline and the assumed true one. The approach used is fully automated and can be applied to other datasets in other study areas.

The research group plans to develop further applications based on the use of different image types including those presenting higher geometric resolution.

ACKNOWLEDGMENT

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Using GIS Tools For Mapping Sea Level Rise Impacts On Casal Velino Coast (Italy)

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***Abstract*— Sea level rise, the global and relative increase in the surface of the oceans, caused primarily by the thermal expansion of water due to global warming and the melting of glaciers and polar ice caps, poses risks to coastal areas, such as flooding and erosion. Correct mapping of the risk areas is essential for a correct understanding of the impacts of the phenomenon and for planning interventions aimed at preserving and improving natural and man-made defense works to counteract such impacts. A very simple method, known as the bathtub model, allows for rapid mapping of floodable areas by directly comparing the terrain elevations derived from Digital Elevation Model (DEM) with the predicted value of the sea level rise in the examined area: the pixels below this rise are submerged when the flow of water coming from the sea is not impeded. This article has a dual purpose: on the one hand, to evaluate the feasibility of implementing the bathtub method in a GIS environment, on the other, to establish how the DEM resolution can influence the flood risk mapping. The study area is the coast of Casal Velino, an Italian municipality located in Cilento (southern Campania). Four different scenarios envisaged by the COPERNICUS project for sea level rise by the year 2100 are considered, that is, relating to different hypotheses such as different concentrations of greenhouse gases in the air. Two DEMs with different resolutions are used, one at 10 m, the other at 5 m. The results confirm the easy implementation of the bathtub method in GIS and the high variability of the flood risk maps in relation to the resolution of the DEM used.**

Keywords—Sea level rise, Bathtub model, Digital Elevation Model (DEM), Geographic Information System (GIS), flooded area mapping.

I. INTRODUCTION

The phenomenon of sea level rise (SLR), that is, the long-term increase in the global average height of the oceans, is one of the most significant consequences of climate change. Sea levels rose by approximately 15-25 cm from 1901 to 2018, with the rate of rise having nearly doubled in the last two decades; if natural phenomena or human interventions are not implemented to counteract this trend, sea levels are expected to rise for centuries [1]. This is primarily due to ocean warming, which causes water to expand, melting of glaciers and ice sheets, and changes in terrestrial water reserves (groundwater depletion and water sequestration in basins). The scenarios projected for the future are alarming: if greenhouse gas emissions are drastically reduced, sea levels will rise by 30-60 cm by 2100, or by 60-100 cm if emissions remain high.

As sea levels rise at the rate they have in recent years, devastating impacts on coastal habitats inland become frequent and widespread: destructive erosion, flooding of wetlands, salt contamination of groundwater and agricultural land, and habitat loss for fish, birds, and plants [2].

Due to a variety of regional and coastal factors, such as land subsidence and uplift (bradyseism), erosion, and regional ocean currents, sea level changes can vary locally, reaching values lower or higher than the global average [3]. The areas most affected by SLR will be low-lying coastal areas and river deltas, with Asia at particular risk, where many of the most exposed populations live. Europe will also see significant impacts, as demonstrated by the forecasts for Italy, which include both coastal areas like the Adriatic Sea and cities like Venice [4] and Lecce [5].

Geographic Information Systems (GISs) are highly effective tools for mapping areas affected by SLR. Using these tools, data can be analyzed, predictive models created, and future flood scenarios visualized to support land-use planning and risk reduction decisions. In fact, mapping sea level changes in GIS gives the user the ability to overlay the potentially impacted areas with other data such as critical infrastructure, roads, ecologically sensitive areas, demographics, and economics [6]. By integrating geographic data (elevation, slope, land use) with SLR projections, it is possible to identify the most vulnerable areas and communities due to their proximity to the coast, population density, and infrastructure [7].

The operations to be performed in GIS to achieve the goal are part of Map Algebra, the powerful set of functions that allows operator to combine, compare, and manipulate layers of geographic data using mathematical, statistical, and logical operators to solve complex spatial problems [8].

There are many studies in literature on GIS solutions for supporting sea level change studies and modeling SLR impacts. An interesting review on this aspect is provided by Sarrau [9]. Below are two examples that highlight the versatility of GIS to support broad-spectrum SLR impacts, the first at a global scale, the second at a local level.

In 2009 Li et al [10] developed GIS methods to assess and visualize the global impacts of potential inundation using the best available global datasets; considering a hypothetical global sea level increased of one meter in future scenario, they estimated that the size of the inundated areas is 1.055 million km^2 with population of 108 million people at risk. Using many thematic layers including maps of administrative boundaries, the rail and road networks, irrigation, and urban areas, Abou Samra et al [11] investigates the actual impacts of SLR and associated shoreline retreat at Damietta coast (Egypt) using GIS despite current uncertainties about SLR values.

To accurately map areas at risk of flooding due to SLR, a Digital Elevation Model (DEM) is essential. A DEM provides key terrain elevation data, allowing the identification of coastal areas that are below or at a critical elevation relative to predicted sea levels and tides. DEM resolution is crucial for accurately determining areas flooded by sea level rise: a high-resolution DEM (a few decimetres per pixel, often obtained with technologies such as LiDAR) provides a more detailed and accurate representation of coastal topography, including micro-elevation variations and small natural or artificial barriers. This results in much more precise maps of flooded areas. Models based on low-resolution DEMs can underestimate or overestimate the extent and depth of flooded areas, leading to unreliable risk assessments.

This article aims to demonstrate that mapping areas at risk of flooding due to SLR is easy with GIS but requires important considerations regarding the resolution of the DEM used. Specifically, the Casal Velino coast in Campania (Italy) is analyzed using Copernicus data for SLR that are compared with two digital elevation models (DEMs) at different resolutions, exactly 10 m and 5 m. The flooded areas are mapped, and the results are compared to quantify the differences found due solely to the different resolution of the two DEMs. Quantum GIS software version 3.40 is used to carry out all the experiments [12].

The article is structured as follows. After Section 1 that introduces the topic and the main purpose of this study, Section 2 describes the study area (Casal Velino coast), and data used (predicted scenarios for SLR and DEMs at 10 m and 5 m). Section 3 presents the adopted methods for mapping inundated areas in GIS and Section 4 discusses the results. Section 5 concludes the article, summarizes the main findings and highlights the significance and implications of the study, identifying its limitations and suggesting possible directions for future research.

II. Study Area and Datasets

A. Study area

The applications concern the Casal Velino coastline in Campania Region (Italy) included between the following ellipsoidal coordinates referred to World Geodetic System 1984 (WGS84):

λ_1=15°05′42.6″ E, ϕ_1=40°09′36.6″ N

λ_2=15°08′48.1″ E, ϕ_2=40°10′38″ N.

Known until 1893 with the name of "Casalicchio" (from the medieval Latin casalicolus, "small farmhouse"), Casal Velino is an Italian municipality of 5,375 inhabitants in the province of Salerno. The Casal Velino coastline is part of the broader geological landscape of Cilento, renowned geographical and cultural region located in the southern part of Campania, in the province of Salerno, characterized by a varied alternation of low, sandy shores and stretches of high, rocky coastline. Much of the Casal Velino territory extends over a coastal plain, part of the larger Alento Plain. This area is primarily composed of recent (Quaternary) alluvial sandy and pebbly deposits, forming terraces at varying heights. The main feature of the Casal Velino coastline is its wide expanse of fine, light-colored sand [13]. The beach is protected by breakwaters (parallel barriers) that help mitigate coastal erosion, a widespread problem along many stretches of the Cilento coast, which has often been particularly severe along the Casal Velino coastline.

Fig. 1 shows the geolocation of the Municipality of Casal Velino in the Campania Region, Fig. 2 shows the coastline of that municipality at its current state, and Fig. 3 shows a bird's-eye view of a stretch of the coastal strip covered by this study.



Fig. 1. Geolocalization of the study area: the municipality of Casal Velino in Campania Region (Italy) in equirectangular projection and ellipsoidal coordinates referred to WGS84.



Fig. 2. The coastline of Casal Velino municipality at its current state.



Fig. 3. Bird's-eye view of a stretch of Casal Velino coastal area.

B. Datasets

The experiments described in this article use Copernicus data [14]. The Copernicus project, the European Union's Earth observation program, provides free and accessible data and information to monitor the planet and the environment, address climate change, and improve citizen safety. It uses satellite data, ground-based surveys, and numerical models to offer services in six thematic areas: atmosphere, marine environment, climate change, security, emergencies, and land.

The Representative Concentration Pathways (RCP) used by Copernicus and other research institutions are projections of future climate scenarios, which determine SLR. They describe how future greenhouse gas concentrations will affect global temperatures, and consequently sea levels, due to processes such as ocean thermal expansion and ice melt.

The RCP4.5 and RCP8.5 scenarios are two RCPs used to project future climate change and SLR. RCP4.5 is a stabilization scenario with emissions mitigation, leading to a more moderate SLR, while RCP8.5 is a "business-as-usual" scenario (without mitigation) that projects a sharp increase in emissions and a consequent more drastic SLR.

Copernicus databases include SLR due exclusively to warming of seas and oceans (Relative Sea Level Rise, RSLR) as well as SLR due to a combination of warming of seas and oceans, high tides and exceptional events such as storms (Extreme Sea Level, ESL) [15].

Copernicus data are collected for more than 20,000 points located along the coasts of seas and oceans of the entire planet. We use the most appropriate of them because positioned in the study area (λ_1=15°13′ 35.39″ E, ϕ_1=40°06′ 12.51″ N).

The experiments described in this article concern sea level rises (median values) related to RCP4.5 and RCP8.5 in 2100 and concerning both RSLR and ESL.

The digital elevation models used present different resolutions. The first is extracted by TINITALY that is a digital elevation model (DEM) of the Italian territory, developed by the National Institute of Geophysics and Volcanology (INGV) [16]. It covers the entire country with a resolution of 10 meters per pixel and is available free of charge in GeoTIFF format for public use, provided the source is cited. This DEM is in UTM-WGS84 Zone 32 N planimetric datum. The elevations are referred to the vertical datum for continental Italy named Genoa 1942, which establishes the average Italian sea level using data from the Genoa tide gauge for the period 1937-1946.

The second DEM is produced by the Campania Region starting from the 1:5,000 scale cartography. It refers to the UTM-WGS84 Zone 33 N planimetric datum and the Genoa 42 vertical datum. This DEM covers the entire Campania region at 5-meter resolution, is organized according to the cartographic set of 1:5,000 scale maps and consists of several hundred files. Specifically, the area of interest includes four files identified by the numbers 519021 to 519024.

III. Methods

A. Data preprocessing

The UTM-WGS84 Zone 33 N planimetric reference system and the Genova 42 altimetric reference system are chosen for QGIS project. Consequently, a planimetric datum transformation is necessary for the TINITALY DEM (transition from Zone 32 N to Zone 33 N).

Similarly, the Copernicus data referred to the global mean sea level are converted to the local vertical datum. This operation requires comparing the geoidal undulations of the two vertical datums, that is, the distances separating the two respective geoids from the WGS84 ellipsoid [17, 18].

ITALGEO 2005 [19] is the local geoid model for Italy while Earth Gravitational Model 2008 (EGM2008) [20] is a global geoid model that represents the mean sea level for the entire planet.

Developed and distributed by Istituto Geografico Militare (IGM), or Military Geographic Institute, the cartographic body of the Italian State, ITALGEO 2005 provides geoidal undulation values according to a 2' grid spacing for an area between 35° and 48° north latitude and 5° and 20° east longitude. It represents an updated and more accurate version compared to previous models (such as ITALGEO99).

Usually available in grid form 2.5' x 2.5' as well as 1'x1', EGM2008 defines the geoidal undulation values at global scale.

The differences between the values provided by the two geoid models at certain points can even reach several decimetres.

B. Map algebra

Map algebra allows you to combine and process raster data (such as DEMs) using mathematical, logical, and statistical expressions. It allows you to combine multiple information levels (layers) to create new ones with derived information, through the application of formulas and operations that can be local, zonal, focal or global [21]. In the context of flood

modelling, it is primarily used for implementing several actions such as those reported below.

Elevation to sea level comparison: the most straightforward operation is to subtract a specific predicted SLR (e.g., + 1 m) from the DEM. The resulting cells with a value equal to or less than zero indicate the areas that would be submerged.

Vulnerability analysis: using logical operators, you can identify risk zones based on different SLR scenarios (e.g., low, intermediate, high) proposed by organizations such as the those available in Copernicus project.

Simplified hydraulic modelling: although more sophisticated hydraulic models use specialized software, map algebra offers expeditious methods for preliminary delineation of large-scale flood areas.

Data integration: this allows the DEM to be integrated with other raster datasets, such as land use, population density, or the presence of infrastructure, to assess the potential impact of flooding in terms of economic and social damage.

Risk mapping: by combining maps of flooded areas with exposure and vulnerability maps, detailed risk maps can be created, essential for land-use planning and risk mitigation.

C. Bathtub model

To map the submerged areas due to the SLR values in the different scenarios considered, the method present in the literature known as bathtub is used in this study.

This method projects a flood surface onto a DEM by simply checking where the new water level would be higher than the land elevation. However, it ignores other factors like drainage systems, levees and groundwater [22]. It assumes water rises uniformly over an area, ignoring how water moves in reality [23].

Bathtub method fails to account for natural and man-made defenses like levees, storm drains, and pumping systems that manage water flow. However, it is an effective method at least as a first estimate of the flooded areas. In fact, it is computationally inexpensive and requires less data, making it useful for quick, large-scale estimates in areas where more sophisticated models are not feasible.

To establish that an area is flooded, the principle of hydrological connectivity must be respected that is, the continuity of the water flow must be guaranteed. In addition to being below the flood level, an area must be hydrologically connected to the source of the flooding (e.g., the ocean or river) for it to be inundated [24].

Ultimately, the bathtub method is implemented in QGIS through the following operations:

1. using raster calculator, a specific predicted SLR is subtracted from the DEM;
2. pixels with a value equal to or less than zero are selected;
3. the areas including the selected pixels are automatically vectorized;
4. only those polygons connected to the sea are considered flooded areas;
5. the extension of each flooded polygon is calculated.

IV. RESULTS AND DISCUSSION

The following figures show the flooded areas in 2100 resulting from four of the cases studied that are all based on ESL median value. Specifically:

Fig. 4 concerns RCP4.5, DEM 10 m;

Fig. 5 concerns RCP8.5, DEM 10 m;

Fig. 6 concerns RCP4.5, DEM 5 m;

Fig. 7 concerns RCP8.5, DEM 5 m.

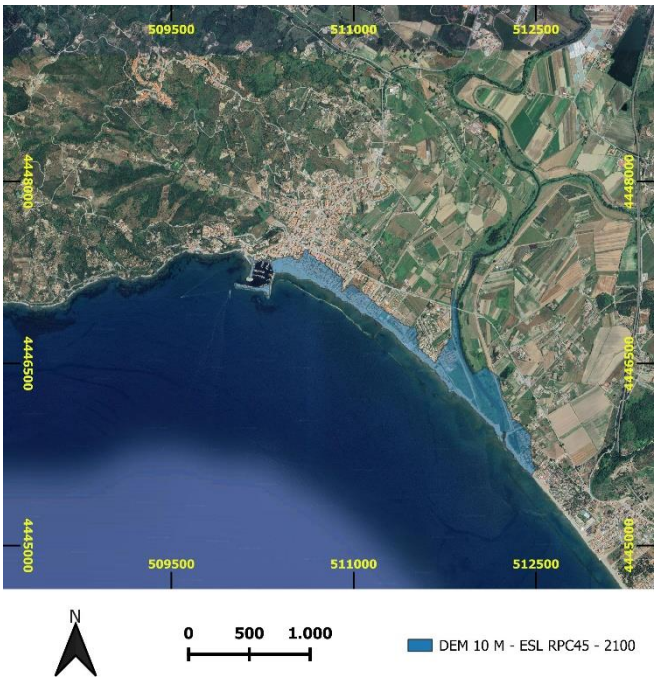


Fig. 4. Flooded areas resulting from RCP4.5, DEM 10 m, ESL median value in 2100.

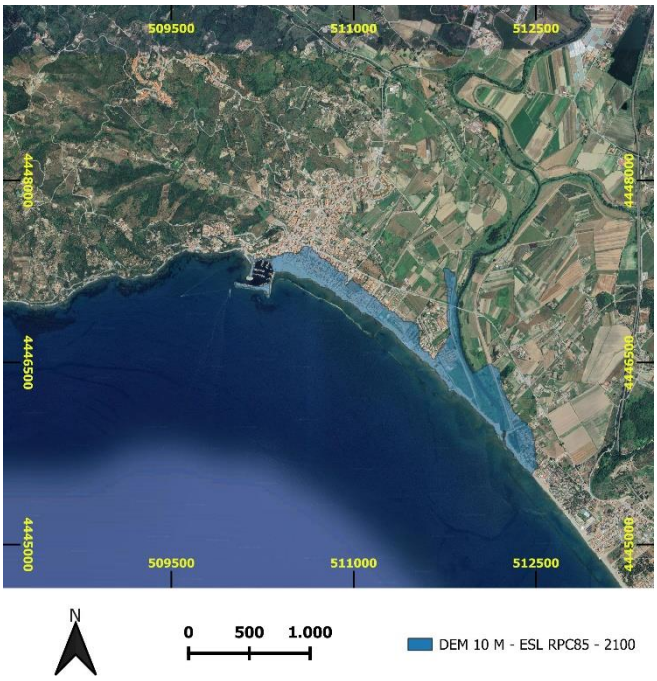


Fig. 5. Flooded areas resulting from RCP8.5, DEM 10 m, ESL median value in 2100.

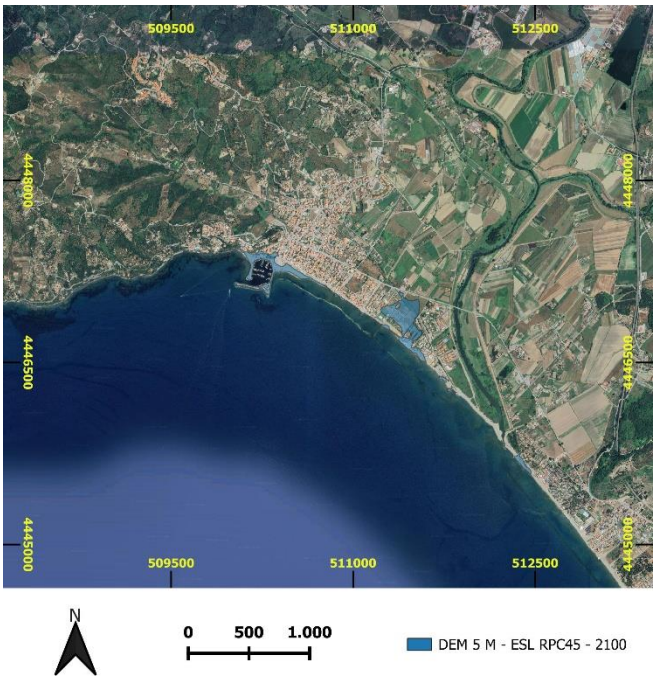


Fig. 6. Flooded areas resulting from RCP4.5, DEM 5 m, ESL median value in 2100.

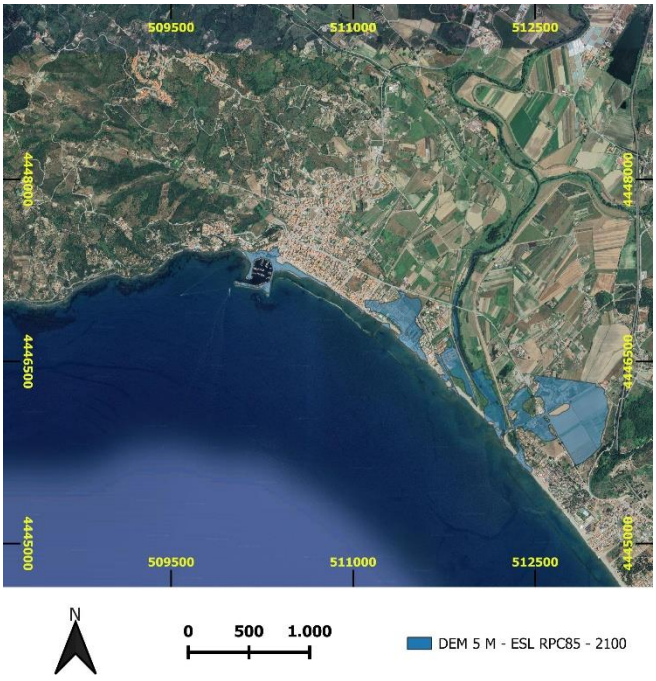


Fig. 7. Flooded areas resulting from RCP8.5, DEM 5 m, ESL median value in 2100.

Table 1 shows the extension of the flooded areas calculated for each considered scenario and using different DEMs.

As the data in the table demonstrates, the extent of the areas, all other reference elements being equal, varies significantly with the resolution of the DEM used. This is attributable to two fundamental factors: if the two DEMs provide different values at the same point, this can lead to a different classification (flooded or non-flooded) and a variation in the hydrological connectivity model. The results confirm that DEM resolution is crucial for the accuracy of flooded area mapping when using the bathtub method [25, 26].

TABLE I - FLOODED AREAS RESULTING FROM EACH CONSIDERED SCENARIO

	Flooded areas (km^2)	
Scenario	**Using DEM 10 m x 10 m**	**Using DEM 5 m x 5 m**
RSLR_RCP4.5 2100	0.152	0.017
RSLR_RCP8.5 2100	0.235	0.028
ESL_RCP4.5 2100	0.535	0.147
ESL_RCP8.5 2100	0.640	0.682

In any case, the maps and data highlight the criticality of the Casal Velino coastal strip which, due to its morphology, remains one of the areas most exposed to flooding due to SLR.

V. CONCLUSIONS

The applications described in this article demonstrate how mapping flooded areas due to predicted SLR values is easily accomplished using the bathtub method implemented in a GIS environment. The operations to be performed involve the use of functions typical of spatial analysis and available in all GIS software: from DEM management to database queries, from map construction to area calculation.

Comparing SLR data with the heights provided by DEMs requires datum uniformity, both horizontally and vertically. Regarding the latter, it is important to consider that if the reference zero for the heights is not the same, this can lead to incorrect mapping of the flooded areas.

The case study proposed for the coast of the municipality of Casal Velino in Campania also highlights how the results vary significantly with changes in DEM resolution. Indeed, the two principles on which the bathtub method is based, i.e. the direct comparison of elevation with the predicted SLR value and the hydrological connectivity that allows water flow from the sea to the land, provide different results at different resolutions.

ACKNOWLEDGMENT

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From Grape Waste to Measurable Value: Metrological and Metagenomic Insights into Wine By-Products

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***Abstract*— *Despite a global decline in wine production, Italy continued to grow, generating large amounts of by-products such as pomace, stalks, and lees. While these residues are often sent to distilleries for grappa production, this practice does little to contribute to a true circular economy. Rich in sugars, polyphenols and lignocellulosic compounds, these residues represent a valuable resource for use in bioactive extraction, bioenergy production, the creation of biosurfactants and environmental remediation. However, advanced valorization technologies remain underutilized, with most studies focusing on chemical compounds. Our research, however, addresses the microbiological potential of pomace through molecular screening, with the aim of characterizing its microbiota for future applications. As well as being rich in nutrients, pomace also contains beneficial microorganisms, such as lactic acid bacteria, whose activity can transform polyphenols into postbiotics with antioxidant, anti-inflammatory, and antimicrobial properties. The antioxidant and antimicrobial activity of aqueous extracts of the pomace under examination was measured.*

Keywords*— *Wine, Winemaking, Lactic acid bacteria, waste, Pomace, Antioxidant activity, Antimicrobial activity

I. Introduction

2024 has been a year worldwide characterised by a historic decline in wine production due to adverse weather events and a decrease in vineyard area. Despite this, according to the latest OIV (International Organisation of Vine and Wine) report, Italy was the only one of the world's seven largest wine producers to continue to record a positive trend, reaching 728 kha of area under vine [1]. Italian wine production amounted to 44.1 million hectolitres; therefore, based on a survey conducted by ENEA in 2018 [2], an average of 882 million kg of pomace, 170 million kg of stalks, and over 280 million kg of lees and clarification solids were also produced. In general, the production of stalks and pomace varies between 20 and 35% of the grapes vinified, with larger quantities generated by small businesses. According to Decree Law 7407/2010, these products can be repurposed for agricultural, food, pharmaceutical, cosmetic and energy uses. The delivery to distilleries to produce grappa remains one of the most widely used methods, particularly among large companies who benefit economically from it. However, this technique only removes 0.1% of the weight of the pomace, so it does not create a true circular economy of the by-product. This waste is extremely rich in residual sugars, polyphenols, and lignocellulosic compounds, making it a promising resource for many applications. These include the extraction of bioactive molecules, the production of bioenergy and biosurfactants, and its use in environmental remediation [3, 4]. Despite their vast potential, advanced technologies for exploiting them are still not widely used in wineries, with research mainly focusing on the extraction of chemical compounds. Research has repeatedly emphasised the effectiveness of pomace extracts in combating microbes, with numerous studies underscoring their antimicrobial and antifungal properties. The mechanisms responsible for these properties have been studied in depth. For instance, they can inhibit microbial enzymes and proteins by chelating iron, forming hydrogen bonds and interacting with other enzyme structures. Synergistic interactions with antibiotics, particularly tannins and flavonoids, have also been observed in relation to bacterial biofilms [5]. Studies also show that the chemical composition of pomace can vary greatly depending on the grape variety used, the vinification method employed, and the post-harvest management of the pomace. These factors obviously influence its possible applications. Generally, white pomace contains more carbohydrates but fewer total phenols, whereas red pomace contains more proteins and condensed polyphenols. The composition also differs between fresh and treated pomace (e.g. composted, vermicomposted or fermented), reflecting the enormous complexity and versatility of this by-product [6]. Conversely, our research has focused more on the microbiological aspects of pomace. Studies reported in the literature have mainly focused on characterising the microbiota of grapes and subsequent stages of wine fermentation. However, the microbiota of pomace has received less attention. Generally, studies have reported statistically significant differences in the microbiota and mycobiota depending on the vineyard's

location and the type of grape [7]. Our preliminary objective was to perform an initial screening and comparison of the pomace microbiota from different grape varieties, with the goal of characterising the overall microbial community and evaluating its potential for future applications.

II. MATERIALS AND METHODS

The investigation comprised four distinct types of pomaces: red grapes (Piedirosso), white grapes (Biancolella), a blend of red grapes (Mixed Red), and a specimen already in the process of composting, collected after 40 days on the ground (Mixed). All samples originated from DOC wine production in the Campania region, Italy. Specifically, the pomace was collected after the 2024 harvest. The white pomace sample was obtained from the vinification of pure Biancolella grapes, with fermentation taking place at a controlled temperature of around 16-18°C. The vineyard is located on the south-eastern side of the volcanic island, at an altitude between 200 and 400 metres above sea level. The red pomace sample comes from the vinification of Per' 'e Palummo grapes, grown in Campagnano at altitudes ranging from 50 to 400 metres above sea level. In this case, too, maceration on the skins lasts 4–6 days at a controlled temperature. The mixed red grape pomace was collected from the vinification of various grape varieties typical of the island, situated between the municipality of Ischia and the village of Campagnano. Preliminarily, classical microbiological analyses were conducted to evaluate the total microbial and fungal load, in accordance with the relevant ISO standards. Subsequently, total DNA was extracted using a suitably optimised CTAB protocol. The modified protocol started with 5 g of fresh pomace, treated with NaCl to promote the detachment of microorganisms, and then the aqueous phase was concentrated on a 0.45 µm membrane. Subsequently, the 16S rRNA bacterial gene was amplified using V3-V4 primers, which were then sequenced with MiSeq Illumina (Illumina, United States). The raw fastq sequences were filtered according to quality. A total of four samples were analysed, yielding 33,368 high-quality sequences that were assigned to 2,995 unique features. The number of reads per sample ranged from 6,358 to 12,042, with an average of 8,342 reads per sample. The distribution of sequencing depth showed a first quartile of 6,768 reads per sample, a median of 7,484 reads per sample, and a third quartile of 9,058 reads per sample. Despite the variability observed, all samples exhibited sufficient sequencing coverage for downstream analyses. Subsequent analyses were performed with Qiime 2 and R Software. Hot aqueous extracts were obtained from the pomace of Piedirosso and Biancolella grapes, starting with fresh and dried pomace, which was then freeze-dried. The extracts were tested for antimicrobial activity against *Listeria monocytogenes* ATCC® 19115 and *Salmonella enterica* serovar *Typhimurium* ATCC® 14028, as well as for antioxidant activity. Preliminary antimicrobial tests were conducted using a standardised Kirby-Bauer disk diffusion assay to evaluate the inhibition zone in mm. Activity was evaluated on a bacterial inoculum of 10^7 CFU mL^{-1}, seeded on Mueller-Hinton agar. Oxoid discs were impregnated with 10 µL of the substances, under examination, at various concentrations ranging from 2 mg to 250 µg. Subsequently, the minimum inhibitory concentration (MIC) test was performed on the extracts to evaluate concentrations on the plate of 16–0.25 mg mL^{-1}. The compounds were placed in contact with inocula of 2×10^6 CFU mL^{-1} of the target microorganisms used in the preliminary tests. The positive and negative controls are represented respectively by ciprofloxacin, used at the same concentration as the extracts, and TSB culture broth. The test was performed on a Thermo Scientific Varioskan LUX multimodal reader, using turbidity readings taken every hour for 24 hours at a wavelength of 560 nm. The following formula was used to calculate the percentage inhibition of microorganism growth:

$$\%\ Growth\ inhibition = 100 \times \left(1 - \frac{Abs\,560\,nm\ of\ test\ sample}{Abs\,560\,nm\ of\ CTR}\right)$$

ANOVA analysis indicates statistical significance between the sample and the positive control. Values of $p < 0.05$ were considered statistically significant and are indicated as *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, and ****$p < 0.0001$. All experiments were conducted in triplicate.

The ORAC (oxygen radical absorbance capacity) test was used to evaluate the antioxidant properties of extracts from 250 to 3.12 µg mL^{-1}. The test was performed according to the instructions provided by the manufacturer Thermo Scientific, "Determination of antioxidant capacity on the Thermo Scientific Varioskan LUX multimodal reader". The protocol involves measuring fluorescence (Ex. 485 nm, Em. 518 nm) in a kinetic reaction every 30 seconds for 90 minutes. The first four cycles are used to record the background signal, after which the addition of AAPH to all reaction wells initiates the oxidative reaction. At the end of the reaction, the AUC value (area under the curve) is obtained, representing the loss of fluorescence signal. A standard curve is then generated by plotting the AUC values as a function of Trolox concentrations. Trolox equivalent value of the substance is determined from the equation of the standard curve.

III. RESULTS AND DISCUSSION

A. Microbiological analysis

As shown in Fig. 1, a microbial load, bacterial and fungal, ranging from 10^6 to 10^8 CFU/g was detected in all types of samples analysed. These values confirmed the high microbial vitality still present in the by-product. In particular, the microbial load was slightly higher in the mixed pomace samples and in those already undergoing composting, suggesting that the microbial diversity present in the samples derives both from the substrate and the type of grape, but also from the degradation process underway, which may favour the proliferation of specific bacterial communities. Conversely, the fungal community seems to have steady levels across the various samples, with a minor decline seen in pomace from white grape vinification.

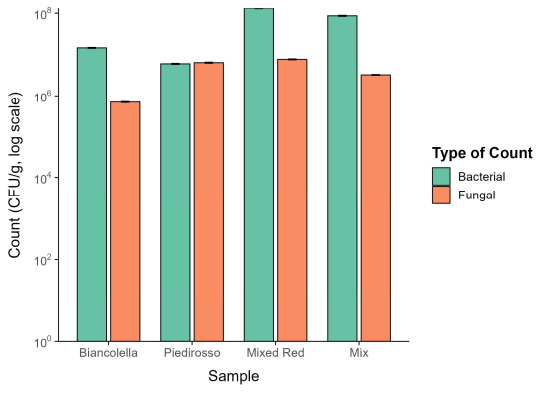


Fig. 1. Bacterial and fungal counts in different pomaces samples (mean values ± standard error).

Microbiological analyses were also carried out to assess the presence of other indicators of contamination, such as *Escherichia coli*, Coliforms, Enterococci, Salmonella spp., *Listeria* spp., Staphylococci and *Clostridium* spp., which gave negative results.

B. Next Generation Sequencing

The Shannon index, shown in Fig. 2, increases as the number of species increases. It ranges from 1.84 in Piedirosso to 2.69 in Mixed, passing through Biancolella at 2.14 and Mixed Red at 2.31. These values indicate that the Mixed community is more diverse and uniform, with a high number of species and an even distribution of abundance among all microorganisms. The Mixed Red community has moderately high diversity, but lower than the former. Biancolella has average diversity, but lower than the previous two. Finally, Piedirosso has a much less varied community, dominated by a few very abundant microbial species, and therefore lower richness. Ultimately, as expected, mixed wines have greater diversity. Mixing different grape varieties or origins probably leads to a greater variety of ecological niches and consequently more microorganisms. Furthermore, differences also stem from different terroirs, as the final microbial community is influenced by soil, climatic conditions, and agricultural practices in the harvesting area.

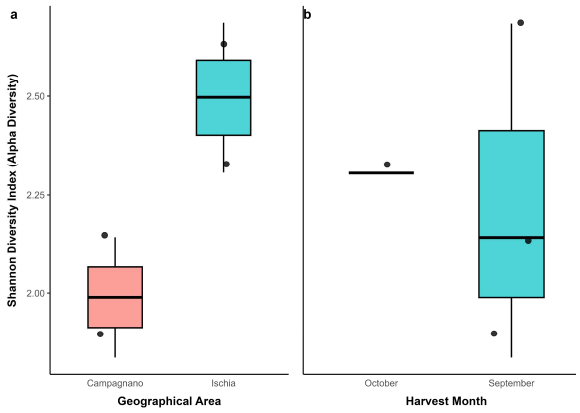


Fig. 2. Investigation of the microbial alpha diversity based on the Shannon index in grape pomace: (a) bacterial diversity based on the geographical area; (b) bacterial diversity based on the grape harvest month.

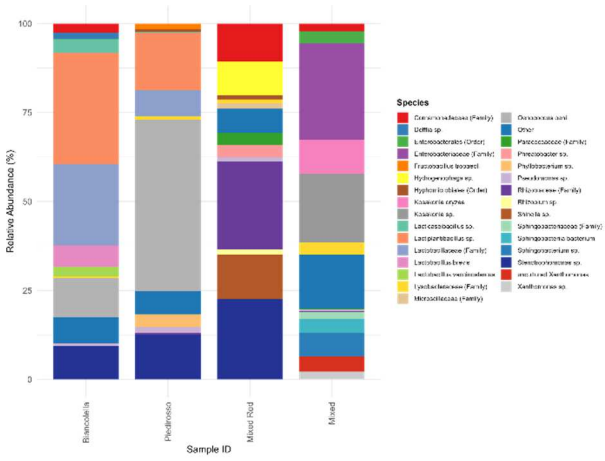


Fig. 3. Mean relative abundances of the dominant species in pomaces.

The investigation of the microbial composition showed notable variations between the pomace specimens. A particularly heterogeneous community was shown by the pomace derived from white grapes, dominated by *Lactiplantibacillus* sp. (31.21%) and other species belonging to the Lactobacillaceae family (22.89%). The most represented microorganisms also included *Oenococcus oeni* (11.02%), *Stenotrophomonas* sp. (9.40%) and *Lactobacillus brevis* (6.01%), together with minor species such as Lacticaseibacillus sp. (3.88%), *Lactobacillus vaccinostercus* (2.73%), *Levilactobacillus* sp. (1.38%), *Acetobacter pasteurianus* (1.16%) and *Acetobacter sp.* (1.03%). In the case of red pomace, on the other hand, the microbial community was more unbalanced towards a few dominant species: *Oenococcus oeni* accounted for almost half of the total microbiota (48.20%), followed by *Lactiplantibacillus* sp. (16.14%) and *Stenotrophomonas* sp. (12.54%). Less abundant species included members of the Lactobacillaceae family (7.34%), *Phyllobacterium* sp. (3.64%), *Fructobacillus tropaeola* (1.65%), *Pseudomonas* sp. (1.55%) and *Fructobacillus ficulneus* (1.44%).

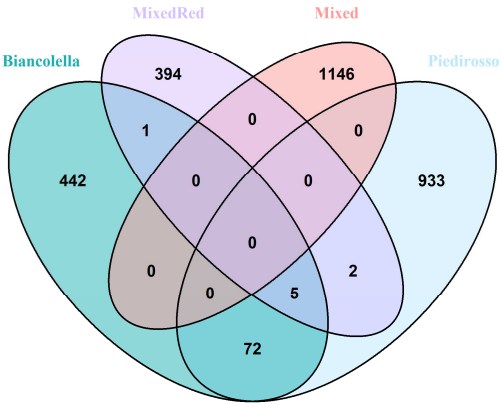


Fig. 4. Venn diagram, distribution of microbial species and their overlaps in the four pomaces samples.

The predominant microbial composition in mixed red grape marc is even more diverse, with abundant species of the Rhizobiaceae family (24.67%) and genera such as *Stenotrophomonas* sp. (22.60%), *Shinella* sp. (12.48%), *Hydrogenophaga* sp. (9.35%), *Phreatobacter* sp. (3.50%), *Rhizobium* sp. (1.5%), and *Pseudomonas* sp. (1.21%) are abundant. Species from the Comamonadaceae (10.73%), Paracoccaceae (3.34%), Microscillaceae (1.59%) and Lysobacteraceae (1.06%) families are also represented.

Finally, in the pomace sent for composting and left on the ground for 40 days, species of the Enterobacteriaceae family (26.95%), Comamonadaceae (2.18%) and Sphingobacteriaceae (1.86%) predominate.

Kosakonia oryzae (9.58%) and *Pseudomonas boreopolis* (1.08%) were also detected, along with the genera *Sphingobacterium* (6.64%), *Xanthomonas* (2.16%) and *Komagataeibacter* (1.48%). This difference is clearly visible in the Venn diagram in Figure 4, which shows that the overlaps between ASVs at species level are very limited, with only 76 overlaps between Biancolella and Piedirosso, 5 between Biancolella, Piedirosso and Mixed Red, 2 between Piedirosso and Mixed Red, and only 1 between Biancolella and Mixed Red.

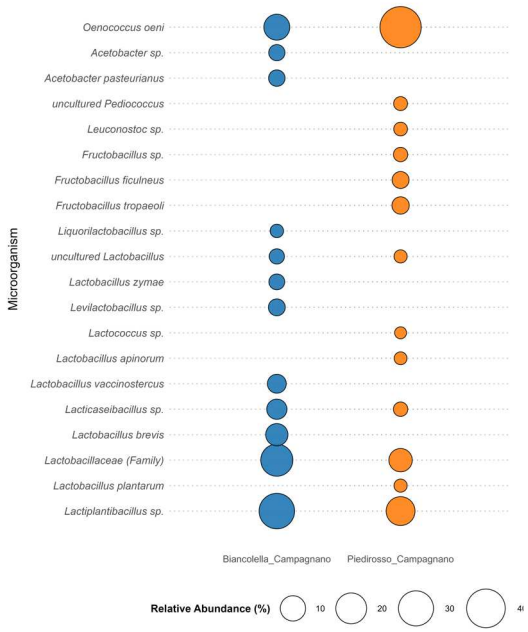


Fig. 5. Diversity and Abundance of Beneficial Microorganisms in Wine Fermentation

An in-depth analysis, showed in Fig. 5, of beneficial microorganisms in winemaking revealed that samples of Biancolella and Piedirosso pomace still contain significant amounts of various beneficial organisms, including those belonging to the Lactobacillus (LAB) class. These organisms are useful in food fermentation as they are responsible for acidification processes, the production of antimicrobial compounds, modulation of the microbiota and possible antioxidant activities. During winemaking, these organisms primarily facilitate malolactic fermentation, thereby enhancing the wine's aroma and structure, reducing its acidity and improving its overall microbiological stability [8].

In particular, *L. plantarum* can grow on pomace, contributing to secondary fermentation and improving antioxidant activity while reducing residual carbohydrates and increasing lactic acid production. It has probiotic properties and a more diverse enzyme profile than *O. oeni*, which is traditionally used as a starter.

The production of bioactive compounds (e.g. exopolysaccharides and vitamins) and its antimicrobial activity against undesirable microorganisms have made it a competitive candidate for possible use in recent decades [9]. *Fructobacillus*, *Leuconostoc* and *Pediococcus* may also contribute to flavours and secondary fermentation, but this depends greatly on the strain and the conditions (pH, oxygen, alcohol, etc.)

C. Antimicrobial activity of grape pomaces

TABLE I. ANTIBACTERIAL ACTIVITY USING THE KIRBY-BAUER DISK DIFFUSION METHOD. RESULTS ARE REPORTED AS INHIBITION ZONE DIAMETERS (MM) ± STANDARD DEVIATION (SD) AGAINST TESTED BACTERIAL STRAINS.

Kirby-Bauer Disk Diffusion Method	Inhibition zone (mm)																	
	BS				BF				PS				PF				CTR+	CTR-
Target microorganism	2 mg	1 mg	500 µg	250 µg	2 mg	1 mg	500 µg	250 µg	2 mg	1 mg	500 µg	250 µg	2 mg	1 mg	500 µg	250 µg		
Listeria monocytogenes ATCC®19115	7 ± 0,2	0	0	0	6 ± 0,2	0	0	0	0	0	0	0	0	0	0	0	17 ± 0,2	0
Salmonella Typhimurium ATCC®14028	0	7 ± 0,2	0	0	0	0	0	0	0	9 ± 0,1	0	9 ± 0,1	0	7 ± 0,2	0	10 ± 0,1	20 ± 0,3	0

The grape pomace extracts showed minimal antimicrobial activity on the tested strains at concentrations of 250 µg and 1-2 mg. In particular, the Biancolella Dry (BS) grape pomace extract showed a halo of microbial growth inhibition on *Listeria monocytogenes* at 2 mg and on *Salmonella Typhimurium* at 1 mg. The extract from Fresh (BF) grape pomace also showed activity on *Listeria monocytogenes* at 2 mg, but with a slightly reduced inhibition zone. The extract from dry Piedirosso grape pomace (PS) showed inhibitory activity on *S. Typhimurium* at a concentration of 1 mg and 250 µg. The same extract but derived from fresh grape pomace (PF) also showed activity at the same concentrations on the same microorganism but slightly higher than those of PS.

The assessment of antimicrobial activity using the MIC method revealed a marked reduction in the microbial load of *L. monocytogenes* (Figure 6b). All extracts showed a 99% reduction at the concentration of 15 mg mL^{-1} and an inhibition consistently above 50% at 7.5 mg mL^{-1} and 3.5 mg mL^{-1}. Notably, the extract obtained from fresh Piedirosso grape pomace maintained high activity even at the lowest concentrations, with approximately 80% growth inhibition. *S. Typhimurium* strain was generally less sensitive to the extracts at lower concentrations (Figure 6a); however, at the highest concentration tested, growth inhibition reached 97%, 43%, 86%, and 61.62% for the BS, BF, PS, and PF extracts, respectively. Condensed tannins and proanthocyanidins, which are abundant in grape seeds and skins, have been identified as the compounds responsible for the antimicrobial activity. Oligomeric proanthocyanidins found in grape seeds appear to provide protection against *S. enterica*, while the flavan-3-ol compounds have shown broad-spectrum inhibition against various pathogens, including *L. monocytogenes* [10].

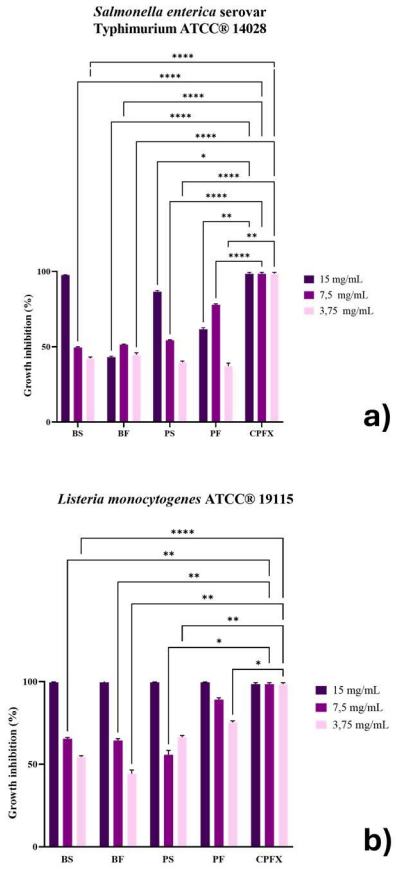


Fig. 6. Antimicrobial activity of BS, BF, PS, PF (15, 7,5 and 3,75 mg/mL) against pathogens: (a) S. *Typhimurium* and (b) *L. monocytogenes*. Significance levels indicated: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$, $****p < 0.0001$.

D. Antioxidant activity of grape pomaces

The ORAC assay results showed that all tested grape pomace extracts possess antioxidant activity. Unlike the antibacterial activity - which is most pronounced at milligram-level concentrations - the antioxidant effect reaches its maximum at 250 µg mL^{-1} for white grape pomace extract and at 100 µg mL-1 for the Piedirosso extracts. Notably, the fresh Piedirosso grape pomace extract displays a particularly strong antioxidant capacity, exceeding a TEAC (Trolox Equivalent Antioxidant Capacity) value of 350 at 100 µg/mL. Since TEAC values reflect a compound's ability to neutralize free radicals, higher values correspond to stronger antioxidant activity. Below 100 µg/mL, TEAC values generally decrease for Biancolella as well as for both fresh and dried Piedirosso extracts, indicating a decline in antioxidant efficacy at lower concentrations. In general, the extract from fresh grape pomace consistently shows higher antioxidant activity than its dried counterpart. This bioactivity of grape pomace has been extensively studied using various analytical and qualitative methods, such as DPPH, ORAC, CBA, and FRAP, revealing interesting properties also in cellular in vitro models [11].

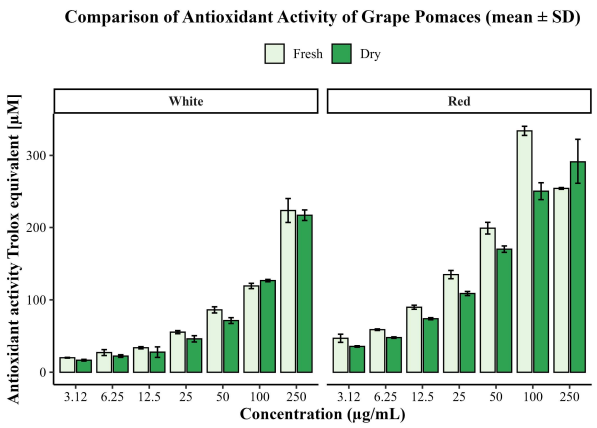


Fig. 7. ORAC assay results for pomace extract, expressed as µM Trolox equivalents, obtained by testing the compounds at scalar concentrations ranging from 250 to 3.12 µg mL^{-1}

IV. CONCLUSIONS

Thanks to its highly significant residual chemical characteristics, pomace has already found application in various innovative sectors, such as the production of fibres, fabrics and paper, as well as animal feed. However, it also represents a valuable resource in microbial fermentation, providing a sustainable way to transform production waste into valuable food ingredients.

The study identified microorganisms, particularly lactobacilli, which could be reused to enhance the nutritional and functional properties of pomace, providing potential prebiotic and antioxidant benefits. The antioxidant activity already observed in grape pomace, along with its natural ability to defend itself against foodborne pathogens such as *S. enterica* and *L. monocytogenes*, makes it a highly promising resource for various sectors, including the food and cosmetic industries. Moreover, post-fermentation processes may further enhance its beneficial properties. In addition to the food sector, pomace could have significant implications to produce compost, fertilisers and biochar, positively affecting soil quality and reducing the need for chemical fertilisers.

Nevertheless, further research is required to optimise processes, develop suitable techniques and equipment, and fully exploit this resource. The characterisation of additional pomace from different terroirs and grape varieties typical of Campania is set to be a key focus in future research. In addition, the extraction of dry and fermented pomace using microorganisms isolated from it is poised to be a significant area of exploration. The aim is twofold: firstly, to enhance the manufacturing of substances with antioxidant and antimicrobial properties, and secondly, to establish a distinct microbial and fungal profile of grape pomace.

ACKNOWLEDGMENT

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Sustainable Cultivation of Arthrospira platensis Using Aquaculture Wastewater: Bioremediation Potential, Biomass Quality, and Life Cycle Assessment

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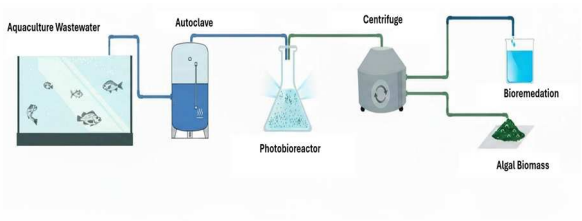
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Graphical Abstract



***Abstract*— The increasing global demand for sustainable protein sources calls for innovative solutions that integrate food production with environmental protection. Thanks to its high nutritional value and proven bioremediation potential, the microalgae *Arthrospira platensis* (also known as Spirulina) emerges as a promising candidate for this role. Cultivating high-quality Spirulina on alternative substrates—such as aquaculture wastewater—instead of conventional industrial media could apply circular economy principles to the aquaculture sector, enhancing its sustainability. In this study, pure Spirulina cultures were grown under controlled laboratory conditions for seven days using three different culture media: the conventional Zarrouk medium (control), aquaculture wastewater (WW), and bicarbonate-enriched wastewater (WW+B). We evaluated algal biomass, protein content, phycocyanin and chlorophyll concentrations, and nutrient removal efficiency. Additionally, a Life Cycle Assessment (LCA) was conducted using the ISO 14040 methodology to compare the environmental performance of the three cultivation systems. The results demonstrated that both the quantity and quality of Spirulina cultivated using WW and WW+B are comparable to those obtained with conventional industrial media. Furthermore, the addition of a growth supplement (bicarbonate) did not lead to any significant improvement in these parameters. The accompanying life cycle assessment (LCA) revealed a substantial reduction in environmental impacts for the system using wastewater alone, identifying it as the most sustainable option overall. This approach enables the production of high-quality biomass with minimal environmental footprints. These findings support the development of a circular economy model in which the resulting algae can serve as an alternative protein source in aquafeeds for farmed fish. This study integrates quantitative assessment methods, including statistical analysis of biomass and pigment production, as well as computational life cycle modeling, to provide a robust evaluation of bioremediation efficiency and environmental performance.**

Keywords—Spirulina; Arthrospira platensis; Aquaculture wastewater; Bioremediation; Life Cycle Assessment; Phycocyanin; Sustainable protein production

I. INTRODUCTION

The projected growth of the global population, estimated to reach 9.8 billion by 2050 and 11.2 billion by 2100 [1], will inevitably lead to an increased demand for food, energy, and raw materials [2; 3]. Aquaculture and fisheries have become one of the fastest-growing food production sectors, currently supplying approximately 17% of the global demand for animal protein and generating revenues of about US$472 billion annually [4]. However, aquaculture effluents can be detrimental for the environment since they are mainly composed of uneaten feed and organisms' metabolites [5] such as phosphorus and nitrogen in the form of ammonium, nitrite, nitrate, and phosphate, which at high concentrations could be toxic for organisms and lead to eutrophication [6]. The technologies used in treating wastewater are currently too expensive to be used across the aquaculture industry [7]; therefore, many researchers are searching for alternative, eco-friendly methods. In this context, microalgae bioremediation appears to be a promising solution, given that microalgae are already utilized in various applications, including the treatment of agricultural, industrial, and municipal wastewater [8; 9]. The microalgae *Arthrospira platensis* (Nordstedt) (Spirulina) can serve as a bioremediation agent due to its capacity to reduce pollutant loads while producing valuable biomass rich in protein, fatty acid, linoleic acid, vitamins, minerals, biliproteins, chlorophylls, and carotenoids [10; 11]. However, although microalgae are effective at removing dissolved nutrients, their use in aquaculture is limited because the algae themselves must also be removed afterward, requiring additional treatment steps like flocculation, sedimentation, or filtration [12; 13]. In this context, this work aims to use a multidisciplinary approach to transform the wastewater bioremediation process into a production process of Spirulina with qualitative characteristics suitable for its use as an alternative protein feed in the diet of fish reared in an aquaculture system, in line with a circular economy perspective. To this aim, total protein content, antioxidant activity, phycocyanin and chlorophyll levels, along with the bioremediation capacity of spirulina grown in aquaculture wastewater, were analyzed. The study was conducted by comparing the results obtained using three different culture media. Finally, a Life Cycle Assessment methodology [14] was applied to compare the three cultivation strategies to determine which substrate provides the most sustainable path for spirulina production, taking into account both environmental impact and resource efficiency. In addition to the biological characterization, the study incorporates quantitative and computational tools, including mass-balance calculations for nutrient removal, statistical evaluation of biomass and pigment production, and an ISO 14040–compliant LCA model implemented in SimaPro. These quantitative methods strengthen the engineering and modeling dimension of the work.

II. MATERIALS AND METHODS

Experiments were performed with pure cultures of Arthrospira platensis (Nordstedt),kindly provided by ATI Biotech. The cells were grown in standard medium (Zarrouk medium, pH 9) at 20-24°C under continuous light (light intensity, 100 µmol photons m-2 s-1) and flushed with filtered (sterile filter CA 0.22 µm) air. At late exponential phase (OD8001.5), the cells were divided into three experimental cultures: 1. Control: cells grown in Zarrouk medium; 2. Wastewater culture (WW): cells grown in the wastewater from a fish tank; 3. Bicarbonate-enriched culture (WW+B): cells grown in wastewater enriched with bicarbonate (17g/L). Wastewater was obtained from the maintenance facility for goldfish (Carassius auratus, provided by a local fish farm, CARMAR, Italy) of the Department of Biology of the University of Naples Federico II. Animal care was in accordance with the European and Italian laws and approved by the Institutional Animal Care and Use Committee (CESA) of the University of Naples Federico II, Naples, Italy (N. 767/2023-PR). All culture media (Zarrouk medium, wastewater, and bicarbonate-enriched wastewater) were autoclaved, filtered with 0.20 µm porosity filters, and frozen at - 20°C. Subsequently, they were used for pH measurements, and ionic composition determination (Conductivity, mS/cm; Salinity; Reactive Phosphorus, P, measured as P_2O_5, mg/L; NO_3^-, g/L; NO_2^-, mg/L; NH_4^+, mg/L; SO_4^{2-}, g/L; Chemical Oxygen Demand, COD, mg O_2/L) [15]. The evaluation of P_2O_5, NO_3^-, NO_2^-, NH_4^+, SO_4^{2-}, and COD was conducted at the Department of Science and Technology of the University of Naples Parthenope, and performed at the beginning and end (after 7 days) of algal growth. These data were used to determine the removal efficiency according to the following equation:

$$\text{Removal efficiency (\%)} = (C_i - C_f)/C_i \times 100$$

Where C_i and C_f are the initial and final concentrations (mg L^{-1}) of ions in the culture media.

After the algal growth period, 100 mL of culture was harvested by centrifuging for 10 min at 5000 rpm. The packed cells were resuspended in 5 mL of cold extraction buffer (50 mM phosphate, pH 7.5) and broken by passing them twice through a French cell press (1000 psi). The homogenate was centrifuged at 12,000 ×g and 4 °C for 15 min, and the clear supernatant was used as crude extract. The Spirulina protein content was measured by using the Bradford reagent according to the manufacturer's instructions (Bio-Rad, Hercules, CA, USA). Phycocian content [16] and chlorophyll content [17] were evaluated on spirulina homogenates. Statistical analyses were performed by using GraphPad Prism software, version 9.0 (GraphPad Software Inc., San Diego, CA, USA). The normality of data was assessed using the Shapiro–Wilk test. The equality of the standard deviations was assessed by the Brown-Forsythe test. The algal biomass and protein, phycocianin, and total chlorophyll content were evaluated on three

biological replicates (each one representing the media of three technical replicates) by Ordinary One-Way ANOVA, followed by Tukey post-hoc test ($p<0.05$ was taken as significant). All data concerning the growth and quality of Spirulina were collected at the Department of Biology of Federico II University in Naples.

The Life Cycle Assessment (LCA) in this study followed the ISO 14040 methodology [14]. It was conducted using SimaPro 9 software (PRé Sustainability B.V., Amersfoort, The Netherlands) in conjunction with the ReCiPe Midpoint (H) impact assessment method [18]. Spirulina production was simulated, with primary information on infrastructure and process operations obtained from a local company's production facilities. Experimental data on growth performance, including biomass concentration and productivity, were obtained from the laboratory conditions and subsequently used to model Spirulina yields within the environmental assessment. The functional unit (FU) for input and output flows was 1 kg of dry spirulina protein from the biomass. The main aim of the process analyzed was the production of proteins for potential use in aquaculture as an alternative to fishmeal. Using protein as the functional unit, rather than total dry biomass, allows for a more accurate representation of the product's functional role, facilitating the comparison with other protein sources used in feed formulations. This study also included the bioremediation potential of Arthrospira platensis. The initial concentrations of nitrate, phosphorus, COD, and sulfate were modeled as emissions to water in the baseline scenario, while their reduced concentrations after the growing period were used to represent the improved environmental performance of the system due to bioremediation. Therefore, the analysis not only evaluates the environmental impacts associated with Spirulina production but also quantifies the microalga's contribution to wastewater treatment, highlighting its dual role as a biomass resource and bioremediation agent.

III. RESULTS

The chemical analysis of WW and WW+B highlighted decreased conductivity and salinity values compared to the Control (Conductivity, 21.23±0.27, 10.35±2.19, and 14.82±0.05 mS/cm; Salinity 15.59±2.97, 5.33±1.62, and 8.57±0.08 g/L, for Control, WW, and WW+B groups, respectively). The pH values were comparable for all culture media (pH 9.29±0.25, 9.55±0.11, and 9.33±0.21 for Control, WW, and WW+B groups, respectively).

Table 1 shows the values of the remediation process carried out by Spirulina, expressed as a percentage of reduction in concentrations measured at the beginning and end of the algae growth period (Removal efficiency), in all culture media. The microalgae can bioremediate both WW and WW+B, with reduction percentages higher than those observed for the Control group. Although the COD values (i.e., the oxidizable organic matter) remain higher in WW and WW+B compared to the industrial medium, *Arthospira platensis* can reduce COD by 51.3% and 36.0% in WW and WW+B, respectively.

Table1. Removal efficiency of *Arthrospira platensis* after 7 days of growth (Control: Zarrouck medium; WW: wastewater; WW+B: bicarbonate-enriched wastewater).

Removal efficiency			
	Control	***WW***	***WW+B***
P_2O_5 (mg/L)	71.0%	99.8%	99.8%
NO_3^- (g/L)	75.0%	94.2%	93.6%
NO_2^- (mg/L)	Nd	Nd	Nd
NH_4^+ (mg/L)	Nd	Nd	Nd
SO_4^{2-} (g/L)	8.0%	32%	12.3%
COD (mg O_2/L)	90.5%	51.3%	36.0%

Fig. 1 shows algal biomass (dry weight g/mL of culture) and the content of total protein, phycocyanin, and total chlorophylls in *Arthrospira platensis* grown on the different culture media. The analyses related to the algal biomass, total protein content, and total chlorophyll content of *Arthrospira platensis* obtained with WW and WW+B did not show any significant difference, neither between the aquaculture wastewater and the one supplemented with sodium bicarbonate, nor with respect to the control group (Figure 1, Panels A, B, and D, respectively). The phycocyanin content, however, was significantly increased in both wastewaters compared to the industrial medium (Figure 1, Panel C).

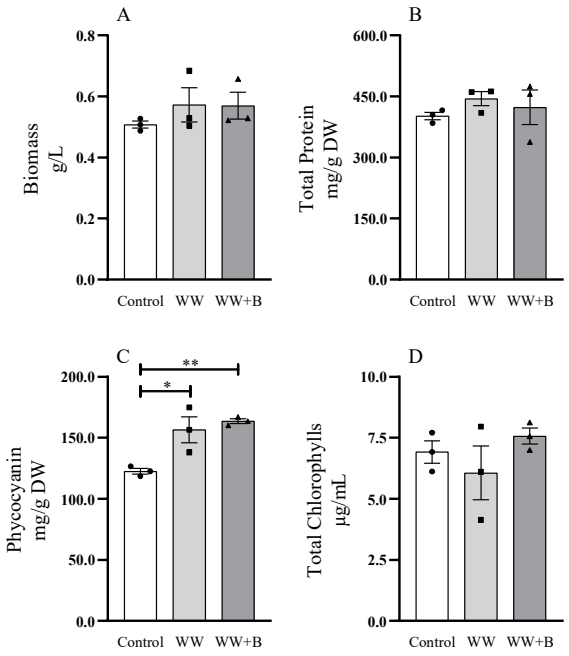


Figure 1: Quality evaluation of *Arthrospira platensis*. Algal biomass (Panel A), Total Protein Content (Panel B), Phycocianin (Panel C), and Total Chlorophylls (Panel D) content, measured in Arthrospira platensis cells grown on industrial medium (Control), wastewater (WW), and bicarbonate-enriched wastewater (WW+B).

Fig. 2 shows the main results of the LCA assessment obtained by comparing Spirulina cultivation on three different culture media. The results of this study demonstrated that producing Spirulina-based protein using WW as a medium represents a more sustainable cultivation than the conventional farming method. In fact, it helps to reduce water pollution and the risk of eutrophication, improving the quality of the water in impact categories such as marine and freshwater eutrophication that undergo a reduction when microalgae absorb pollutants.

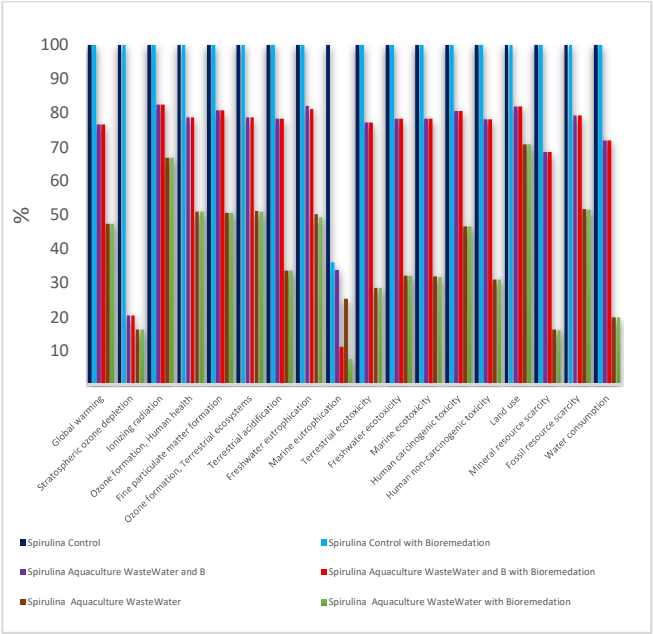


Figure 2. LCA comparison of *Arthrospira platensis* cultivation before and after bioremediation in Control (Zarrouk), aquaculture wastewater and bicarbonate, and aquaculture wastewater.

IV. DISCUSSION

The findings of this study indicate that: (i) both the fish farm wastewater (WW) and the same wastewater enriched with sodium bicarbonate (WW+B) can serve as viable alternatives to the industrial growth medium used for Spirulina cultivation (Control, Zarrouk medium); (ii) among the two, WW is the preferred option due to its lower cost and reduced environmental impact.

The pH values (above 9), salinity (around 9 g/L), and conductivity (approximately 15 mS/cm) of both WW and WW+B — key factors affecting photosynthesis, nutrient uptake, and cellular metabolism — confirm the suitability of fisf farm wastewaters as culture media for algal biomass growth, yielding results comparable to those obtained with the Zarrouk medium. This biomass shows a photosynthetic capacity—assessed through total chlorophyll content—comparable to that of the control Spirulina group. Notably, the protein content of Spirulina cultivated in both types of wastewaters also did not significantly differ from that of algae grown in Zarrouk medium. Thanks to its high protein content (460–630 g/kg of dry matter), comparable to that of meat and soy, Spirulina has attracted growing interest over the past decade as a promising alternative protein source to help mitigate global protein shortages [19]. Consequently, Spirulina cultivated using fish farm wastewater could represent a valuable and sustainable alternative to conventional protein sources.

The analysis of the total phycocyanin content revealed a significant increase in both WW and WW+B compared to the Control, highlighting a reinforcement of Spirulina's photosynthetic capacity and antioxidant

potential, which help to counteract oxidative damage to lipids and proteins caused by reactive oxygen species, unstable molecules generated as by-products of cellular metabolism [20]. It is well established that phycocyanin is the primary photosynthetic pigment in Spirulina, and numerous studies have demonstrated its ability to scavenge various reactive oxygen and nitrogen species, such as superoxide anions ($O_2^{\bullet-}$), singlet oxygen ($^1O_2$), hypochlorous acid (HOCl), peroxyl radicals ($ROO^{\bullet}$), peroxynitrite ($ONOO^-$), nitric oxide ($^{\bullet}NO$), and hydrogen peroxide (H_2O_2). This scavenging occurs through both direct and indirect mechanisms [20].

Removal efficiency analysis revealed that Spirulina cultivated in WW and WW+B has a greater capacity to remove phosphate, nitrate, and sulfate compared to algae grown in Zarrouk medium. The presence of these nutrients in the wastewater is likely due to the breakdown of fish feces and uneaten feed [21]. Furthermore, processes such as nitrification and denitrification contribute to the levels of ammonia, nitrite, and nitrate commonly found in aquaculture wastewater [22]. Since phosphate, nitrate, and sulfate are essential for the growth of photosynthetic microorganisms like Spirulina [23], these findings are consistent with previous studies highlighting the potential of Spirulina for purifying fish farm effluents [24].

The LCA assessment, which included Spirulina's ability to purify water and recover nutrients, indicated that cultivation in unenriched wastewater is the most sustainable. This environmental evaluation is based on a computational modeling framework that integrates experimental biomass yields and nutrient removal rates into ISO-compliant LCA scenarios. This quantitative, engineering-driven approach strengthens the interpretation of the environmental benefits observed. In these conditions, Spirulina reduced all environmental impact categories thanks to the elimination of synthetic fertilizer inputs. Its capacity to efficiently take up nutrients and organic matter from wastewater may contribute to effective resource utilization, in accordance with the circular bioeconomy principles.

V. Conclusion and Future Perspectives

This study demonstrated that aquaculture wastewater can effectively support Spirulina cultivation, yielding biomass of comparable quality to conventional methods while delivering significant bioremediation benefits. The elevated protein and phycocyanin content in wastewater-grown Spirulina enhances its functional and commercial value. Moreover, Life Cycle Assessment identified cultivation without bicarbonate supplementation as the most sustainable strategy, minimizing environmental impacts and advancing circular bioeconomy practices. Integrating Spirulina cultivation into aquaculture systems fosters synergies between the aquaculture and microalgae sectors, closing nutrient loops and enabling the production of sustainable, high-quality biomass. In fact, Spirulina could be directly used as a feed supplement in aquaculture, reinforcing circular economy models.

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Abbreviations and Acronyms

COD – CHEMICAL OXYGEN DEMAND

FU- FUNCTIONAL UNIT

ISO – INTERNATIONAL ORGANIZATION FOR STANDARDIZATION

LCA – LIFE CYCLE ASSESSMENT

WW – AQUACULTURE WASTEWATER

WW+B – AQUACULTURE WASTEWATER ENRICHED WITH BICARBONATE

Commissioning of RadCalc Monte-Carlo IDC model for clinical plan verification and EPID-based *in vivo* dosimetry in radiotherapy

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***Abstract*—RadCalc is a commercially available software developed by LifeLine Software Inc. for independent dose verification in radiotherapy. Originally designed for point dose calculations using conventional algorithms, RadCalc has been widely used in clinical practice as a secondary check system for treatment planning calculations. With the recent integration of a three-dimensional Monte Carlo (MC) algorithm, the software now offers enhanced accuracy and the ability to recalculate full volumetric dose distributions, making it suitable for more advanced applications such as in vivo dosimetry and independent plan verification.**

RadCalc is intended to be integrated into our institution's in vivo dosimetry program through the use of Electronic Portal Imaging Device (EPID)-based techniques. EPID-based in vivo dosimetry encompasses a set of computational methods that, by analyzing the signal recorded by the portal imager after transmission through the patient (transit dosimetry), aim to identify clinically relevant deviations before the therapeutic efficacy of the treatment is adversely affected. The validation of the in vivo dosimetry program using RadCalc necessarily requires an initial tuning and validation phase of the software.

The present work focuses on the validation of the new RadCalc software, equipped with a three-dimensional Monte Carlo module for the recalculation of radiotherapy treatment plans previously optimized within a Treatment Planning System (TPS). This process has been carried out by verifying the dosimetric accuracy of treatment plans recalculated with RadCalc Monte Carlo algorithm, with the aim of achieving a virtual Dose Quality Acceptance (DQA) passing through an Independent Dose Calculation (IDC) algorithm.

Despite their current prominent level of accuracy, radiotherapy treatment plans remain subjected to various sources of uncertainty, arising both from limitations inherent to the TPS dose calculation algorithms and from physical variabilities associated with the treatment delivery system. Consequently, this work represents not only a crucial initial step in the implementation of an EPID-based in vivo dosimetry program, but also an effective strategy to streamline conventional phantom-based DQA procedures for treatment plans.

Keywords—Radiotherapy, Monte Carlo, RadCalc, Dose Quality Acceptance, EPID-based dosimetry

I. Introduction

External beam radiation therapy (EBRT) currently represents one of the primary treatment modalities employed in the management of most oncological diseases [1], [2], [3], [4], [5], [6], [7], [8], [9]. The introduction of intensity-modulated radiation therapy (IMRT) and its subsequent evolution into volumetric modulated arc therapy (VMAT) marked a major milestone, establishing radiation therapy as a first-line treatment option for a wide range of malignancies [10], [11]. Technological advancements in the modulation of radiation beams delivered by linear accelerators (LINACs) have led to a significant improvement in treatment accuracy [1], [8]. In particular, VMAT—by combining continuous

gantry rotation with dynamic beam segmentation through modern multi-leaf collimator (MLC) systems—enables highly conformal dose distributions even in the presence of complex and heterogeneous target volumes, while ensuring substantial sparing of adjacent organs at risk (OARs) [12]. The high level of precision currently achieved by both treatment delivery systems and treatment planning systems (TPSs), as utilized by medical physicists and radiation oncologists, is a key factor in the success of most radiotherapy treatments [13], [14]. Nonetheless, treatment plans remain susceptible to various sources of uncertainty, stemming both from intrinsic limitations of the TPS dose calculation algorithms and from physical variations associated with treatment delivery by the LINAC—particularly in highly segmented and modulated plans [15]. In this context, Dose Quality Assurance (DQA) programs play a fundamental role in verifying the quality of planned treatments by analyzing deviations between calculated and measured dose distributions [16], [17], [18]. These verifications are typically performed using phantoms specifically designed for pre-treatment validation of radiotherapy plans, allowing the identification of potential errors before the actual delivery of the treatment, thus ensuring both its safety and effectiveness [19]. However, such procedures, while essential, are time-consuming and occupy valuable LINAC time that could otherwise be dedicated to patient treatments. A valid alternative to phantom-based DQA is offered by independent dose calculation (IDC) methods for plans optimized with TPSs [20]. IDC-based DQA is typically implemented using software equipped with Monte Carlo calculation algorithms. A further evolution in quality assurance strategies is represented by the implementation of in vivo dosimetry, which allows verification of the delivered dose directly on the patient during treatment [21]. This advanced methodology relies on the use of Electronic Portal Imaging Devices (EPIDs). EPID-based in vivo dosimetry encompasses a set of computational methods that, by analyzing the signal recorded by the portal imager after the beam has passed through the patient (transit dosimetry), aims to identify clinically relevant deviations before the therapeutic efficacy of the treatment is adversely affected. The signal acquired by the EPID is used to reconstruct the actual delivered dose distribution, enabling the detection of discrepancies with respect to the planned dose in near-real time, and thus providing an additional safety layer in clinical practice. When such discrepancies are identified, a thorough analysis is required to determine their origin—whether due to patient positioning, anatomical changes, delivery errors, or limitations in the treatment planning system—and, if necessary, the treatment plan must be adapted or re-optimized to ensure continued dosimetric accuracy and clinical efficacy. Within this framework, the newly updated RadCalc software—now equipped with a three-dimensional Monte Carlo calculation module—has been developed for the implementation of an IDC-DQA program, enabling independent secondary validation of treatment plans. The present study focuses on the initial commissioning and validation of this Monte Carlo module within RadCalc, with the aim of assessing its clinical reliability as a tool for treatment plan verification.
The ultimate goal of this validation process is to support the implementation of an institutional EPID-based in vivo dosimetry (IVD) program.

II. Materials and Methods

A. RadCalc software commissioning

The latest version of RadCalc software (v7.3) has been implemented at the Radiation Oncology Department of the Istituto Nazionale Tumori IRCCS "Fondazione G. Pascale" in Naples, Italy. The Monte Carlo model was commissioned by providing the manufacturer with the dosimetric specifications of the Elekta (Stockholm, Sweden) Versa HD LINAC, configured for 6 MV photon beams, and equipped with the Agility multi-leaf collimator (MLC) model. The data supplied included machine parameters (gantry, couch, collimator angles; field size parameters at isocenter distance; asymmetry configurations), treatment aids (e.g., physical wedges), dose calculation algorithms (Monte Carlo and Collapsed Cone Convolution), as implemented in the TPS RayStation™ (Tecnologie Avanzate) version 2024B used for RadCalc validation in our institution.

Additionally, clinical setup conditions were provided, including source-to-surface distance (SSD), source-to-axis distance (SAD), and reference field sizes. The dosimetric specifications were commissioned in the form of absolute dose calibration (1 Gy/100 MU for a 10×10 cm² field at SSD = 90 cm and SSD = 100 cm, depth = 10 cm), output factors in water and in air (for field sizes ranging from 1×1 cm² to 40×40 cm²), wedge factors and relative dosimetry (PDD and profile) all measured using a PTW 60019 microDiamond detector and the PTW Mephysto v4.6.5 scanning software. The CT calibration curve for the Canon Aquilion scanner, used for patient image acquisition, was derived directly from the HU-to-electron density (ED) conversion table. These CT data are essential for delineating the structures of interest—targets and organs at risk (OARs)—and for calculating the dose distribution within both the TPS and RadCalc environments. The datasets related to the acquired CT images, including structure sets, dose distributions, and the full set of treatment plan information (typically exported from the TPS to the treatment delivery system), were transferred to RadCalc in Digital Imaging and Communications in Medicine (DICOM) format.

B. Tuning of RadCalc ARLF

The optimization of the RadCalc Monte Carlo model was achieved by tuning the *Additional Radiation to Light Field Offset* (ARLF) parameter, following the methodology proposed by Sceni et al. [22]. ARLF accounts for the geometric discrepancy between the visually defined light field and the actual radiation field produced by a linear accelerator. This offset arises due to mechanical or alignment tolerances in the collimation system and may lead to a mismatch between the intended and delivered treatment fields. The ARLF value, typically expressed in centimeters, is applied to adjust the field size used in dose calculations to better reflect the true radiation field, thereby improving the accuracy of patient dose verification.

To this end, seven clinically accepted treatment plans using 6 MV photon beams were selected and initially planned in the RayStation™ TPS. For each plan, a corresponding DQA RT plan was generated on a virtual CT dataset of the Scandidos Delta⁴ phantom. These DQA RTplans were subsequently exported into RadCalc and recalculated varying the ARLF parameter, which represents the geometric offset (in centimeters) between the visual light field and the actual radiation field, across four values (0.00, 0.02, 0.04, 0.06), resulting in a total of 28 recalculated plans (7 clinical plans x 4 ARLF values).

The optimal ARLF value was determined by computing a weighted average of the ARLF values, where the weights corresponded to the maximum Gamma Passing Rate (GPR) achieved for each setting. The maximum GPR is chosen as the weight to prioritize ARLF values that achieves the highest local agreement between TPS and RadCalc dose distributions, ensuring that the tuning favors configurations with optimal dose conformity. The GPR analysis was performed using acceptance criteria of 2% dose difference (DD) and 2 mm distance to agreement (DTA). An acceptance threshold of the 90th percentile was adopted, in accordance with the recommendations of Task Group 218 (TG-218) of the American Association of Physicists in Medicine (AAPM) [23], which remains the most widely recognized guideline for gamma analysis in the absence of an equivalent European consensus.

For the tuning procedure, the comparison was made between the dose distribution recalculated with RadCalc and the reference distribution previously generated by the treatment planning system (TPS), both mapped on the virtual CT dataset of the Delta⁴ phantom.

C. RadCalc Validation

The validation of the RadCalc Monte Carlo dose calculation model was performed following the ARLF tuning procedure on a cohort of clinically approved VMAT treatment plans, developed in the RayStation™ TPS for various oncological sites (breast cancer, gynecological cancers, rectal cancer, prostate cancer, head and neck cancer, and glioblastoma).

The optimized RT plan files, together with each patient's original CT images, RTstruct, and RTdose datasets, were exported to RadCalc. Dose distributions were recalculated using the RadCalc Monte Carlo algorithm after appropriate tuning. This enabled an independent comparison between the dose distributions calculated by the TPS and those recalculated by RadCalc.

The agreement between the two dose calculation models was again evaluated using an acceptance threshold of the 90th percentile GPR, with a passing criteria of 2% DD and 2 mm DTA.

D. Evaluation Metrics for Model Performance

The performance of the RadCalc Monte Carlo calculation model, following ARLF tuning, as a tool for the implementation of independent dose calculation for DQA (IDC-DQA), was assessed using the following descriptive metrics, in accordance with the methodology employed by Sceni et al. [22]: Accuracy (1), Error Rate (2), Recall (3), Precision (4), Specificity (5), and F-Score (6):

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (1)$$

$$Error\ Rate = \frac{FP + FN}{TP + TN + FP + FN} \quad (2)$$

$$Recall = \frac{TP}{TP + FN} \quad (3)$$

$$Precision = \frac{TP}{TP + FP} \quad (4)$$

$$F - Score = \frac{2 \cdot Recall \cdot Precision}{Recall + Precision} \quad (5)$$

The performance of the model was evaluated by comparing the IDC-DQA results obtained with RadCalc against the dose distribution calculated by the TPS, and by comparing the phantom-based DQA—i.e., the dose distribution measured with the Delta⁴ phantom—with the

corresponding TPS-calculated distribution. The analysis was conducted based on the evaluation of the confusion matrix presented in **Table 1**, where the Delta⁴ measurements were considered the reference standard for classification purposes.

Table 1. Confusion matrix for the evaluation of the performance of the RadCalc Monte Carlo calculation model in the context of its validation for use as an IDC-DQA tool. For both the RadCalc vs TPS and the Delta⁴ vs TPS comparisons, the Gamma Passing Rate (GPR) with 2%/2 mm criteria was assessed using the 90th percentile threshold.

		Delta⁴ vs TPS	
		GPR 2%2mm < 90%	**GPR 2%2mm** ≥ 90%
RadCalc vs TPS	**GPR 2%2mm** ≥ 90%	**False Positive (FP)**	**True Positive (TP)**
	GPR 2%2mm < 90%	**True Negative (TN)**	**False Negative (FN)**

III. Results

A. ARLF Plot Profiles

The mean of the ARLF values weighted over the maximum Gamma Passing Rate (GPR) at 2%/2 mm (RadCalc vs TPS) obtained for each of the selected plans as a function of the ARLF parameter, is reported in **Table 2** and **Figure 1**.

Table 2. Gamma Passing Rate (GPR) values at 2%/2 mm for RadCalc vs TPS, evaluated for the seven selected plans as a function of the ARLF parameter. The highest GPR values for each fixed ARLF are highlighted in red.

Tuning Values and Plot Profiles				
GPR 2%2mm (RadCalc vs TPS) - 6 MV - RayStation™				
Plans	**ARLF (cm)**			
	0	**0.02**	**0.04**	**0.06**
1	93.66	93.65	93.06	97.59
2	97.73	98.22	97.96	97.83
3	97.98	98.25	99.89	97.92
4	95.44	96.33	95.94	95.53
5	99.35	99.37	99.69	100
6	98.82	99	98.97	99.01
7	99.09	99.25	99.79	98.92
$ARLF_w$ = 0.04 cm				

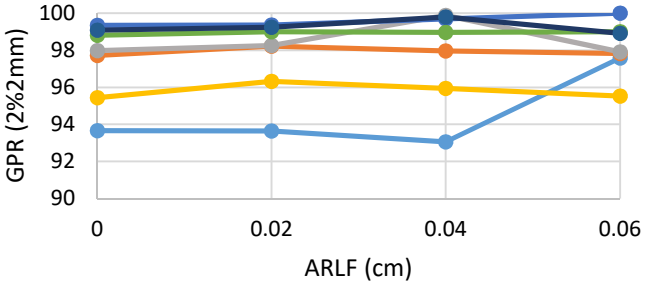


Figure 1. Plot profile of the Gamma Passing Rate (GPR) at 2%/2 mm for RadCalc vs TPS as a function of the ARLF parameter, used for tuning the RadCalc Monte Carlo dose calculation model.

The resulting value of the weighted ARLF was 0.04 and was subsequently implemented in the RadCalc Monte Carlo calculation model associated with the RayStation™ TPS.

B. Validation of the RadCalc Monte Carlo Dose Calculation Model

The validation of the RadCalc Monte Carlo dose calculation model, aimed at the development of an IDC-DQA program, was carried out by comparing the Gamma Passing Rates (GPR) at 2%/2 mm from Delta⁴ vs TPS with those obtained from the comparison between RadCalc (tuned) and TPS. The acceptance threshold was set at the 90th percentile, as shown in Figure 2, and the results of the validation metrics derived from the confusion matrix data are reported in Table 3.

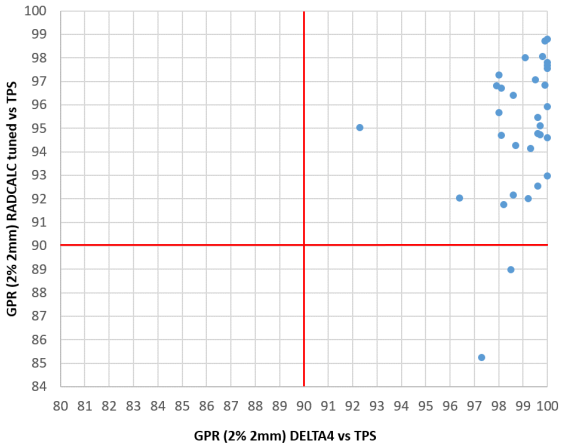


Figure 2. Distribution of GPR (2%/2 mm) pairs between phantom-based DQA measurements obtained with the Delta⁴ (x-axis) and IDC-DQA calculations performed by the tuned RadCalc model (y-

axis), both relative to the dose distribution calculated by the RayStation™ TPS. The validation threshold was set at the 90th percentile.

Table 3. Confusion matrix metrics for GPR 2%2mm (threshold ≥90%) comparing RadCalc and Delta⁴ against TPS.

GPR 2%2mm RadCalc vs TPS and Delta⁴ vs TPS (threshold 90%)		
Confusion Matrix	TP	30
	TN	0
	FP	0
	FN	2
Accuracy	93.75%	
Error Rate	6.25%	
Recall	93.75%	
Precision	100%	
F-Score	96.77%	

IV. Discussion

The validation of the RadCalc Monte Carlo model for Independent Dose Calculation (IDC-DQA) demonstrated highly satisfactory performance, confirming its potential reliability for clinical use in pre-treatment verification of radiotherapy plans. The comparison was conducted between RadCalc and the Treatment Planning System (TPS), using the Gamma Passing Rate (GPR) at 2%/2 mm as the reference metric, in accordance with the recommendations of Task Group 218 (TG-218) of the American Association of Physicists in Medicine (AAPM). TG-218 recommends employing the 2%/2 mm criterion with a 90% acceptance threshold as the standard for plan validation, as it represents a balanced compromise between sensitivity and clinical relevance, ensuring a rigorous verification of dosimetric accuracy. The obtained results indicate an overall accuracy of 93.75% and a low error rate of 6.25%. The recall (sensitivity) of 93.75% reflects the model's high capability to correctly identify plans that meet the acceptance criteria, while the precision of 100% indicates the absence of false positives, with all plans deemed acceptable by RadCalc actually conforming to the TPS criteria. The F-score of 96.77%, effectively combining recall and precision, further confirms the robustness and balance of the model. These metrics suggest that RadCalc reliably replicates the dosimetric evaluations of the TPS, while providing an independent and potentially more efficient analysis within the QA workflow. Compliance with TG-218 criteria and the outcomes of this analysis support the use of RadCalc as an independent verification tool in the clinical setting, not only for pre-treatment plan validation but also prospectively for in vivo dosimetry applications. This is facilitated by its Monte Carlo-based algorithm, capable of delivering reliable dose estimates in complex geometries and high-dose gradient regions.

V. Conclusions

The validation results indicate that RadCalc, configured with a Monte Carlo algorithm, is a reliable system for Independent Dose Calculation (IDC-DQA), demonstrating high concordance with the TPS in the evaluation of the Gamma Passing Rate (GPR) at 2%/2 mm. The observed accuracy and precision support the use of RadCalc as a complementary tool for dosimetric QA of radiotherapy treatments, particularly for complex plans such as VMAT. Importantly, implementing a robust MC-based IDC framework offers potential sustainability benefits for clinical operations: by identifying plans that can be safely verified through independent calculation rather than routine measurement, departments may reduce the number of resource-intensive DQA procedures. This reduction can translate into lower equipment usage, decreased consumable waste, and more efficient allocation of machine and staff time, ultimately supporting greener and more streamlined radiotherapy workflows.

The current analysis was conducted on an initial cohort of clinically approved plans, all considered "expected positives," i.e., plans compliant with clinical criteria. Consequently, the resulting confusion matrix included true positives (TP) and one false negative (FN), but no true negatives (TN) or false positives (FP). This entails certain methodological limitations, notably the inability to calculate specificity and the area under the ROC curve (AUC). Nevertheless, metrics such as accuracy, recall, precision, F1-score, and error rate remain fully meaningful and provide reliable indications regarding the model's effectiveness in correctly identifying clinically acceptable plans.

Therefore, future developments of this study should include a larger and more balanced case series encompassing non-compliant plans—either real or simulated—to enable a more comprehensive assessment of the model's discriminative capacity and to calculate currently unavailable metrics. Expanding the cohort will represent the next step toward integrating RadCalc not only in pre-treatment QA but also in in vivo dosimetry, thereby contributing to improved

safety, traceability, and overall quality of the radiotherapy process. In parallel, establishing clear thresholds and decision pathways for MC IDC-driven plan triage could further enhance departmental sustainability, enabling targeted use of measurement-based DQA only when truly necessary and reinforcing a more efficient, clinically responsible, and environmentally conscious workflow.

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External Dosimetry Audit IAEA/WHO for Validation of Megavoltage X-ray Beams

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***Abstract*—In July 2025, an external dosimetry audit was conducted at the Radiotherapy Department of the National Cancer Institute IRCCS "Fondazione G. Pascale" (Naples, Italy), as part of the IAEA/WHO global dosimetry audit program for radiotherapy quality assurance. The objective of the audit was to independently verify the absorbed dose to water delivered by clinical megavoltage X-ray beams produced by a linear accelerator (LINAC) operating at 6 MV, 6 MV FFF, 10 MV, and 15 MV photon energies. The audit employed radiophotoluminescent dosimeters (RPLDs), which were supplied and later analyzed by the Dosimetry Laboratory of the Dosimetry and Medical Radiation Physics (DMRP) Section, Division of Human Health, at the IAEA Seibersdorf Laboratories, Vienna International Centre. Dosimeters were irradiated under reference conditions in a water phantom within the treatment room, following IAEA protocols. For each beam energy, dosimeters were positioned using clinical geometries in terms of source-to-surface distance (SSD), depth, and field size, ensuring standardization and traceability. Following irradiation, the RPLDs were returned to the IAEA laboratory for high-precision readout and analysis. The measured dose values were then compared against the stated institutional dose delivery to assess the accuracy of the beam calibration. Results for all beam qualities were found to be within the IAEA acceptance limits, thereby confirming compliance with international dosimetric standards. This external audit constitutes an essential component of independent quality assurance in radiotherapy, contributing to treatment safety and dosimetric accuracy. The positive outcome of the audit validates the local calibration procedures and supports the continuous implementation of high-quality standards in clinical photon beam dosimetry.**

Keywords—IAEA/WHO, Dose Quality Audit, Radiotherapy, RPLD capsules

I. Introduction

Accurate dose delivery is a fundamental requirement in external beam radiotherapy, where the goal is to maximize tumor control while minimizing radiation exposure to healthy tissues. Achieving this balance relies on the precise calibration and verification of radiation beams, which must be traceable to international metrological standards. Accurate dose delivery is critical in high-precision treatments such as stereotactic radiotherapy, where even minimal discrepancies can compromise treatment efficacy or increase the risk of toxicity. For this reason, independent verification of the dose delivered by radiotherapy units is considered an essential component of comprehensive quality assurance (QA) programs.

Within this framework, independent dosimetry audits represent a reliable mechanism for assessing whether the dosimetric procedures implemented at a radiotherapy facility are sufficient to meet clinical objectives in cancer treatment [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]. These audits play a critical role in the detection of discrepancies and contribute to their systematic resolution. Over time, such auditing practices have enhanced the precision of dose delivery in numerous radiotherapy centres and have contributed to the development and sustained application of appropriate standards in medical physics [13].

To support global efforts in improving treatment quality and patient safety, the International Atomic Energy Agency (IAEA), in collaboration with the World Health Organization (WHO), has established an external dosimetry audit program. This initiative allows radiotherapy centers worldwide to verify the accuracy of their dose delivery using passive dosimeters irradiated under standardized reference conditions. IAEA has established a database describing activities of dosimetry audit networks (DAN) in radiotherapy. Since 2010 the data on different aspects of the dosimetry audit have been collected [1]. The audits are typically performed for Co-60 units and megavoltage X-ray beams using a water phantom, a 10 cm × 10 cm field size, and a 10 cm depth, with the institution's clinically used source-to-surface distance (SSD) or source-to-axis distance (SAD).

In this context, an external dosimetry audit was conducted in July 2025 at the Radiotherapy Department of the National Cancer Institute IRCCS "Fondazione G. Pascale" (Naples, Italy). The audit focused on the independent verification of dose output from clinical photon beams produced by a linear accelerator (LINAC) operating at nominal energies of 6 MV, 6 MV FFF, 10 MV, and 15 MV. Radiophotoluminescent

dosimeters (RPLDs), provided by the Dosimetry Laboratory of the Dosimetry and Medical Radiation Physics (DMRP) Section, Division of Human Health, IAEA Seibersdorf Laboratories (Vienna International Centre), were used for the measurement.

The dosimeters were irradiated under reference conditions using a water phantom, with accurate positioning according to IAEA protocols. After irradiation, the RPLDs were returned to the IAEA laboratory for readout and analysis. The measured dose values were compared to those declared by the institution to assess the accuracy of local beam calibration. All results were found to be within the IAEA's acceptance criteria, confirming dosimetric compliance across all tested beam energies.

This work demonstrates the importance and effectiveness of participating in independent dosimetry audits, not only as a means of quality assurance but also as a validation tool for maintaining high clinical standards in radiotherapy practice.

II. Materials and Methods

A. Specifications of the irradiation unit

In the initial phase of the external dosimetric validation, the technical specifications of the treatment unit used during the audit were documented. Specifically, the irradiation unit was an Elekta (Stockholm, Sweden) Versa HD linear accelerator. The photon beam energies employed for the medical accelerator included 6 MV, 6 MV flattening filter free (FFF), 10 MV, and 15 MV. The beam quality for each energy was characterized in terms of the tissue-phantom ratio at depths of 20 cm and 10 cm ($TPR_{20,10}$), measured for a 10 × 10 cm² field size at a source-to-surface distance (SSD) of 100 cm, in accordance with the guidelines outlined in IAEA TRS-398 [15]. The clinical beam output determined during linear accelerator commissioning was 1 cGy/MU (as of September 2024), applicable at 10 cm depth in water for a 10 × 10 cm² field, at a fixed SAD of 100 cm. Under these reference conditions, the percentage depth dose (PDD) values obtained during LINAC commissioning were reported as follows: 66.06% for 6 MV, 66.14% for 6 MV flattening filter free (FFF), 71.5% for 10 MV, and 74.77% for 15 MV photon beams.

B. MUs Calculation

Monitor units (MUs) calculation were performed using the Elekta Monaco™ Treatment Planning System (TPS), employing the Monte Carlo/Collapsed Cone Convolution dose calculation algorithm (**Figure 1**). Dose calculations were carried out on a virtual water phantom (dimensions 60 × 40 × 60 cm³) to ensure full scatter conditions and in order to reproduce the geometry of the physical PTW BEAMSCAN water phantom employed for measurements, with the objective of delivering a dose of 200 cGy at a depth of 10 cm, using a field size of 10 × 10 cm², a source-to-surface distance (SSD) of 100 cm.

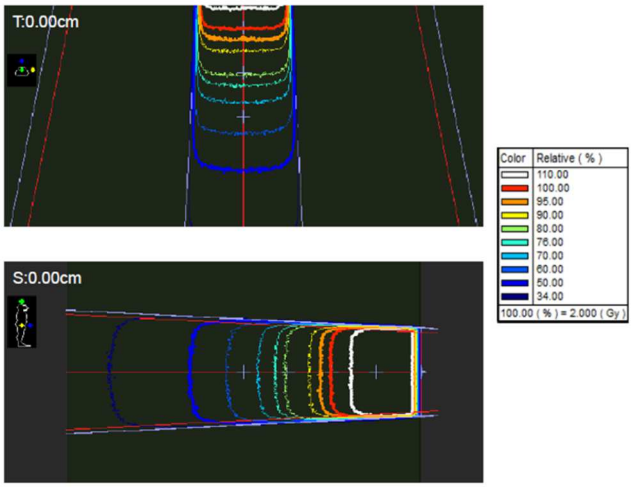


Figure 1. Treatment planning performed using the Monaco Treatment Planning System (Elekta) on a virtual water phantom, simulating the actual experimental irradiation conditions of the RPLD capsules.

C. Irradiation of RPLD capsules

RPLDs are well-suited for dosimetry audits due to their high reproducibility, low signal fading, repeatable non-destructive readout, and low inter-dosimeter variability, ensuring accurate and stable dose measurements over time [14]. RPLD capsules were irradiated at a depth of 10 cm in a water phantom, using a 10 × 10 cm² field size and a fixed source-to-surface distance (SSD) of 100 cm. For each RPLD capsule, the monitor unit (MU) settings and the corresponding delivered dose were determined using the Monaco Treatment Planning System. A total of 240 MUs were delivered, corresponding to a calculated absorbed dose of 2 Gy at the specified reference depth (as described previously in section *B*). The absorbed dose to water at the center of the RPLD capsule was previously verified using an independent dosimetry system consisting of a PTW Semiflex 0.125 cc 31010 ionization chamber connected to a PTW BEAMSCAN electrometer.

The absorbed dose to water calibration coefficient $N_{D,w} = 2.981 * 10^8\ Gy/C$ was provided by the PTW Calibration Laboratory (calibration date: July 2024), and refers to reference conditions of 20 °C and 101.325 kPa. The dose measurement was collected using a water phantom under the following conditions: field size of 10 × 10 cm², SSD of 100 cm, and a chamber measurement depth of 10 cm (geometrical center). The ion chamber readings were recorded as the average collected charge (mean of three measurements), expressed in nanocoulombs (nC), corresponding to a known dose of 2 Gy at the isocenter, as calculated by the TPS. Ambient conditions during the measurement were a temperature of 22.8 °C and an atmospheric pressure of 98.228 kPa. The absorbed dose to water D_w at the position of the RPLD capsule was then determined following the IAEA TRS-398 dosimetry protocol [15], considering the following equation for each investigated energy:

$$D_w = < M > \times K_{TP} \times N_{D,w} \times K_{Q,Q0} \times K_{sat} \times K_{pol} \quad (1)$$

Where:

$< M >$ represents the average collected charge in nC;

$K_{TP} = \frac{(273.15+T)}{(273.15+20)} * \frac{101.3}{P}$, is the correction factor for temperature T (°C) and pressure P (kPa);

$N_{D,w}$, absorbed dose to water calibration coefficient of the ionization chamber;

$K_{Q,Q0}$, allows for the adaptation of the ionization chamber calibration coefficient, originally determined under reference conditions Q0 (typically in a Co-60 beam), to the clinical beam quality Q used during the experimental measurements. $K_{Q,Q0}$ was obtained during the linear accelerator commissioning phase using the following equation:

$$K_{Q,Q0} = -0.5669 * TPR_{20,10}^2 + 0.5951 * TPR_{20,10} + 0.8447 \quad (2)$$

Where the fitting coefficients were obtained according to IAEA TRS 398 reference tables [15], while the factor $TPR_{20,10}$, was obtained considering the following equation:

$$TPR_{20,10} = 1.2661 * \frac{D_{20}}{D_{10}} - 0.0595 \quad (3)$$

with D_{20}/D_{10} obtained from the PDD curve measured using a field size of 10 × 10 cm² and a fixed source-to-surface distance (SSD) of 100 cm (where D_{20} and D_{10} represent the dose values at 10 cm and 20 cm depth in water, respectively);

K_{sat}, is a correction factor applied to the reading of an ionization chamber to account for ion recombination within the chamber. It was determined using the following equation:

$$K_{sat} = 1 + \left(\frac{< M >_{+400\,Volt}}{< M >_{+150\,Volt}} - 1\right) \Big/ \left(\frac{400}{150} - 1\right) \quad (4)$$

where $< M >_{+400\,Volt}$ e $< M >_{+150\,Volt}$ represent the average charge readings obtained with the ionization chamber biased at +400 V and +150 V, respectively.

K_{pol}, is the correction factor for the polarity effect of an ionization chamber. It is used to correct for any asymmetry in the chamber's response depending on the polarity (positive or negative) of the applied voltage. This factor was determined using the following relationship:

$$K_{pol} = (< M >_{+400\,Volt} + |< M >_{-400\,Volt}|)/2 < M >_{+400\,Volt} \quad (5)$$

with $< M >_{-400\,Volt}$ represents the average charge reading obtained with the ionization chamber biased at -400 V, which is opposite in polarity to the standard operating voltage.

It is important to note that all dosimetric values used in these calculations are derived from actual measurements, performed under controlled conditions, in the same manner as the verification conducted prior to the RPLD exposure.

D. Positioning and irradiation of the RPLD capusles

The dosimeter holder was carefully assembled and subsequently positioned within the water phantom (PTW BEAMSCAN) to ensure stable and reproducible placement during irradiation (**Figure 2**). The radiotherapy treatment unit was configured to deliver a vertically oriented photon beam with a standardized field size of 10 × 10 cm², consistent with reference dosimetry conditions. The water level in the phantom tank was meticulously adjusted so that the water surface precisely aligned with the upper edge of the holder, guaranteeing complete submersion of the holder's internal tube. This ensured the absence of air gaps that could potentially influence dose measurements. Concurrently, the setup height was adjusted to maintain the source-to-surface distance (SSD) at 100 cm, adhering strictly to established dosimetry protocols. The alignment of the holder tube with the central axis of the radiation beam was performed using laser guidance and verified by visual inspection to ensure accurate positioning of the dosimeters within the radiation field. It is important to note that RPLD capsules featuring a blue plug were intentionally excluded from irradiation, as these serve exclusively as controls for monitoring environmental factors such as temperature and humidity during transport and storage. Each RPLD capsule was carefully inserted into the designated aperture of the holder, with the marked dot on the capsule oriented to coincide with the geometric center of the holder's tube, thus positioning the sensitive volume of the dosimeter at the reference measurement point (**Figure 3**). Prior to the irradiation procedure, a comprehensive verification was conducted to confirm correct alignment, appropriate field size, accurate water level, and consistent SSD. The RPLD capsules were irradiated with the number of monitor units previously calculated through treatment planning system simulations to deliver the prescribed absorbed dose. Upon completion of the irradiation, each capsule was carefully removed from the holder and gently dried to prevent any contamination or damage. This entire process was repeated for a second RPLD capsule for each nominal photon energy produced by the medical linear accelerator, resulting in the irradiation of two dosimeters per beam quality. This approach allows for reproducibility assessment and enhances the reliability of the dosimetric verification.

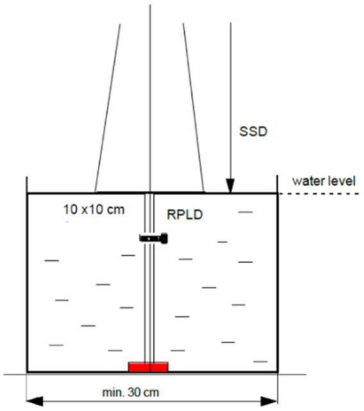


Figure 2. Experimental setup for the irradiation of the RPLD capsules. Irradiation was performed with a 10 × 10 cm² field size,

an SSD of 100 cm, and a measurement depth of 10 cm from the water surface (courtesy of IAEA/WHO instruction sheet).

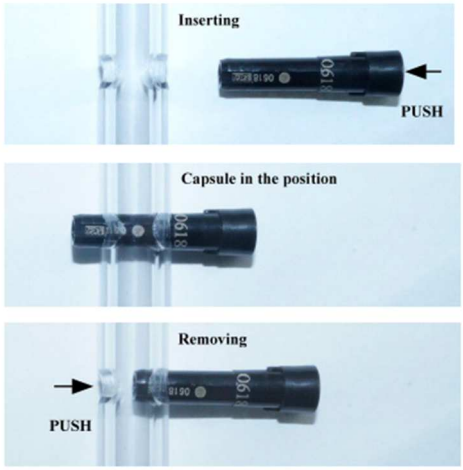


Figure 3. IAEA guidelines for the insertion, positioning, and removal of RPLD capsules within the support holder during external dosimetry audits (courtesy of IAEA/WHO instruction sheet).

III. Results and Discussion

The results of the dosimetric audit are provided by the IAEA one month following the irradiation of the RPLD capsules. For each photon beam energy tested, the IAEA/WHO dose quality audit service presents the mean absorbed dose to water measured from the two RPLD capsules for each set (each set of two capsules specific for tested beam energy). The uncertainty in the RPLD measurement of the dose is 1.5% (this does not include the uncertainty intrinsic to the dosimetry protocol according to IAEA TRS-398). The results of IAEA measurements are reported in **Table 1**. The user stated dose (2.00 Gy for the present study) is compared in terms of percentage deviation to the mean IAEA measured dose (Gy), evaluated on the pair of RPLDs capsules for each energy set, as follows:

$$\% \text{ Deviation} = 100 * \frac{User\ stated\ dose - IAEA\ mean\ measured\ dose}{IAEA\ mean\ measured\ dose} \quad (6)$$

In all cases, the relative difference between the measured and user stated dose values need to remain within the ±5% acceptance threshold established by the IAEA/WHO dose quality service for external audits. This outcome confirms the consistency and reliability of the local absolute dosimetry procedures and supports the accuracy of beam output calibration for the clinical photon energies evaluated. Minor deviations across energies need to take into account expected uncertainties related to measurement, dosimeter response, and environmental factors during storage and transport.

Table 1. Results of IAEA RPLDs measurements for high energy photon beams (6, 6 FFF, 10, 15 MV). The uncertainty in the RPLD dose measurement is of 1.5%.

Beam energy (MV)	Set #	ID	User stated dose (Gy)	IAEA mean measured dose (Gy)	Deviation relative to IAEA mean dose (%)	IAEA measured dose/User stated dose
6	22579	1179 1181	2.00	1.99	0.5	0.99
6 FFF	22580	1182 1183	2.00	1.97	1.3	0.99
10	22581	1184 1185	2.00	1.99	0.5	1.00
15	22582	1186 1187	2.00	1.99	0.3	1.00

From the data reported in **Table 1**. The results of the present dosimetric audit demonstrate a high level of consistency between the user-stated doses and the IAEA reference measurements across all investigated photon beam energies. For the conventional flattened beams (6, 10, and 15 MV), the observed deviations between the stated 2.00 Gy and the IAEA-measured doses are minimal, ranging from 0.3% to 0.5%, indicating excellent agreement and stable calibration performance. A slightly larger deviation of 1.3% is noted for the 6 MV FFF beam, which is consistent with the inherently less homogeneous field profile characteristic of flattening-filter-free modalities and may therefore contribute to a modest increase in measurement variability. Nonetheless, all deviations remain well within the IAEA acceptance criterion of ±5%, confirming that the dosimetric output of all beams meets international quality assurance standards.

IV. Conclusions

The completed IAEA external dosimetry audit has confirmed the high accuracy of absolute dose delivery at the Radiotherapy Department of the National Cancer Institute IRCCS “Fondazione G. Pascale.” The measured deviations between user-stated and IAEA-verified doses were minimal for all photon beam energies, remaining between 0.3% and 0.5% for the 6, 10, and 15 MV beams, and reaching 1.3% for the 6 MV FFF beam—an expected finding given the less homogeneous profile characteristic of flattening-filter-free irradiation. Importantly, all results lie well within the IAEA acceptance threshold of ±5%, thereby providing strong external validation of the department’s reference dosimetry and confirming compliance with international quality assurance benchmarks.

Beyond methodological verification, successful participation in such audits represents a foundational requirement for the safe adoption of advanced and highly specialized treatments, including pediatric radiotherapy, which remains a strategic clinical priority of the department. The positive audit outcome constitutes an internationally recognized endorsement of the quality of the radiotherapy service, enabling the institute to engage in multicenter clinical trials and to offer treatment to patients requiring complex or protocol-driven radiotherapy approaches. Moreover, the standardized audit framework promotes long-term sustainability by fostering reproducible quality assurance practices, optimizing resource use, and supporting the routine integration of independent verification into departmental workflows. In this regard, achieving and maintaining certification is essential not only for strengthening patient safety and sustaining high clinical standards, but also for reinforcing the institute’s role as an active contributor to the international advancement of radiotherapy practice.

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***Abstract*— GammaPod™ is an innovative radiotherapy platform specifically developed for noninvasive stereotactic treatment of early-stage breast cancer. Designed to overcome the geometric and dosimetric limitations of conventional Accelerated Partial Breast Irradiation techniques, it delivers highly conformal ablative doses via 25 fixed ^{60}Co sources arranged in a hemispherical configuration. The system relies on a vacuum-assisted breast immobilization cup embedded with a wire-shaped fiducial marker, enabling the creation of a stereotactic coordinate system for submillimeter target localization.**

As of July 2025, GammaPod™ has been implemented in only 5 centers worldwide, with 2 units currently operational in Italy. The forthcoming installation at our institution will represent the 3rd in the country and the 6th globally, underscoring the pioneering nature of this clinical deployment. Commissioning activities will be conducted in preparation for clinical deployment of GammaPod™ at the Istituto Nazionale Tumori IRCCS Fondazione G. Pascale (Naples, Italy) scheduled for January 2026. Planned procedures will include mechanical reproducibility tests of the motorized couch, assessment of vacuum seal stability, and absolute dose calibration using PMMA phantoms combining the AAPM TG-51 protocol and the IAEA TRS-483 code of practice. Radiation protection assessments will be performed to verify the shielding effectiveness of the device, given the presence of fixed radioactive sources and the extended patient setup times required, which may involve staff proximity to the treatment unit. The clinical deployment of GammaPod™ will require the establishment of dedicated commissioning procedures, institution-specific infrastructure adjustments, and its systematic integration into established radiotherapy workflows. This system may represent a paradigm shift in stereotactic breast radiotherapy, offering precise treatment delivery with reduced toxicity and patient burden. Furthermore, by condensing treatment into a limited number of sessions, GammaPod™ may contribute to the sustainability of radiotherapy services through optimized scheduling and improved patient throughput. The upcoming commissioning phase will define the framework for its safe and effective clinical integration.

Keywords*— *GammaPod, Breast Cancer, Stereotactic Breast Cancer Radiotherapy, Stereotactic Radiotherapy, Stereotactic Partial Breast Irradiation, Breast-Conserving Surgery

I. Introduction

Breast cancer is the most commonly diagnosed malignancy among women worldwide and a major contributor to cancer-related deaths. In 2022, over 2.3 million new cases and approximately 685,000 deaths were reported globally [1], [2]. In Italy, around 55,900 new cases were estimated in 2023, making it the most frequent cancer among women. Five-year survival exceeds 88%, particularly in early-stage diagnoses, while mortality continues to decline due to improved screening and treatments [3]. Although primarily affecting women, breast cancer also occurs in men, with roughly 500 cases per year in Italy. Risk factors include BRCA1/2 mutations, hormonal exposure, obesity, alcohol use, and sedentary lifestyle [4], [5]. Given its high incidence and impact, breast cancer remains a priority for prevention, early detection, and therapeutic innovation.

In the management of early-stage breast carcinoma (stages I and II), breast-conserving treatment (BCT) has emerged as a clinically validated and oncologically safe alternative to mastectomy. The standard therapeutic protocol consists of a segmental mastectomy (lumpectomy) followed by adjuvant radiotherapy, typically delivered in 25 to 30 fractions over the course of 5 to 7 weeks, with treatments administered 5 days per week. Modern radiotherapy increasingly aims to reduce treatment duration and patient burden by transitioning toward hypofractionated regimens, potentially limiting the number of fractions to as few as 1 to 5. Initiation of radiotherapy is generally deferred for several weeks postoperatively to

facilitate partial resolution of surgical site edema and seroma accumulation, thereby allowing adequate tissue recovery and optimizing subsequent radiation planning and delivery [6], [7].

Over the past several decades, numerous advanced techniques have been engineered to confine radiotherapeutic doses exclusively to targeted breast regions. These modalities encompass intracavitary brachytherapy, intraoperative radiation therapy (IORT) employing either electron beam or low-energy photon sources, alongside external beam radiation therapy (EBRT) modalities utilizing three-dimensional conformal radiation therapy (3D-CRT) or intensity-modulated radiation therapy (IMRT) frameworks to optimize dose distribution and minimize exposure to surrounding tissues [8], [9], [10], [11].

The National Surgical Adjuvant Breast and Bowel Project (NSABP) B-06 trial, a landmark randomized study evaluating breast cancer treatments, showed that approximately 75% of local recurrences occurred at or near the lumpectomy site [12]. These findings support limiting radiotherapy to the lumpectomy site instead of the whole breast. Whole breast radiation therapy (WBRT) carries risks of acute and chronic toxicities, including pulmonary [13] and cardiovascular [14] complications, as well as adverse cosmetic effects from fibrosis and telangiectasia [15]. Additionally, the prolonged treatment duration poses logistical challenges, restricting WBRT accessibility for some patients.

Accelerated Partial Breast Irradiation (APBI) targets the lumpectomy cavity plus a margin, significantly reducing treatment time while maintaining comparable local control in early-stage breast cancer patients[16], [17]. Despite the diversity of existing APBI methods, challenges persist related to dose conformity, invasiveness, and geometric constraints. To address these limitations, the GammaPod™ system was developed under National Institutes of Health (NIH) funding, utilizing stereotactic radiotherapy principles to deliver highly precise ablative doses with steep dose gradients. This technology relies on accurate target localization via a stereotactic coordinate system.

Our Radiation Oncology Department at Istituto Nazionale Tumori IRCCS Fondazione G. Pascale is equipped with state-of-the-art technology and a multidisciplinary team dedicated to delivering advanced radiotherapy treatments across multiple tumor sites [18], [19], [20], [21], [22].

In this conference proceedings, we present a detailed overview of the GammaPod™ device, scheduled for clinical implementation starting January 2026 at our Institute. Particular emphasis will be placed on the metrological challenges encountered during the commissioning of this novel radiotherapy system. A key dosimetric challenge arises from the fact that conventional reference dosimetry is typically performed in water phantoms using a 10×10 cm² reference field, whereas the GammaPod™ operates under conditions that deviate from both of these standards.

II. Materials: GammaPod

The GammaPod™ system integrates three principal modules[23]: a dedicated breast immobilization apparatus enabling precise stereotactic localization, a prone-position patient support with dynamic alignment capabilities, and a gamma radiation assembly housing the ^{60}Co sources alongside a collimation mechanism (Fig. 1).

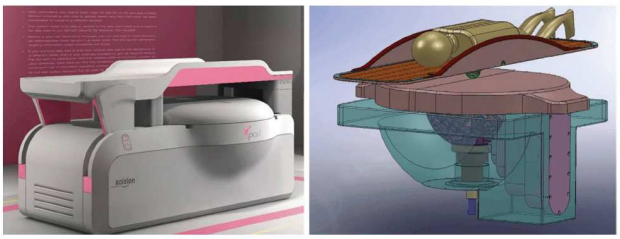


Figure 1: A conceptual illustration (left) and a 3D schematic (right) of the GammaPod™ demonstrating the patient positioned in a prone orientation [23].

Central to patient immobilization is a dual-layer breast cup designed to secure the breast in a reproducible and stable configuration. The inner cup, available in 9 graduated sizes per outer cup dimension (small, medium, large), accommodates breast volumes ranging from 230 cm³ up to 1700 cm³. The outer cup, constructed from rigid plastic, interfaces with a vacuum system generating a negative pressure that stabilizes the breast tissue by filling the inner cup contour and rigidly fixing the breast to the immobilization device. This arrangement reduces breast motion relative to the coordinate frame established by spirally arranged, CT- and MRI-compatible fiducial wires embedded within the outer cup. This fiducial array enables the creation of a stereotactic coordinate system for accurate target localization during treatment planning (Fig. 2).

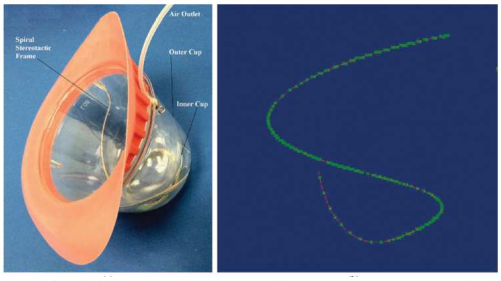


Figure 2: On the left, a vacuum-assisted breast cup is depicted, illustrating components such as the outer and inner cups, silicone flange, locking mechanism, and the localization frame. On the right, the stereotactic localization frame is visualized as identified from a series of CT scans (marked by square dots), alongside the intended theoretical positions based on the device's design [24].

Patient positioning occurs with the subject prone, the treated breast nested within the immobilization cup (Fig. 1). The design inherently displaces breast tissue anteriorly away from thoracic structures, thereby increasing spatial separation from critical organs including ribs, lungs, and, for left-sided tumors, the heart. This mechanical displacement, coupled with prone positioning, yields dosimetric advantages by reducing radiation exposure to these sensitive structures [25].

The patient couch, engineered to integrate seamlessly with the immobilization device via machined pegs, maintains rigid registration and ensures reproducible patient alignment. Equipped with three-dimensional motorized controls, the couch enables precise translational movements and dynamic motion synchronized with beam delivery. This motion facilitates the modulation of dose distribution dynamically across the target volume, resulting in improved homogeneity relative to static multi-shot techniques traditionally employed in stereotactic radiosurgery.

The radiation unit employs a hemispherical source carrier containing 25 individual ^{60}Co sources totaling 4320 Ci at

installation. Sources are arranged in six spiral columns, each separated longitudinally by 60° and positioned with 10° increments per source, spanning latitudes between 18° and 53°. This unique spatial configuration ensures that each source occupies a distinct angular coordinate on the hemispherical surface, enabling precise collimation and beam convergence (Fig. 3).

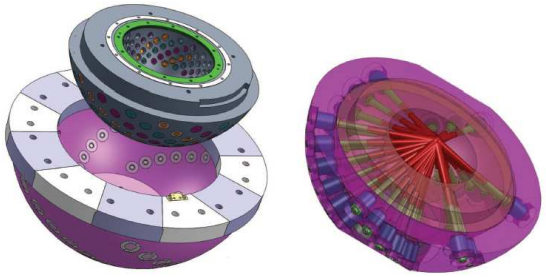


Figure 3: Hemispherical source carrier and collimator components are arranged in a concentric layout. The left panel illustrates the outer bowl-shaped source carrier and the inner collimator—featuring three selectable apertures (1.5 cm, 2.5 cm, and a blocked setting)—distinguished by color coding. On the right, the figure depicts the convergence of 25 individual beams forming a high-dose spherical distribution centered at the isocenter [23].

Primary collimators direct each source's gamma emission toward a focal isocenter located 38 cm from the sources at the hemisphere's geometric center. Secondary collimators, hemispherically shaped with precision-drilled apertures aligned to source positions, provide final beam shaping. By synchronously rotating the source carrier and collimator, the system generates non-coplanar conical arcs converging on the target, enabling 25 highly conformal dose delivery with sharp gradients (Fig. 3).
The system described utilizes interchangeable 1.5 cm and 2.5 cm collimators to enhance dose sculpting capabilities. This dual-collimator approach allows greater flexibility in tailoring treatment volumes and sparing adjacent normal tissues.

III. Methods: Procedures for Commissioning and Clinical Acceptance

A. Mechanical tests

The treatment couch operates with high precision to align the fixed isocenter to the planned target position within the breast. Positional accuracy is assessed by translating the couch into known increments and measuring displacements using digital calipers. Reproducibility is evaluated through repeated loading cycles to the home position, recording deviations along all three axes. To characterize vertical deflection (sag), a dial micrometer measures displacement under distributed loads of 50 and 150 kg. These evaluations confirm the mechanical reliability essential for stereotactic delivery. The measurement setup is illustrated in Figure 4.

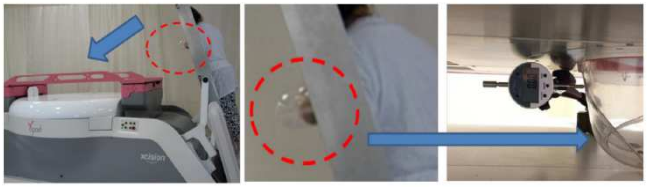


Figure 4: Experimental configuration for evaluating couch repositioning consistency: the breast cup position is recorded at each load cycle using digital calipers, while the couch undergoes repeated loading and unloading to assess mechanical reproducibility [26].

B. Dosimetric Characterization of the GammaPod System

Accurate dosimetric calibration in stereotactic breast radiotherapy necessitates standardized measurement protocols. For this purpose, Xcision Medical Systems has developed a polymethyl methacrylate (PMMA) breast phantom to enable absolute dose calibration. In our commissioning process, a combined approach based on the AAPM TG-51 [27] protocol and the IAEA TRS-483 [28] code of practice for small field dosimetry will be adopted to ensure accurate and traceable dose measurements under non-standard reference conditions. This PMMA phantom supersedes previous polyethylene (PE) phantoms [23] by providing improved material consistency and compliance with TG-51 reference standards.
Dose output is defined in the treatment planning system (TPS) as absorbed dose to water in Gy/min. Measurements, with specific ionization chambers, are performed at the isocenter within the PMMA cup, assuming an average tissue-equivalent depth of 80 mm. The 25 mm collimator is used for absolute dose calibration, while both the 25 mm and 15 mm collimators are employed to verify output factors. The methodology aligns with previous works [23], [26], with PMMA now used instead of PE. Detector-specific correction factors derived from this protocol suggest adjustments of approximately 1%.

C. Radiation Protection

The GammaPod™'s radiation shielding closely parallels that of the Gamma Knife rather than linear accelerators [26]. Leakage radiation is evaluated with the sources secured in a shielded state and the main shielding door closed. Measurements occur at operator locations, including alongside the device and on the treatment couch, reflecting typical staff positions during patient setup or quality assurance procedures. Notably, patients may remain on the couch for durations extending from 20 minutes up to one hour during treatment: this extended time frame reflects a workflow in which, following acquisition of the simulation CT scan, target and organ-at-risk contouring and treatment planning are performed in rapid succession. All leakage dose rates are recorded using a calibrated ionization chamber survey meter [26].
Patient whole-body dose exposure is monitored under conditions simulating patient transitions into and out of treatment positions, as well as during therapy. These measurements involve an open shielding door with sources blocked or in treatment position. Initially, leakage "hot spots" are localized by placing a grid of radiographic films on the treatment couch moved into the treatment position, with sources blocked under service mode to isolate shielding leakage. Subsequent dose rate measurements are conducted at identified hotspots at the surface and at 30 cm and 1 m heights. Radiation levels above the GammaPod™ and vault walls are measured, with emphasis on ceiling and upper sidewalls due to device orientation.

D. Safety Systems Overview

The GammaPod™ system relies on three core components: the Treatment Planning System (TPS), the Treatment Control System (TCS), and the Programmable

Logic Controller (PLC). Each is supported by an Uninterruptible Power Supply (UPS) with backup batteries. In case of electrical failure, the PLC triggers automatic shielding of the radiation source. Power loss to the TPS does not halt therapy but delays data storage. Interruptions to the TCS or PLC would stop treatment unless protected by UPS. Manual safety tools, such as a hand crank and emergency cup-release cable, allow safe patient removal in extreme conditions. Breast immobilization is achieved through a dual-cup vacuum-assisted interface that stabilizes shape and lifts tissue from the chest wall. Two vacuum-sensitive interlocks ("cup suction fault" and "suction fault latch") monitor pressure and interrupt treatment if thresholds are exceeded. Additional safeguards include emergency stop buttons, room interlocks, and plan file verification [24], [26].

E. Image-Guided Localization and Cup Determination

The TPS currently performs a dual-phase process to align patient anatomy with the stereotactic coordinate grid. First, the outer immobilization cup, embedded with a radiopaque spiral wire, serves as a geometric marker. The TPS detects this pattern in CT imaging to reconstruct the spatial orientation of the cup in real time. Simultaneously, it analyzes the patient's breast volume and contour to algorithmically select the appropriate inner and outer cup combination for optimal immobilization. During system verification, all outer cup sizes and representative inner cups undergo imaging, with the TPS registering each set and predicting suitable sizing. Registration errors and size outputs are recorded and reviewed for accuracy. This process ensures both localization fidelity and anatomical conformity for individualized treatment planning [24], [26].

IV. DISCUSSION AND CONCLUSIONS

Stereotactic radiotherapy has emerged as a valuable strategy in early-stage breast cancer management, especially in the context of partial breast irradiation. The GammaPod™ system introduces a novel paradigm based on precise, noninvasive stereotactic localization and delivery, specifically engineered for breast anatomy. Its design addresses longstanding limitations associated with conventional techniques, offering significant improvements in dosimetric accuracy, treatment efficiency, and patient safety.

Accelerated partial breast irradiation (APBI) techniques have aimed to shorten treatment duration and reduce radiation exposure to non-target tissues. While traditional methods—such as brachytherapy, intraoperative radiation therapy, and external beam techniques—offer varying degrees of success, they frequently face challenges in achieving optimal dose conformity, reproducibility, and geometric stability. GammaPod™ overcomes several of these barriers through a combination of advanced immobilization, image-guided localization, and dynamic beam delivery.

The use of a vacuum-assisted dual-layer breast cup ensures highly reproducible positioning, establishing a stereotactic coordinate system based on CT- and MRI-compatible fiducial markers. Prone positioning further enhances spatial separation between the target and critical thoracic structures, minimizing incidental exposure to the lungs, ribs, and heart. These features collectively contribute to improved organ-at-risk (OAR) sparing compared to supine whole breast radiotherapy or non-stereotactic APBI.

Dosimetric delivery is achieved through a hemispherical configuration of 25 ^{60}Co sources arranged in spiral columns. This architecture enables the generation of multiple non-coplanar arcs that converge at the isocenter, producing a highly conformal spherical dose distribution with steep gradients. The system's capacity to switch between 1.5 cm and 2.5 cm collimators provides flexibility in shaping dose to diverse target volumes while maintaining minimal exposure to surrounding normal tissue.

From a radiobiological perspective, this level of conformity and accuracy facilitates the safe administration of ablative and hypofractionated doses. The ability to deliver high biological effective doses (BED) in a limited number of sessions may enhance local tumor control while reducing overall treatment burden for patients. This approach aligns with broader trends in oncology toward shorter, more efficient treatment regimens without compromising therapeutic efficacy.

Despite these advantages, the introduction of GammaPod™ into clinical practice entails significant technical and logistical challenges. Commissioning procedures diverge substantially from those of other linear accelerators. Mechanical reliability of the couch, vacuum seal stability, and stereotactic localization fidelity require dedicated quality assurance protocols. Dosimetric calibration must be conducted using PMMA phantoms in accordance with TG-51 protocols, and additional evaluation of small-field dosimetry corrections—such as those proposed by the IAEA TRS-483—remains essential.

Radiation protection also demands tailored consideration. Unlike LINACs, GammaPod™ employs fixed radioactive sources, generating a continuous radiation field that necessitates enhanced shielding and spatial planning. Leakage measurements, hotspot identification, and whole-body exposure simulations must be systematically performed to meet occupational and environmental safety standards. These requirements increase the complexity of installation and may impact facility infrastructure and staffing workflows.

System safety architecture incorporates multiple redundancies, including pressure interlocks, emergency release mechanisms, and independent power supply backups. Disruptions to critical components such as the treatment control system or vacuum system trigger automatic beam shutdowns. Integration of these safety features ensures compliance with regulatory standards, though it simultaneously increases the need for operator training and procedural familiarity.

Clinical indications for GammaPod™ currently center on early-stage, node-negative breast cancer following breast-conserving surgery. However, its potential applications may extend beyond this setting. The precision and dose delivery characteristics suggest utility in neoadjuvant scenarios, multifocal tumors, and possibly in the treatment of select high-risk subtypes where local control is paramount. One of our upcoming objectives is to investigate the feasibility of single-fraction treatment protocols to be delivered either before or after surgery. This research direction aims to further streamline therapeutic pathways, reduce overall treatment time, and evaluate the potential radiobiological benefits of early, high-precision dose delivery. Ongoing clinical trials and long-term outcome studies will be essential to validate these hypotheses and define the role of GammaPod™ within evolving treatment strategies.

The device also prompts reconsideration of conventional radiotherapy planning. By decoupling treatment from traditional fractionation and immobilization methods, it invites new workflows that prioritize individual anatomical geometry and stereotactic reproducibility. As such, the transition to GammaPod™ use is not limited to technology acquisition but requires institutional adaptation at multiple levels, including medical physics, clinical protocols, radiation safety, and patient education.

From a sustainability standpoint, the implementation of GammaPod™ can also be viewed as a step toward more sustainable healthcare delivery. By concentrating treatment into a single or few sessions, this technology optimizes clinical workflow and reduces waiting lists, thereby improving access to care without requiring additional infrastructure or staff expansion. This rationalization of time and resources enhances the overall efficiency of radiotherapy departments, a key aspect of operational sustainability in modern oncology.

In conclusion, GammaPod™ represents a distinct advancement in the field of breast radiotherapy. Its stereotactic capabilities, dosimetric precision, and workflow innovations offer a potentially transformative alternative to existing APBI techniques. While initial implementation is resource-intensive and necessitates rigorous commissioning, the long-term benefits may include improved local control, reduced toxicity, and enhanced patient convenience. By enabling treatment delivery in 1 to 5 fractions, this approach not only improves patient comfort and compliance, but also optimizes the use of linear accelerator resources—an important consideration given the high prevalence of breast cancer and the resulting impact on waiting lists. As radiotherapy continues to evolve toward personalization and precision, devices like GammaPod™ may redefine treatment standards and clinical expectations in early-stage breast cancer care.

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***Abstract*—The increasing complexity of radiotherapy techniques such as IMRT and VMAT demands highly accurate yet time-efficient quality assurance (QA) procedures. While conventional phantom-based systems remain the reference standard, they are often resource-intensive and decoupled from real-time treatment conditions. LINACWatch® (Qualiformed, La Rochesur-Yon, FRA) is a log file-based system designed to complement traditional QA workflows by enabling fast, non-invasive verification of beam delivery parameters. LINACWatch® automatically reconstructs the delivered fluence and compares it to the planned distribution, calculating quantitative indicators such as the γ-index without requiring physical detectors. Its integration into clinical practice has allowed session-specific QA in real time, reducing the number of phantom-based measurements in selected cases and improving operational efficiency without compromising safety. This study aims to assess the error-detection capability of a log file–based platform LINACWatch® in view of its potential integration into routine clinical practice for both machine and patient quality assurance (QA). Its performance was compared against the Delta4® measurement system in the context of QA for VMAT treatment deliveries.**

Keywords— LINACWatch, Log file, Quality Assurance (QA), Volumetric Modulated Arc Therapy (VMAT), Intensity-Modulated Radiation Therapy (IMRT), Dose Verification

I. INTRODUCTION

In modern radiotherapy practice, each phase of the therapeutic workflow, from image acquisition to treatment delivery, requires a high degree of precision, multidisciplinary coordination, and systematic verification. The use of advanced Treatment Planning Systems (TPS), especially when used in high-precision modalities such as Intensity-Modulated Radiation Therapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT), or in hypofractionated protocols like Stereotactic Body Radiation Therapy (SBRT), require stringent quality control measures across the entire treatment workflow [1], [2], [3], [4], [5], [6]. Contemporary radiotherapy planning frameworks employ highly sophisticated optimization and dose computation algorithms designed to maximize treatment efficacy and minimize toxicity. Despite these advancements, the accuracy of such systems can be compromised by several sources of uncertainty, including but not limited to the modeling of narrow irradiation fields, the inherent limitations of dose calculation algorithms, and mechanical effects such as the "tongue-and-groove" design of multileaf collimators and associated interleaf transmission and leakage phenomena [7], [8]. The dynamic parameters governing beam delivery, namely, the gantry angle, collimator rotation, individual leaf trajectories, and real-time modulation of radiation output, play a pivotal role in determining the conformity and homogeneity of the resulting dose distribution. Moreover, precise spatial alignment of the patient is essential, with particular attention to the tumor volume, to ensure the accurate correspondence between the planned and delivered dose. Any deviation in patient positioning or system parameters may lead to significant dosimetric discrepancies and compromise treatment outcomes.

Within this framework, Quality Assurance (QA) constitutes a structured set of procedures aimed at ensuring that treatment planning is accurate, reproducible, and clinically safe. Conventional patient-specific QA is commonly carried out by comparing the planned and delivered dose distributions using gamma index (γ) analysis [9]. This process requires individualized verification, performed prior to the first treatment fraction, through measurements acquired with a range of dosimetric tools, including 2D or 3D diode arrays, ionization chambers, and radiochromic films. Among the most widely used systems are Delta4®, MapCHECK® and ArcCHECK® which rely on phantom-based setups to assess the accuracy of dose delivery[10], [11]. However, these methods are time-intensive, as they require dedicated QA sessions outside of clinical workflow. Furthermore, they fail to capture the actual beam fluence during treatment delivery, limiting the evaluation to simulated conditions rather than session-specific parameters. To address these limitations there is a growing interest in log file-based verification systems. These approaches leverage dynamic data recorded by the linear accelerator's control system to retrospectively or in real time assess the accuracy of beam delivery. Among these, LINACWatch® has emerged as a robust and efficient solution for routine QA of complex treatments like VMAT and IMRT. By analyzing mechanical and dosimetric parameters, including MLC leaf positions, gantry speed, and dose rate, LINACWatch® enables rapid, non-invasive verification without the need for physical detectors or phantom setups. This system enhances workflow efficiency and provides session-specific QA, bridging the gap between planned and delivered treatments [12], [13], [14]. In this conference proceeding, we provide a comprehensive description of

LINACWatch®, currently implemented at our radiotherapy department at Emicenter, Naples, Italy. The facility is equipped with three treatment units: a Varian TrueBeam® (Fig. 1), an Elekta Agility®, and a Radixact® Tomotherapy system, LINACWatch® is currently implemented on the first two, allowing comprehensive evaluation of its integration and performance across different conventional delivery platforms. This study investigates the ability of a log file–based QA platform LINACWatch® to detect delivery errors, with the objective of establishing its applicability in routine clinical workflows for both machine and patient quality assurance. A key component of the work is the direct comparison with the Delta4® measurement system, providing a critical evaluation of their relative performance in error detection during VMAT treatment verifications.



Figure 1: Linear Accelerator Varian TrueBeam

II. Materials and Methods

A. LINACWatch®

The LINACWatch® system continuously analyzes dynamic log files generated by linear accelerators during the delivery of radiation beams in IMRT and VMAT procedures. It enables real-time, high-precision monitoring of the linear accelerator's adherence to the parameters defined by the treatment planning system. The software tracks multiple variables, including the trajectories of individual MLC leaves, jaw positions, monitor units (MU), cumulative fluence, as well as the rotational angles of both gantry and collimator, and any beam-off delays. LINACWatch® rapidly computes the integrated fluence - defined as the MU delivered per unit area over the full treatment duration - at a reference distance of 100 cm from the radiation source, completing the calculation in under one second. At each control point defined in both the log file and the RT-plan DICOM data, LINACWatch® extracts the corresponding MLC leaf positions and the delivered MU. It then reconstructs the integrated fluence by incrementally mapping the dose intensity, based on the MU difference between consecutive control points. Building on this reconstruction the software compute quantitative metrics such as γ-index. These data are presented via fluence-map overlays and histograms that facilitate rapid visual and numerical analysis. In our center, LINACWatch® has been implemented on Varian TrueBeam® and Elekta Agility® linacs.

Fig. 2 from [13] displays the graphical user interface of LINACWatch®, which presents: (a) the fluence distribution as planned by the treatment planning system, (b) the reconstructed fluence derived from log file analysis, (c) the comparison between planned and delivered fluence maps, and (d) a histogram illustrating the distribution of γ-index values.

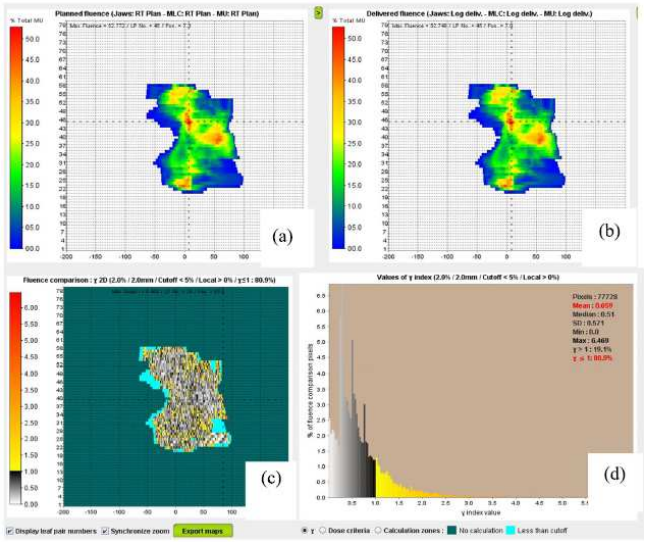


Figure 2: The LINACWatch® interface used for log file analysis, organized into four distinct sections. From left to right, the panels present: (a) the fluence distribution calculated by the treatment planning system, (b) the reconstructed fluence based on log file data, (c) a visual comparison between planned and delivered fluence, and (d) a γ-index histogram summarizing the agreement between the two.

B. LINACWatch® Validation

To evaluate the clinical applicability of LINACWatch® for quality assurance (QA), a retrospective analysis was performed on 23 VMAT treatment plans previously optimized by experienced medical physicists with the Pinnacle TPS and approved for clinical use by radiation oncologists. The dataset covered multiple anatomical sites: breast (n=9), thoracic tumors (n=3), rectal and pelvic malignancies (n=8), head and neck cancers (n=2), and n=1 liver case.

For the validation process, each plan was exported to LINACWatch® and delivered in QA mode using the Delta4® system. This workflow enabled two levels of comparison: (i) between Pinnacle-calculated dose distributions and those reconstructed by LINACWatch® and measured with Delta4®, and (ii) between LINACWatch® reconstructions and Delta4® measurements.

Agreement between the different approaches was quantified using γ passing rate (GPR) analysis. Following published recommendations [15], Delta4® data were evaluated with a

90th-percentile acceptance threshold applying 2% dose difference (DD) and 2 mm distance-to-agreement (DTA). For LINACWatch®, stricter criteria were adopted, requiring 95th-percentile GPR with 1% DD and 1 mm DTA, in order to establish a highly sensitive screening tool, as these thresholds were selected to reflect the different roles of the systems: standard values for conventional phantom-based verification and more stringent limits to maximize the sensitivity of real-time monitoring.

C. *Quantitative Indicators for Model Performance Assessment*

To explore the feasibility of incorporating LINACWatch® into standard clinical QA practice, addressing both machine performance and patient treatment verification, its performance was systematically compared with that of the Delta4® system, employing the evaluation methodology described by [16]:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (1)$$

$$Error\ Rate = \frac{FP + FN}{TP + TN + FP + FN} \quad (2)$$

$$Recall = \frac{TP}{TP + FN} \quad (3)$$

$$Precision = \frac{TP}{TP + FP} \quad (4)$$

$$F - Score = \frac{2 \cdot Recall \cdot Precision}{Recall + Precision} \quad (5)$$

The model was validated through a dual comparison: QA outcomes obtained with LINACWatch® were contrasted with the TPS dose distribution, and phantom-based QA performed with Delta4® compared against the corresponding TPS-calculated distribution. For classification, Delta4® measurements served as the reference, and performance indices were derived from the confusion matrix in Tab. 1.

Table 1. The confusion matrix was constructed to assess the performance of LINACWatch® within its validation as a QA instrument. Specifically, the LINACWatch®–TPS comparison was evaluated using the γ Passing Rate (GPR) under the 1%/1 mm criterion, applying the 95th percentile as the acceptance threshold. In contrast, for Delta4®–TPS comparisons, GPR was calculated with the 2%/2 mm criterion, adopting the 90th percentile threshold for evaluation.

		Delta4® vs TPS	
		GPR 2%2mm < 90%	**GPR 2%2mm** ≥ 90%
LINACWatch® vs TPS	**GPR 1%1mm** ≥ 95%	**False Positive (FP)**	**True Positive (TP)**
	GPR 1%1mm < 95%	**True Negative (TN)**	**False Negative (FN)**

III. RESULTS

Fig. 3 reports the confusion matrix derived from the comparison between LINACWatch® and Delta4® according to the criteria and procedures described in the previous section.

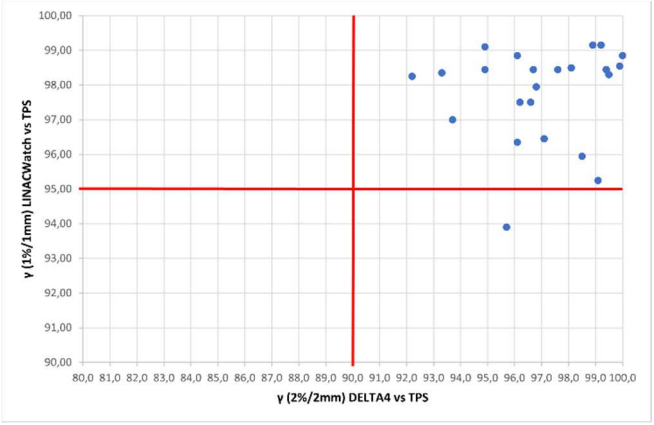


Figure 3: Confusion matrix derived from the comparison of LINACWatch® and Delta4® against TPS. For LINACWatch®, performance was evaluated using the γ Passing Rate (1%/1 mm) with the 95th percentile as acceptance threshold, whereas Delta4®–TPS comparisons employed the 2%/2 mm criterion with the 90th percentile threshold.

Tab. 2 summarizes the corresponding values of TP, TN, FP, and FN extracted from the confusion matrix.

Table 2. values of TP, TN, FP, and FN extracted from the confusion matrix.

TP	22
TN	0
FP	0
FN	1

Consequently, it was possible to compute the metrics (1)-(5) introduced in the previous section, which are summarized in Tab. 3.

Table 3. Performance metrics employed for the comparative evaluation of LINACWatch® and Delta4®. The indices Accuracy (1), Error Rate (2), Recall (3), Precision (4), and F-Score (5) were calculated from the confusion matrix reported in Tab. 2, with Delta4® measurements used as the reference standard.

$\boldsymbol{Accuracy}$	95.65 %
$\boldsymbol{Error\ Rate}$	4.35 %
$\boldsymbol{Recall}$	95.65 %
$\boldsymbol{Precision}$	100 %
$\boldsymbol{F-Score}$	97.78 %

IV. Discussion and conclusions

The integration of LINACWatch® into the clinical workflow has confirmed that log file–based QA can significantly improve the efficiency and accuracy of patient-specific and machine performance verifications in modern radiotherapy. By reconstructing the delivered fluence from treatment log files and comparing it with the planned distribution, LINACWatch® provides session-specific QA without the need for dedicated phantom measurements. This approach ensures that any deviation in dynamic parameters, such as MLC leaf trajectories, dose modulation, gantry or collimator angles, is detected immediately at beam-off, offering a level of detail and immediacy not achievable with conventional systems. Several studies have demonstrated that such log file–based QA approaches can deliver results comparable to, or in some cases even more sensitive than, traditional measurement-based systems, highlighting their reliability in both IMRT and VMAT scenarios [12], [14].

Our results demonstrate strong agreement between LINACWatch® and the reference Delta4® system, with excellent performance metrics in terms of accuracy, precision, and F-score. These findings are consistent with prior investigations on logfile-based verification platforms [12], [13] confirming the reproducibility of dose delivery assessments derived from dynamic machine parameters. Importantly, LINACWatch® successfully identifies both routine delivery variations and occasional mechanical anomalies, such as subtle leaf-position drifts or transient gantry-speed fluctuations, that might otherwise only emerge during scheduled phantom QA. Such deviations, although often clinically negligible in isolation, may accumulate over time or across multiple fractions, thus emphasizing the importance of continuous monitoring to ensure mechanical reliability and treatment reproducibility [6], [8]. One of its main strengths lies in its role as an intelligent triage tool: specific thresholds for the γ-index allow the software to automatically flag plans requiring further verification with conventional methods. This targeted approach optimizes resource allocation, enabling physics staff to concentrate on flagged cases while reducing unnecessary phantom measurements. This concept aligns with emerging QA paradigms promoting adaptive and risk-based verification, where only plans that exceed customized tolerance criteria undergo additional testing [3], [10].

Moreover, log analysis is performed immediately after beam-off, without prolonging the occupation of the treatment room or requiring patient repositioning, nor the installation of any additional equipment within the treatment area. This seamless integration reduces organizational burden and streamlines the clinical workflow. Beyond these operational benefits, logfile-based QA also enables continuous tracking of linac performance, supporting preventive maintenance and the early detection of mechanical drifts [4], [12]. Furthermore, the implementation of log file–based QA systems such as LINACWatch® supports healthcare sustainability by reducing material consumption, waste generation, and machine occupancy times associated with phantom-based verifications. This optimization of resources aligns with the broader principles of sustainable healthcare, contributing to environmentally responsible clinical practice without compromising patient safety or treatment quality. Future integration with in vivo dosimetry or surface imaging systems could further expand LINACWatch® into a comprehensive QA ecosystem, encompassing both mechanical accuracy and patient-specific verification.

A key limitation of the present study is the relatively small number of cases included. To strengthen the statistical power and generalizability of the findings, future work should encompass a broader range of anatomical sites and include more complex treatment modalities. Cross-validation with independent dosimetric systems - such as EPID-based verification or ion chamber arrays - would further confirm the robustness of LINACWatch® in diverse clinical contexts [10], [11], [14]. As the dataset grows, efforts will also be directed toward achieving a more balanced representation of treatment sites, ensuring a comparable number of analyzed

plans across different anatomical districts. Expanding the validation to a larger and more diverse patient cohort will be essential to confirm these preliminary findings and strengthen the clinical evidence for large-scale adoption.

In conclusion, LINACWatch® emerges as a robust complement to conventional QA tools. Its ability to provide rapid, session-specific verification enhances dosimetric precision, operational efficiency, and resource optimization, while maintaining high standards of treatment safety. As radiotherapy evolves toward increasingly automated and data-centric paradigms, systems like LINACWatch® are expected to play a pivotal role in shaping the future of intelligent, log-driven quality assurance.

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Phantom-Based Image Quality Assessment of the ImagingRing Scanner for Image-Guided ^{192}Ir High-Dose-Rate Brachytherapy planning

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Abstract*— Standard brachytherapy treatment planning typically relies on simulation computed tomography (CT) images to delineate the tumor target and organs-at-risk, and to calculate the radiation dose distributions. Performing 3D image-guided planning for each treatment fraction is crucial to ensure accurate dose delivery, particularly in cases with anatomical variability or organ motion, such as those encountered in gynecological brachytherapy. To support this approach, a dedicated mobile cone-beam computed tomography (CBCT) scanner, the ImagingRing, was installed at our institution in November 2023. This system enabling image acquisition directly on the treatment couch, thereby eliminating patient transfers and facilitating real-time planning in high-dose-rate ^{192}Ir brachytherapy workflows. To evaluate the system performance and monitor long-term stability, we established quality assurance (QA) protocol. Since installation, image quality assessments have been conducted at six-month intervals. During each session, CBCT images of a CatPhan phantom were acquired using dedicated protocols. Quantitative image quality metrics were analyzed, including Hounsfield Unit linearity, uniformity, noise, contrast-to noise ratio and spatial resolution. The latter was defined by the modulation transfer function (MTF) and reported as the spatial frequencies corresponding to 50% and 10% MTF. The ImagingRing system demonstrated stable image quality across all QA sessions. HU linearity and uniformity remained consistent, and spatial resolution was preserved over time. This innovative CBCT scanner may represent a key asset for adaptive gynecological brachytherapy planning. The ability to perform in-room imaging at the time of applicator insertion positively impacts patient comfort, minimizing workflow efficiency and supporting a more sustainable clinical resources. Future work should focus on the quantitative analysis of clinical images, in order to fine-tune acquisition parameters and optimize them for the anatomical and procedural variability of gynecological brachytherapy, beyond the limitations of standard preset protocols.

Keywords — Brachytherapy, IGRT, CBCT, ImagingRing, Quality Assurance

I. INTRODUCTION

Brachytherapy (BRT) is a form of internal radiotherapy that delivers high doses of radiation directly to the tumor through a miniaturized radioactive high-dose-rate (HDR) source, commonly ^{192}Iridium, using intracavitary applicators (e.g. gynecological implants) [1], [2]. This technique enables rapid dose fall-off, with the prescription dose decreasing significantly within a few millimeters from the source position, allowing precise targeting of the tumor while sparing nearby healthy tissues. Today, BRT plays a central role in the treatment of gynecological malignancies. With the development of novel applicators and the availability of treatment planning systems (TPS) based on 3D imaging, it has become feasible to achieve dose distributions highly conformal to the target anatomy [3], [4]. Treatment planning typically relies on post-insertion imaging, where the applicator is already in place. Traditionally, this imaging relies on fan-beam computed tomography (CT) imaging acquired in a dedicated imaging room. The resulting images are used to delineate anatomical structures, reconstruct the applicator geometry and perform dose calculations [5]. However, this workflow requires patient transfer between the treatment room and the imaging suite, which may lead to anatomical changes or applicator displacement, especially in the pelvic region where bladder and bowel filling can vary significantly [6]. To overcome these challenges, mobile in-room cone-beam computed tomography (CBCT) systems offer a promising solution and by further clinical implementations confirming its integration in HDR workflows. These scanners can acquire 3D images directly on the treatment couch, minimizing patient motion and enabling real-time planning. Currently, such systems are not yet widely adopted in routine practice, due to concerns related to image quality, workflow integration and cost. Cone-beam geometry presents intrinsic limitations, including a high photon scatter fraction in the

projection images due its large cone angle, which is significantly wider than that of fan-beam geometries. The increased scatter degrades image quality by reducing contrast, increasing noise levels and introducing artifacts such as cupping, which leads to attenuation values underestimation in the central regions of the image volume [7], [8]. These limitations are particularly critical in pelvic imaging, where soft tissue contrast may not be sufficiently recovered through software-based scatter correction. Accurate visualization of soft tissues is essential not only for anatomical contouring, but also for verifying the position and the geometry of the brachytherapy applicators. While bony anatomy is generally well visualized, due to its inherent high contrast, plastic or low-Z applicators may be poorly distinguishable from surrounding soft tissue. This issue is relevant in HDR treatment planning, where accurate reconstruction of the applicator geometry directly determines source dwell positions and times, thereby affecting both the precision and safety of dose delivery. The ImagingRing system represents a promising solution as a dedicated scanner for in-room 3D imaging in brachytherapy, whose interest has been renewed by the recent works of Karius et. al. [9], [10] who confirmed its long-term stability and feasibility for clinical integration. In this context, ensuring consistent and verifiable image quality becomes essential—not only to support clinical workflows, but also in compliance with regulatory requirements. In particular, the Italian Legislative Decree 101/2020 mandates periodic quality controls on radiological equipment, specifically aimed at verifying and maintaining diagnostic image quality in clinical settings. In this work, we present a preliminary technical evaluation of the ImagingRing system through a phantom-based quality assurance (QA) protocol. Image quality metrics were assessed across three QA sessions over a two-year period, with the aim of verifying temporal stability and identifying imaging characteristics critical for adaptive treatment planning [11]. Structureted QA can contribute to sustainable practices by optimizing resource utilization and equipment lifetime through preventive performance monitoring.

II. Materials and Methods

A. ImagingRing System Description

The ImagingRing (Elekta AB, Stockholm, Sweden) was installed in our Radiation Oncology department in November 2023, with the aim of optimizing the brachytherapy workflow by enabling imaging, treatment planning and dose delivery to be performed within a single dedicated room. The system consists of a full-ring gantry with a 121-cm bore, mounted on a robotic base, allowing flexible positioning around the treatment couch. It includes a flat-panel detector (43.2 × 43.2 cm^2) capable of independent rotation and supports non-isocentric imaging, dynamic collimation, motorized wheels, battery-powered mobility and wireless remote control via tablet PC **(Figure 1)**. The X-ray source is a high-frequency, computer-controlled tube optimized for rotational CBCT imaging with two selectable focal spot size: 0.3 mm for high resolution acquisitions and 0.6 mm for high-output protocols, useful for dense anatomy or shorter scan times. It operates within a tube voltage range of 40–120 kV, with tube current ranging from 5–30 mA (small spot) or 40–80 mA (large spot). Beam filtration includes a fixed inherent filtration of 4.4 mm Al sheet permanently placed in the beam path. Additional protocol-specific filters are applied via a motorized filter carriage. A four-blade collimation system is used to define the X-ray cone beam and limit the irradiated field of view (FOV) according to the selected protocol. By dynamically shaping the beam, the system minimizes unnecessary exposure and optimizes imaging for pelvic applications. The detector is based on CsI:Tl scintillator technology, with a 150 µm pixel pitch and resolution up to 2880 × 2880 pixel, yielding a maximum field of view (FOV) of 49.1 × 49.1 × 25.4 cm^3. The system supports full 360° gantry rotation and both continuous and pulsed acquisition modes. Acquisition parameters (tube voltage, current, scan time, and gantry speed) are preset and standardized by the manufacturer.

B. Phantom-based Imaging QA Procedure

To assess the technical performance and long-term stability of the ImagingRing, a structured QA protocol based on phantom measurements was implemented. The Catphan 600 phantom (The Phantom Laboratory, USA), a widely used standard for CBCT image quality evaluation, was adopted [12]. This cylindrical phantom (20 cm diameter × 20 cm length) consists of a series of modular inserts, each designed to assess specific set of tests, including spatial resolution, low-contrast detectability, Hounsfield Unit (HU) linearity, uniformity, and noise. During each QA session, the phantom was aligned along the scanner's longitudinal axis using the internal laser positioning system and immobilized to the treatment couch.

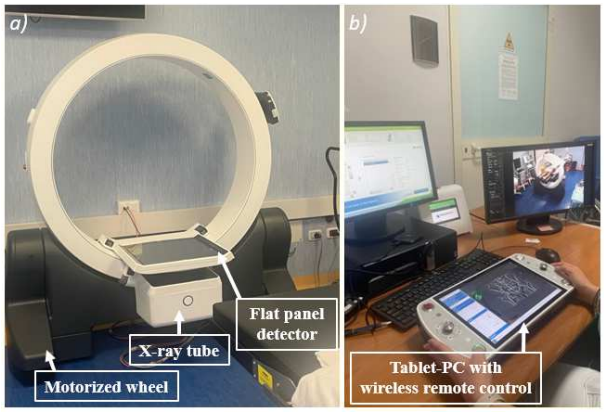


Figure 1. a) The ImagingRing CBCT installed in the brachytherapy treatment room. The system features a full-ring gantry, integrated X-ray source and a flat panel detector and is designed for in-room 3D imaging directly on the treatment couch; b) Wireless remote operation via Tablet-PC, enabling control of positioning and imaging parameters from outside the treatment room.

Table 1. Image quality parameters evaluated using the Catphan 600 phantom. Each module includes dedicated inserts for assessing specific metrics relevant to CBCT performance.

Parameter	Module	Specifications
HU accuracy	CTP404	7 target materials: air, polymethylpentene (PMP), low-density polyethylene (LDPE), polystyrene, acrylic, Delrin, Teflon
HU linearity		
Uniformity	CTP486	Uniform material with typical values of HU between 5 and 18 HU
Noise		
Line pair high resolution	CTP515	1-21 lp/cm high resolution test gauge
Line pair MTF		
Low resolution visibility	CTP528	3 groups: nominal 1%, 0.5%, 0.3% contrast levels. 9 targets in each group with diameters between 15 and 2 mm. All 40 mm in length
Contrast		

Table 2. Nominal characteristics of the insert materials in the CTP404. The table reports chemical formula, relative electron density (ED), linear attenuation coefficient at the effective beam energy (μ (E_{eff}) and expected Hounsfield Unit (HU).

Material	Formula	Relative ED (e/cm^3)	μ (E_{eff}) (cm^{-1})	HU
Air	75%N,23.2% O,1.3%Ar	0.001	0	-1000
PMP	$C_6H_{12}(CH_2)$	0.853	0.164	-200
LDPE	C_2H_4	0.945	0.181	-100
Water	H_2O	1.000	0.192	0.0
Polystyrene	C_8H_8	0.998	0.196	-35
Acrylic	$C_5H_8O_2$	1.147	0.227	120
Delrin	Proprietary	1.363	0.260	340
Teflon	CF_2	1.868	0.395	990

Dedicated acquisition protocols were selected according to the module under investigation, to ensure appropriate exposure settings and reconstruction parameters. Although the manufacturer predefines these presets, they were kept consistent across all sessions to ensure reproducibility and enables longitudinal comparisons. **Table 1** summarizes the contribution of each Catphan 600 module to the quantitative assessment of relevant image quality parameters.

C. Image Quality Metrics and Analysis

Quantitative parameters were extracted according to the recommendations provided by the EFOMP-ESTRO-IAEA joint report 2017 on *quality assurance of image-guided radiotherapy systems* and the AAPM TG-179, as follow [13]:

- *Uniformity and noise*: uniformity was assessed on CTP486 module **(Figure 2 a)**, which contains a homogeneous insert composed of a material designed to be within ±2 % of water density. Round regions of interest (ROIs) were placed – one at the image center and four at peripheral positions (top, bottom, left and right). For each acquisition the average HU values among these ROIs were recorded. Uniformity was evaluated according to the following formula:

$$\mathrm{UF} = \frac{\mathrm{HU_{max}} - \mathrm{HU_{min}}}{\mathrm{HU_{max}} + \mathrm{HU_{min}}} \qquad (1)$$

where HU_{max} and HU_{min} represent the highest and the lowest mean HU values measured among the selected ROIs. A lower value of U indicates better uniformity across the image.
Image noise was quantified as the standard deviation (SD) of voxel values within the central ROI. This metric was tracked across successive QA to highlight any potential drift in detector performance or reconstruction settings. To reduce slice-to-slice variability, the assessment of both uniformity and noise was conducted by averaging the values across three consecutive axial slices (the central slice and the adjacent slices immediately above and below).

- *HU accuracy and linearity:* were evaluated using the CTP404 module **(Figure 2 b)),** which includes inserts of material with known physical properties. Circular ROIs were placed at the center of each insert to extract mean HU values. HU linearity was assessed by a linear regression between the measured HU values and the nominal relative electron density (ED) of each material. The coefficient of determination R^2 was calculated to quantify the degree of linearity, with values close to 1 indicates high correlation. **Table 2** summarizes the nominal properties of the reference materials.

- *Contrast scale (CS):* provide a quantitative measurement of the system's ability to distinguish between materials of similar relative ED and is defined as,

$$\mathrm{CS} = \frac{\mu_1(\mathrm{E_{eff}}) - \mu_2(\mathrm{E_{eff}})}{\mathrm{HU_1}(\mathrm{E_{eff}}) - \mathrm{HU_2}(\mathrm{E_{eff}})} \qquad (2)$$

where μ_1 and μ_2 are the linear attenuation coefficients (in cm^{-1}) of two low-Z materials (eg. acrylic and solid water) at the effective X-ray energy E_{eff}, and HU_1, HU_2 are their corresponding HU values.

- *Spatial resolution:* was assessed using the high-resolution CTP515 module **(Figure 2 c)** specifically designed to evaluate the ability of an imaging system to resolve fine details. This module includes a series of line patterns with spatial frequencies ranging from 1 to 21 line pairs per centimeter (lp/cm), embedded in a low-density background. The spatial resolution was evaluated by calculating the Modulation Transfer Function (MTF). To derive the MTF curve, line profiles were extracted across the bar structures at each spatial frequency and the modulation contrast ($C_{mod,f}$) was computed as:

$$\mathrm{C_{mod,f}} = \frac{\mathrm{HU_{max}} - \mathrm{HU_{min}}}{\mathrm{HU_{max}} + \mathrm{HU_{min}}} \qquad (3)$$

where HU_{max} and HU_{min} are the minimum and the maximum HU values measured along the line profile at a given frequency f. The MTF was then obtained by normalizing the modulation values $C_{mod,f}$ to the maximum contrast C_{max}

$$\mathrm{MTF(f)} = \frac{\mathrm{C_{mod,f}}}{\mathrm{C_{max}}} \qquad (4)$$

The MTF was plotted as a function of spatial frequency. The spatial resolution was than, expressed in terms of $f_{MTF50\%}$ and $f_{MTF20\%}$, corresponding to the spatial frequency at which the MTF drops to 50% and 20% of its peak value, respectively. These values were determined by linear interpolation from the MTF curve and monitored across all QA sessions.

-*Low resolution:* low-contrast detectability was evaluated using CTP528 module (**Figure 2 d)),** which consists of different target groups with nominal contrasts ranging from 1.0%, to 0.3% relative to background material. For each acquisition, the subslice targets with 1%, z-axis length of 3, 5 and 7 mm and diameters of 3, 5, 7 and 9 mm, were analyzed. In addition to visual scoring, the contrast-to-noise ratio (CNR) was calculated for selected targets according to:

$$\mathrm{CNR} = \frac{\mathrm{HU_{target}} - \mathrm{HU_{bkg}}}{\sigma_{\mathrm{bkg}}} \qquad (5)$$

Where HU_{target} and HU_{bkg} are the mean CT numbers in circular ROIs placed over the target and background, respectively, and σ_{bkg} is the standard deviation of the background ROI.
The CNR values were monitored across QA sessions to monitoring potential degradations in low-contrast visibility.

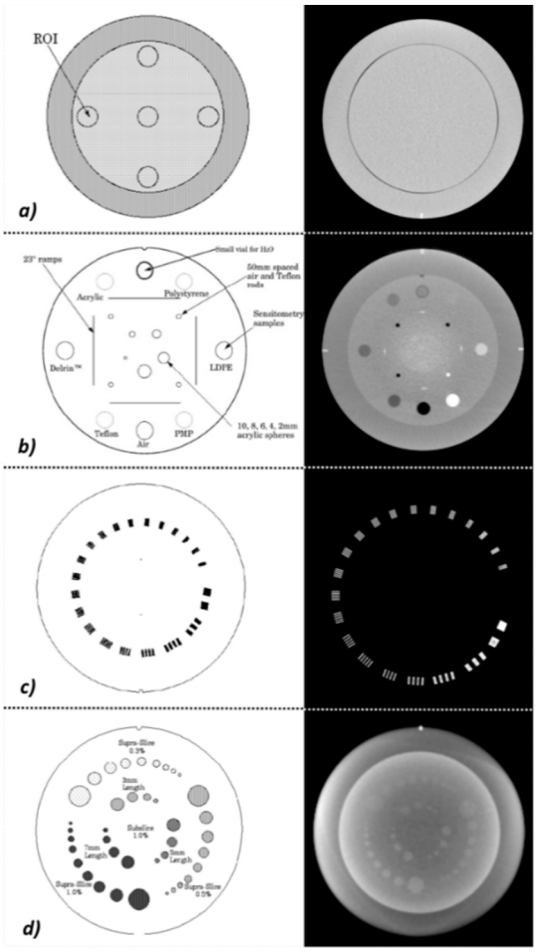


Figure 2. Overview of the four Catphan600 modules analyzed in the QA protocol. a) CTP486 - for image uniformity and noise assessment; b) CTP404 - for Hounsfield Unit (HU) accuracy and linearity; c) CTP515 - for high-contrast spatial resolution d) CTP528 – for low-contrast detectability analysis.

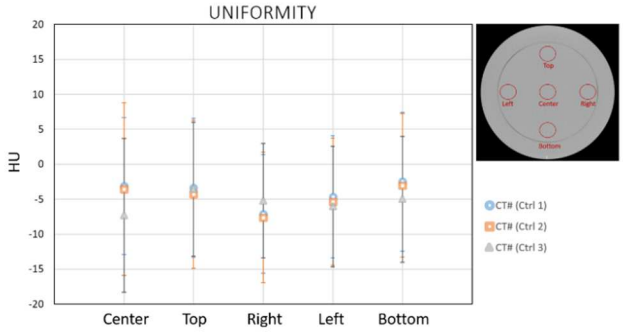


Figure 3. Mean values and standard deviations of HU within the ROIs (Center, Top, Right, Left, Bottom) of the CTP486 module, measured to assess the grayscale uniformity across the three analyzed QA sessions (Ctrl 1, Ctrl 2, Ctrl 3).

Table 3. Summary of mean Hounsfield Unit (HU), Uniformity Factor (UF), and mean standard deviation (DS) values measured in the CTP486 uniformity module across three QA sessions.

	Ctrl 1	**Ctrl 2**	**Ctrl 3**
mean HU	-4.16	-4.78	-5.44
UF	0.48	0.43	0.34
mean DS	9.38	10.31	9.28

III. Results and Discussions

A. Uniformity and Noise

The quantitative assessment of the CTP486 uniformity module over three QA sessions revealed mean HU values ranging from -4.16 to -5.44 (**Figure 3** and **Table 3**), with uniformity factors decreasing from 0.48 to 0.34, and standard deviations remaining relatively stable between 9.28 and 10.31 HU. While these parameters exhibit measurable variability, such fluctuations fall within the expected measurement uncertainty and tolerance thresholds defined by AAPM TG-179. The moderate variations in mean HU and uniformity factor (**Figure 4**) likely reflect normal system variability influenced by factors such as phantom positioning, detector calibration, and environmental conditions, rather than true performance degradation. The stability of noise levels, indicated by consistent standard deviations, further supports the reliability of the imaging system over time. Overall, these results confirm that the CBCT system maintains consistent grayscale uniformity and noise characteristics, with observed oscillations remaining within acceptable QA limits.

B. Contrast scale (CS)

The CS metric, derived from the CTP404 module by comparing acrylic and solid water inserts, remained consistently on the order of 2.85×10^{-4}, with maximum deviation below 0.2%. This level of stability reflects consistent system performance over time without appreciable degradation in low-contrast sensitivity.

C. HU Accuracy and Lineaity

Figure 5 shows the relationship between the measured HU and the nominal ED for the reference material included in the CTP404 module, across the three QA sessions. The linear fit trend line of the curves demonstrated a strong linear correlation, with R^2 values exceeding 0.99 and a maximum relative difference of 0.3%. Slight fluctuation in intercept values (within ± 1.7%) were observed between the Control 2 and Control 3, with larger variations were noted in Control 1. These differences are likely attributable to the use of a larger FOV during Control 1, which may have influenced reconstruction parameters and scatter contribution. The variations observed in the HU values remain within the tolerances generally accepted for CBCT-based image-guided based RT systems.

According to AAPM TG-179, CT number accuracy becomes relevant when the CT images are employed for model-based dose calculation methods that use the HU-to-ED calibration curve to estimate tissue ED for photon dosimetry. For BRT applications, this issue is generally less critical, since dose calculation was based to AAPM TG-43 formalism, which assumes water equivalent density for all tissues. Consequently, the fluctuations observed in the HU linearity curve are expected to have a minimal impact on the clinical brachytherapy workflow, particularly for image registration or catheter reconstruction.

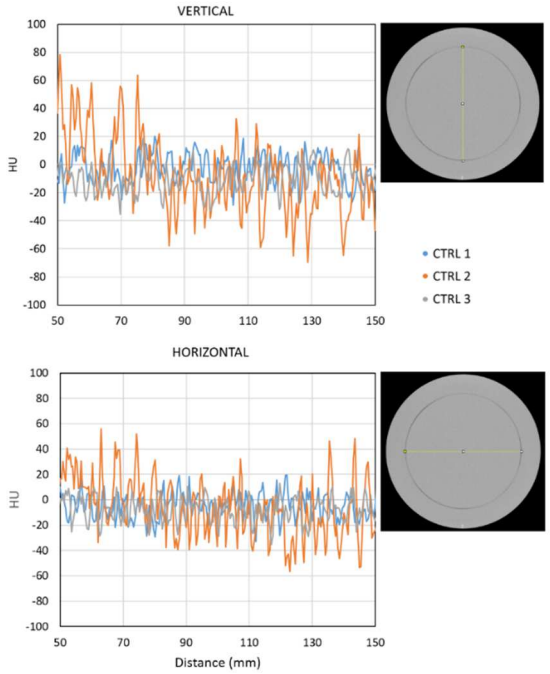


Figure 4. Horizontal and vertical HU profiles across the center of the CTP486 uniformity module, extracted within the 50–150 mm radial distance range. These curves were used to assess grayscale uniformity and calculate the Uniformity Index across the three analyzed QA sessions (Ctrl 1, Ctrl 2, Ctrl 3).

D. High-contrast spatial resolution

The Modulation Transfer Function (MTF) analysis across the three QA sessions (**Figure 6** and **Table 4**) demonstrates stable and consistent high-contrast spatial resolution performance of the imaging system. The $MTF_{50\%}$ values increased slightly from 1.47 to 1.64 line pairs per millimeter (Lp/mm), corresponding to improved spatial resolution from 0.68 mm to 0.61 mm. Similarly, the $MTF_{20\%}$ values remained relatively constant, fluctuating marginally between 1.88 and 1.99 Lp/mm, with corresponding resolution values ranging from 0.50 mm to 0.53 mm. These results indicate that the system consistently resolves fine structural details with minimal variability over time, reflecting robust imaging performance. The small variations observed fall within expected measurement uncertainties, confirming the reliability and stability of the spatial resolution characteristics throughout the QA sessions.

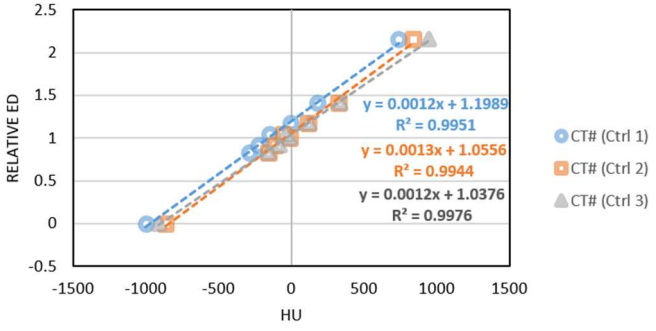


Figure 5. Correlation between relative electron density (ED) and measured CT number (CT#) expressed in Hounsfield Unit (HU) for the three QA sessions (Ctrl 1, Ctrl 2, Ctrl 3).

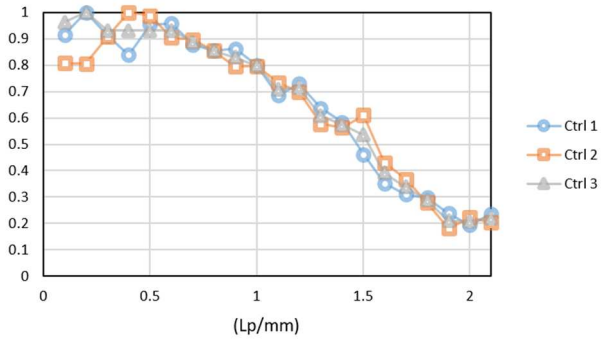


Figure 6. Modulation Transfer Function (MTF) curves as a function of spatial frequency (Lp/mm) obtained from the high-resolution CTP515 module across the three analyzed QA sessions (Ctrl 1, Ctrl 2, Ctrl 3).

Table 4. High-contrast spatial resolution metrics derived from Modulation Transfer Function (MTF) analysis across three QA sessions.. Values are reported for $MTF_{50\%}$ and $MTF_{20\%}$ in line pairs per millimeter (Lp/mm) and the corresponding spatial resolution in millimeters (mm), $f_{MTF50\%}$ and $f_{MTF20\%}$, respectively.

High Contrast Resolution	***Ctrl 1***	***Ctrl 2***	***Ctrl 3***
$MTF_{50\%}$ (Lp/mm)	1.47	1.56	1.64
$f_{MTF50\%}$ (mm)	0.68	0.64	0.61
$MTF_{20\%}$ (Lp/mm)	1.99	1.88	1.95
$f_{MTF20\%}$ (mm)	0.50	0.53	0.51

E. Low-resolution

The CTP528 analysis showed stable performance in terms of low-contrast detectability. For the 1% contrast group, targets down 6 mm in diameter were consistently visible in all sessions, meeting the recommendations of EFOMP guidelines. The CNR analysis of selected 1% contrast targets demonstrated fluctuations within the 10% threshold recommended by the EFOMP.

These findings indicate that low-contrast visibility in the ImagingRing system remained within acceptable limits for brachytherapy applications, although performances in the lowest contrast levels were limited by system geometry.

IV. CONCLUSIONS

The ImagingRing system demonstrated stable and reproducible image quality performance over time. The proposed QA protocol – combining standardized phantom measurement with guideline-base analysis – provide a simple tool for detecting early performance drift, thereby supporting safe and reliable image-guided brachytherapy treatments. Its implementation fosters operational efficiency and sustainable equipment management within image guided workflows [14]. The longitudinal results confirmed that all parameters remained within acceptable tolerance limits, with only minor fluctuations attributable to routine operation variability rather than real degradation in performance. Particular attention will be given to improving low-contrast resolution, which is critical for accurate visualization of soft-tissue structures and remains a limitation of the CBCT systems [15], [16].

Further investigations are needed on patient CT images with brachytherapy applicators in place with the aim of optimizing acquisition protocols for clinical use.

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SERS Detection of Cypermethrin Using Gold-Coated MgFe Hydrotalcite Nanostructures on Sustainable Cellulose Substrate

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***Abstract*— The increasing demand for sustainable, rapid, and label-free sensing technologies in precision agriculture has driven the development of biodegradable alternatives to conventional sensors. In this study, we present a SERS platform based on ethyl cellulose, a renewable and solvent-processable substrate, functionalized with gold-coated MgFe hydrotalcite nanoplatelets for detecting cypermethrin, a common pyrethroid pesticide. The performance of the cellulose-based sensor was compared to a silicon-based counterpart. Despite its biodegradable nature, the ethyl cellulose sensor achieved a comparable limit of detection (1.6 µM vs. 1.3 µM), demonstrating its potential as a high-performance, eco-friendly alternative for Raman sensing applications.**

Keywords*— *Biopolymers films, MgFe Hydrotalcites nanoplatelets, Ethyl Cellulose substrate, Cypermethrin detection, SERS pesticide sensor

I. INTRODUCTION

Sustainability is now a central requirement in developing technologies that address the complex challenges of the 21st century. In agriculture, this means creating affordable, eco-friendly tools that enhance productivity while reducing soil degradation and agrochemical use [1–4]. A key priority is the development of sensing technologies for real-time, in-field monitoring of pollutants and pesticide residues [5–9]. The transition toward sustainable monitoring systems is particularly relevant in modern precision agriculture, where data-driven approaches are reshaping crop management and environmental protection strategies. Integrating smart, low-impact sensors within agricultural practices not only helps optimize pesticide application but also prevents excessive chemical dispersion into soil and water ecosystems.In this context, green electronics offers a promising pathway, enabling the fabrication of functional, biodegradable devices that degrade safely after use [10–12], aligning with the objectives of the UN 2030 Agenda. Such approaches support circular-economy principles, encouraging material recovery and end-of-life recyclability, while reducing electronic waste in large-scale deployments.

Among relevant applications, sustainable pesticide sensing is especially important. Cypermethrin, a widely used pyrethroid in crop production, poses monitoring challenges due to its persistence and toxicity [13–17]. Despite its efficiency as an insecticide, cypermethrin can accumulate in food chains, raising concerns over its chronic exposure risks to humans and non-target organisms. Therefore, its rapid and reliable detection in agricultural matrices has become an urgent analytical priority. While conventional techniques like HPLC, ESI-MS, and GC-MS offer high sensitivity [18–20], they are unsuitable for on-site use due to their cost, complexity, and infrastructure requirements [21]. These limitations highlight the urgent need for portable, low-cost sensing solutions that combine high performance with environmental responsibility. Moreover, the ability to perform in-situ analyses without extensive sample preparation could significantly reduce laboratory workloads and allow real-time decision-making in the field.

In contrast to traditional detection methods, Raman sensing presents a highly promising alternative that effectively addresses their major limitations [22–25]. Its key advantage lies in label-free detection, enabling the direct identification of compounds like cypermethrin via unique vibrational fingerprints, without requiring complex sample preparation or labeling [26–28]. Additionally, Raman spectroscopy provides molecular-level specificity, making it possible to distinguish

structurally similar pesticide residues—a crucial feature for multi-residue analysis in real agricultural samples. This not only streamlines analysis and reduces costs but also enables rapid, real-time monitoring, which is crucial for precision agriculture. Recent advances in miniaturized Raman instrumentation and portable systems have further expanded the applicability of this technique for on-field testing and quality assurance in food and environmental safety.

The sensitivity of Raman spectroscopy is further enhanced by incorporating plasmonic nanostructures, which intensify local electromagnetic fields through surface plasmon resonance, allowing for trace-level detection [29–31]. This phenomenon, known as Surface-Enhanced Raman Scattering (SERS), has enabled detection limits down to the micromolar and even nanomolar range for various pesticides, depending on the nanostructure design and material composition. To align with sustainable technology goals, the use of environmentally friendly nanomaterials, such as nanoclays, adds significant value [32–34]. Nanoclays are low-cost, easy to process, and offer tunable surface chemistry, making them ideal supports for plasmonic nanoparticles in eco-friendly SERS-based pesticide sensors. Their intrinsic biocompatibility and abundant availability make them appealing candidates for scalable production of green sensing devices that minimize the environmental footprint of advanced analytical technologies.

A key innovation of this work is the development of flexible and biodegradable ethyl cellulose (EC) films as substrates for SERS sensors, functionalized with gold-coated MgFe hydrotalcite (MgFe-HTlc) nanoplatelets [35]. Over the past two decades, hydrotalcites and hydrotalcite-like compounds have been widely employed in the fabrication of nanostructured surfaces for sensor applications [36–41]. Their layered double hydroxide structure offers high surface area and controllable composition, making them ideal platforms for anchoring plasmonic metals such as gold and silver while maintaining mechanical and chemical stability. The novelty of this approach lies in the combination of eco-friendly, solvent-cast cellulose films, presenting a sustainable alternative to traditional substrates such as silicon, with HTlc-based nanomaterials, offering a greener pathway for advanced sensing platforms. Sensor performance was evaluated by comparing the Raman response of cypermethrin at concentrations ranging from 120 mM to 0.012 mM. The limit of detection was 1.3 μM on silicon (used as reference) and 1.6 μM on cellulose, confirming the viability of the biodegradable platform. Importantly, these detection limits are comparable to those achieved with conventional SERS systems reported in the literature, demonstrating that sustainability and analytical performance can successfully coexist in the same sensing architecture. Thanks to its flexibility, the cellulose-based sensor can be deployed directly in the field, for instance, on plant leaves, for on-site pesticide detection using portable Raman systems. This property not only enhances operational versatility but also opens up new avenues for integrating sensing functionalities into packaging materials or smart labels for food traceability and environmental monitoring. Gold, the only non-biodegradable material, is used in trace amounts (<80 μg per cm²), ensuring minimal environmental impact. These findings support the development of sustainable, high-performance sensing technologies for precision agriculture. Based on these considerations, the proposed cellulose-based SERS platform represents a tangible step toward greener analytical tools, bridging nanotechnology, materials science, and sustainable agriculture

II. Materials and Methods

A. Ethyl cellulose substrate fabrication

Ethyl cellulose (EC) with an ethoxy content of 48–49.5% was obtained from Sigma. The EC dispersion was prepared by dissolving EC in ethanol under stirring at 45 °C until complete dissolution. The EC substrate was then produced at room temperature using the solvent casting method from a 10% w/w ethanol-based dispersion. The detailed preparation procedure and film characterization are explained in previous publications [42, 43].

B. MgFe synthesis

Nanoplatelets of MgFe hydrotalcite-like compounds (HTlc), with the nominal composition $[Mg_{0.76}Fe_{0.24}(OH)_2]Br_{0.12}(CO_3)_{0.06}\cdot 0.65H_2O$, were synthesized through a water-in-oil double microemulsion approach, adapted from the protocol described by Bellezza et al. [44]. This procedure involves the separate preparation of two microemulsions: one containing an aqueous solution of magnesium and iron nitrates, and the other comprising a suitable precipitating agent. Upon mixing equal volumes of the two emulsions, hydrotalcite-like nanoparticles are formed within the confined environment of reverse micelles. The suspension is subsequently aged at 70 °C for 16 hours to promote nanoparticle growth. The formed solids are then separated by centrifugation, washed repeatedly with a combination of ethanol, chloroform, and deionized water to eliminate residual surfactants and reagents, and finally dried at 60 °C. This method consistently produces nanoplatelets with an average diameter of around 30 nm.

C. Morphological characterization

Morphological analysis was carried out by means of optical microscopy (Horiba Xplora Plus microscope) to disclose the overall surface texture of the samples. To investigate the topographical uniformity of MgFe-HTlc nanoplatelets, their texture and size distribution were examined using field emission scanning electron microscopy (FESEM, ZEISS SIGMA 300). The analysis was performed at a low accelerating voltage of 1 kV to enhance surface resolution. Prior to imaging, the samples were coated with an ultra-thin gold layer to reduce surface charging and improve image quality.

D. Sensor Fabrication

The sensor fabrication involves the definition of active regions composed of MgFe-HTlc nanoplatelets coated with gold on a silicon wafer and on EC film (**Fig. 1**). In case of silicon substrates, we used a 3''<100> wafer with a nominal resistivity of 1-10 ohm cm and a thickness of 380 μm.

The process started with the evaporation of a protective bilayer consisting of 5 nm of titanium and 100 nm of gold onto the substrate. This layer serves to minimize potential signal interference from the ethyl cellulose during Raman analysis and to further enhance Raman signal. Subsequently, MgFe-HTlc nanostructures were deposited by pipetting an 80 μL aliquot of a 6 mg/mL solution onto the substrate. The sample

was then placed in an oven at 70 °C for 3 hours to evaporate the solvent, resulting in the formation of a uniform, rounded area containing the nanoplatelets. Finally, a 75 nm thick gold layer was deposited via thermal evaporation to complete the sensor fabrication.

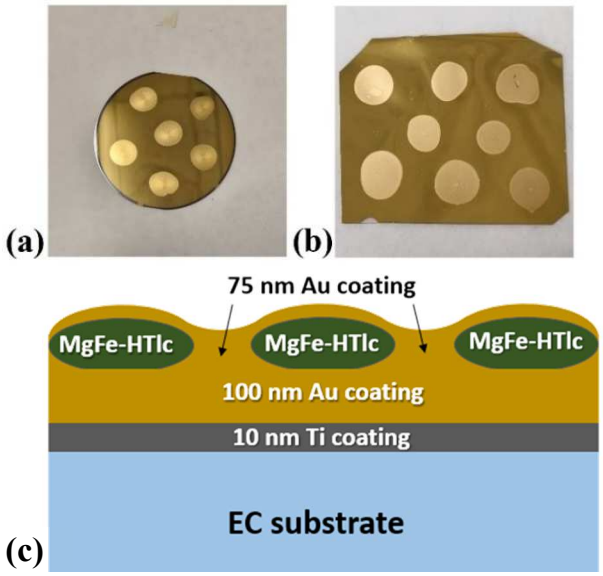


Fig. 1. A picture of the Raman sensor made on (a) Silicon wafer (b) EC film. As can be seen, different active sensing areas are embedded in the substrate with the MgFe-HTlc nanoplatelets covered with gold. (c) Schematic representation of the device layout on the EC substrate.

E. Cypermethrin solutions preparation

Cypermethrin samples were prepared using a commercial insecticide, *Insetticida Aficida* (Green Home and Garden), which contains a declared cypermethrin concentration of 120 mM. Aqueous solutions at various dilution levels were prepared by serial dilution with distilled water to obtain pesticide residues concentrations of 1.2, 0.6, 0.12 and 0.012 mM for sensing analysis.

F. Micro-Raman setup

Raman spectra were acquired directly from the analyte droplet deposited onto the SERS-active region of the sensor surface. Measurements were performed at room temperature using a Horiba Xplora Plus Raman spectrometer equipped with a 785 nm laser excitation source. The laser power was set to 50 mW, with a 1200 gr/mm diffraction grating, using a 10X objective. Each spectrum was recorded with an integration time of 20 seconds and one accumulation. Prior to analysis, all spectra were baseline-corrected and smoothed to reduce background noise and improve signal clarity.

III. Results

A. Native sensor's characterization

The morphology of the native sensors produced on silicon and EC substrates was characterized by optical microscopy and SEM analyses (**Fig. 2**). Independently on the supporting platform, **Fig. 2a-b** shows that the MgFe-HTlc nanostructures exhibit an identical surface texture, characterized by a uniform, rounded morphology and a slightly grainy appearance due to the aggregation of the nanoplatelets. As detailed in the inset of **Fig. 2b**, the MgFe-HTlc nanoplatelets on EC scaffolds are well-dispersed across the investigated samples' surfaces with an average size of approximately 30 nm. Given such considerations, the native sensors produced on both silicon and EC substrates is characterized by Raman spectroscopy to acquire the blank spectra.

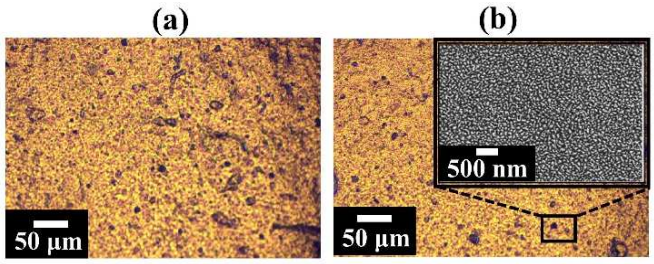


Fig. 2. Representative optical microscope images of gold-coated MgFe-HTlc nanoplatelets on (a) Silicon and (b) EC substrates. Inset: SEM image of the MgFe-HTlc nanoplatelets deposited on the cellulose substrate.

Fig. 3 illustrates the Raman spectral response of gold-coated MgFe-HTlc based SERS sensors fabricated on rigid silicon wafer (top) and flexible EC foil (bottom). Representative Raman spectra acquired from both substrates are shown, comparing the nanostructured regions (labeled "MgFe-HTlc") with adjacent gold-only areas (referred to as "gold"). In both cases, regardless of the supporting material, the spectra collected from the MgFe-HTlc regions exhibit a well-defined and sharp Raman peak centered at around 800 cm^{-1}, which is weaker in the surrounding gold-only regions.

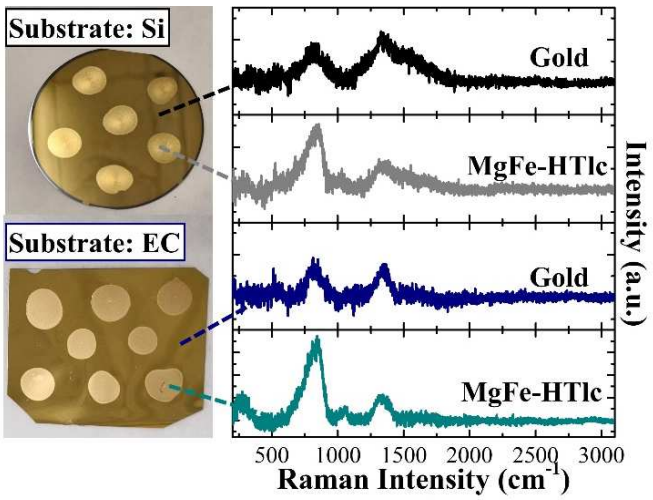


Fig. 3. Representative blank Raman spectra acquired on the unstructured regions (gold) and on the MgFe-HTlc nanoplatelets deposited on silicon and cellulose substrates.

The enhancement of this signal is attributed to the contribution of the MgFe nanoplatelets and is reliably reproduced across both platforms, indicating excellent batch-to-batch reproducibility and substrate-independent structural integrity. Most importantly, this peak can be exploited as a stable and intrinsic spectral marker for intensity normalization in cypermethrin quantification.

Moreover, a key observation is that the native Raman background signals of the substrate (both silicon and cellulose) are effectively suppressed in the SERS-active areas,

due to the presence of the Ti/Au bilayer deposited before nanostructure integration.
This corroborates that such a metallic buffer layer acts as an optical and vibrational shield, preventing interference from underlying substrate-specific Raman bands, which is especially critical for cellulose, a material known for its complex and intense vibrational fingerprint.
Altogether, these findings confirm the effectiveness of the sensor design. Specifically, the nanostructured surface provides enhanced Raman response with minimal background noise, while the gold-coated intermediate layer ensures substrate-independent performance, enabling the use of sustainable cellulose materials without compromising analytical accuracy.

B. Cypermethrine detection

To preliminarily evaluate the SERS activity of the fabricated nanostructured sensors, Raman measurements were performed on droplets of 1.2 mM Cypermethrin (Cy) solution deposited onto both the gold-only region and the MgFe-HTlc nanostructured area of the sensor built on silicon (**Fig. 4**). This concentration was selected as it corresponds to the maximum recommended usage level of the commercial cypermethrin product, according to the manufacturer's guidelines.

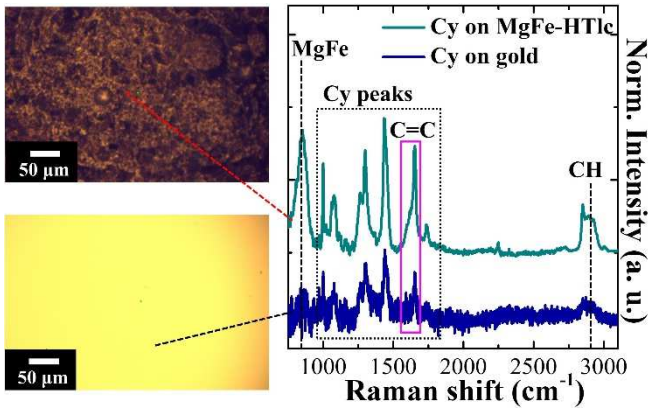


Fig. 4. Representative Raman spectra of 1.2 mM cypermethrin (Cy) solution acquired on the gold-only region (blue line) and on the MgFe-HTlc nanostructured region (dark cyano line) of the SERS sensor fabricated on silicon.

As shown in **Fig. 4**, the acquired spectra display the characteristic Raman bands of cypermethrin, including prominent peaks around 1000, 1200, and 1650 cm^{-1} [32-34]. Notably, the spectra collected from the MgFe-HTlc nanostructured zones exhibit a significant enhancement in signal intensity compared to those acquired on the adjacent gold-only region. This result clearly confirms the SERS ability of the developed MgFe-HTlc/Au nanostructures, validating their effectiveness in amplifying the Raman response of the analyte.
On these bases, the proposed sensors were used to detect cypermethrin concentrations within the range between 120 and 0.012 mM. Before measurement, 10 µl pesticide solution was dropped on the sensing area. **Fig. 5a,b** shows the normalized Raman spectra of cypermethrin at various concentrations from sensors fabricated on silicon (Si) and EC substrates, respectively.

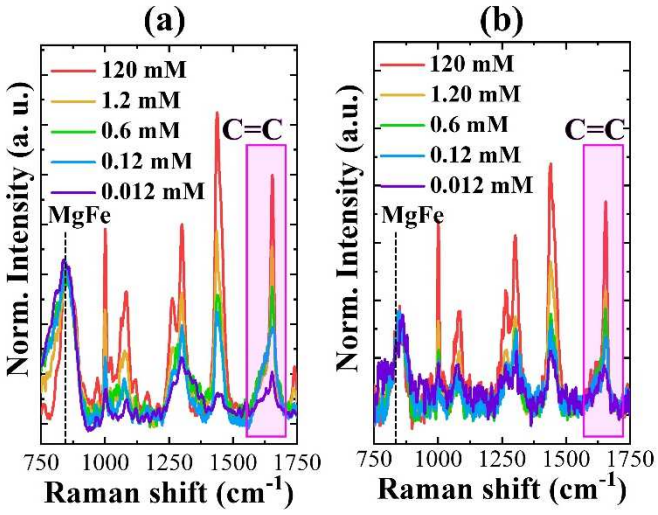


Fig. 5. Representative normalized Raman spectra of cypermethrin solutions at concentrations ranging from 120 mM to 0.012 mM dropped on MgFe-HTlc regions on (a) Silicon and (b) EC substrates.

Independently on the substrate, **Fig. 5** shows that the MgFe reference peak at around 830 cm^{-1} remains visible across all spectra and was used to normalize intensity variations due to experimental conditions. Among the signals attributable to cypermethrin, the Raman band at around 1650 cm^{-1}, corresponding to the C=C stretching of the aromatic rings and vinyl groups, was selected as the marker peak for quantitative analysis. As highlighted with magenta boxes, this peak is consistently observed across all tested concentrations and exhibits a clear and proportional decrease in intensity as the analyte concentration lowers.

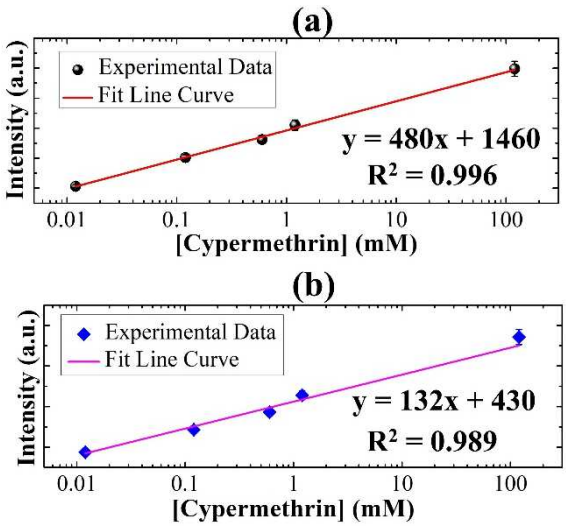


Fig. 6. Calibration curves obtained by plotting the intensity of the 1650 cm^{-1} peak (normalized to the MgFe-HTlc signal) as a function of the logarithm of cypermethrin concentration for the sensors produced on (a) Si and (b) EC substrates.

Importantly, in the same spectral region (1550–1650 cm^{-1}), the native sensor shows negligible Raman background (**Fig. 3**), with a standard deviation lower than ±20 a.u. across three replicate measurements.
The calibration curves obtained by plotting the intensity of the 1650 cm^{-1} peak (normalized to the MgFe signal) as a function of the logarithm of cypermethrin concentration for the sensors produced on Si and EC substrates are shown in **Fig. 6**.

Fig. 6a-b report the calibration curves constructed by plotting the intensity of the 1650 cm^{-1} peak (normalized to the MgFe signal) versus the logarithm of cypermethrin concentration, for Si and EC substrates respectively. Both curves show excellent linearity, with correlation coefficients of $R^2 = 0.996$ (Si) and $R^2 = 0.989$ (EC), indicating reliable quantitative detection over several orders of magnitude.

The limit of detection (LOD) was calculated using the standard IUPAC approach:

$$x_{LOD} = \frac{3 \times \sigma_{blank} - b}{m}$$

$$LOD = 10^{-x_{LOD}}$$

where σ_{blank} is the standard deviation of the baseline signal, b the intercept, and m the slope of the calibration line. The calculated limits of detection (LOD) for cypermethrin using the proposed SERS platforms were 1.3 μM and 1.6 μM for the sensor fabricated on silicon and on EC, respectively. These values are fully consistent with those reported in the literature for similar SERS-based systems. For instance, Leung et al. (2020) [26] demonstrated a LOD of 1 μM (10^{-6} M) using silver nanorods deposited on silicon and a handheld Raman spectrometer. Comparable performances were also reported in a more recent study focused on the using advanced gold or hybrid nanostructures, that allowed for LODs around 10^{-7} M for cypermethrin detection [45, 46]. Therefore, the detection sensitivity achieved in this work is within the expected and practically useful range for environmental and food safety applications.

Notably, the sensor developed on EC provides not only analytical performance comparable to that of conventional silicon-based substrates, but also offers distinct advantages in terms of sustainability and flexibility. This outcome positions cellulose-based platforms as a promising alternative for the development of eco-friendly, disposable, and scalable SERS sensors, particularly suitable for on-site monitoring and point-of-need diagnostics in agricultural and food safety contexts.

IV. Conclusions

This study presents the development of a sustainable SERS platform employing ethyl cellulose (EC) as an alternative to conventional substrates such as silicon. The sensing architecture integrates gold-coated MgFe hydrotalcite (HTlc) nanoplatelets onto solvent-cast EC films through a fabrication process that avoids the use of hazardous chemicals. This design demonstrates that advanced optical functionality can be achieved without compromising environmental compatibility. The resulting SERS sensors are promising for the detection of cypermethrin, a widely used pesticide, across a broad concentration range. Remarkably, the limit of detection (1.6 μM) achieved on the EC-based sensors is fully comparable to that of the silicon reference platform (1.3 μM) and aligns closely with the best-performing SERS systems reported in the literature. These results confirm that sustainable materials can deliver analytical performance equivalent to traditional, non-renewable substrates while significantly reducing the ecological footprint of sensor fabrication. Beyond analytical performance, EC provides several key advantages, including intrinsic biodegradability, mechanical flexibility, and compatibility with soft or irregular surfaces. These features allow the sensors directly on plant tissues, food surfaces, or packaging materials, allowing for in-situ pesticide detection and environmental monitoring using portable Raman systems. The cellulose-based platform also offers potential for integration into smart, disposable labels or paper-like sensing devices, bridging the gap between high-sensitivity spectroscopy and sustainable materials engineering. Overall, this approach demonstrates that sustainable, paper-inspired substrates can successfully host plasmonically active nanostructures while maintaining excellent SERS performance. The combination of low-cost processing, biodegradability, and strong analytical capability highlights a promising direction for chemical sensing technologies applicable to precision agriculture and environmental diagnostics.

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Gamma Irradiation Effect on Ethyl Cellulose Foils: Advancing Sterilizable and Sustainable Biopolymer Materials

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***Abstract*— Ethyl cellulose (EC), a hydrophobic and film-forming cellulose derivative, is gaining attention as a sustainable material platform, particularly in applications demanding water resistance, mechanical durability, environmental resilience and processability. However, its behavior under sterilization conditions, such as gamma irradiation, remains underexplored, despite the growing relevance of such treatments in fields ranging from healthcare to cultural heritage preservation. In this study, transparent EC foils were irradiated at 10 and 25 kGy, and their structural, chemical and mechanical stability was assessed using Raman, FTIR, EPR, DMA and TGA analyses. The results revealed only minor molecular changes, with limited signs of crosslinking or oxidation, negligible radical formation, and a modest increase in thermal stability. These findings confirm EC's robust resistance to gamma-induced degradation, supporting its use in sterilizable, bio-based materials for packaging and related technologies.**

Keywords— Ethyl cellulose, gamma irradiation, oxidation, radical formation, sterilizable materials.

I. Introduction

The transition toward more sustainable technologies is no longer just a scientific trend, but a pressing necessity driven by global environmental challenges and the demand for greener, safer materials [1, 2]. In this context, nature-derived polymers such as cellulose and its derivatives are playing an increasingly central role in the development of functional platforms that are not only biodegradable and biocompatible, but tailorable to meet the specific requirements for applications spanning from health monitoring and food packaging to environmental sensing and cultural heritage preservation [3-6].

Among cellulose-based materials, Ethyl Cellulose (EC) has recently attracted growing interest from the scientific community for peculiarities such as hydrophobic nature, excellent film-forming ability, and stability in aqueous environments. Unlike native cellulose or other hydrophilic derivatives, these features make EC particularly suitable for applications where moisture resistance, mechanical robustness, and long-term integrity are critical. Moreover, EC's wide availability and compatibility with scalable processing techniques make this system an attractive candidate for sustainable and functional material platforms [7-10].

In this intriguing scenario, a key challenge in the real-world implementation of biodegradable and bio-based materials is their response to sterilization treatments, which are essential in sectors such as healthcare, food safety, and heritage conservation. In particular, gamma irradiation technology is a widely adopted method for biodeteriogen eradication and for sterilization, due to its effectiveness and minimal residual contamination. Yet, the structural and chemical effects of ionizing radiation on EC remain poorly understood, especially in comparison to conventional cellulose materials like Microcrystalline Cellulose, Cellulose Nanofibers, Cellulose Nanocrystals or Whatman paper, which are known to experience varying degrees of oxidative degradation and radical generation under irradiation [11-16].

In this study, we explore how optically transparent EC films prepared from ethanol-based formulations via solvent casting [17] respond to gamma irradiation. In particular, the materials are tested at the doses of 10 kGy and 25 kGy, that are commonly used for biodeteriogen eradication and for sterilization, respectively [18-23]. Using a combination of Raman, Fourier Transform Infrared (FTIR), and Electron Paramagnetic Resonance (EPR) spectroscopy, we investigate the extent of molecular rearrangements, oxidation processes, and radical formation induced by irradiation. The coupling of these techniques allows us to build a detailed picture of the chemical and structural stability of EC under conditions relevant for practical use, with a focus on the identification of potential benefits or limitations for specific applications. In this view, we also complement this structural and spectroscopic characterization with thermal and mechanical analyses (TGA and DMA), to evaluate how radiation-induced modifications translate into functional properties changes.

Given the preliminary obtained results, this work contributes to the growing body of knowledge on sustainable polymers by offering new insights into the radiation stability of ethyl

cellulose, highlighting its potential as a robust and sterilizable platform for eco-friendly electronics, smart packaging, medical materials, and cultural preservation technologies.

II. EXPERIMENTAL

A. Samples preparation

The EC samples were prepared as reported in ref [17]. In particular, they were cut into distinct formats, such as square sheets measuring 5 × 5 cm^2, rectangular strips of 1.5 × 0.3 cm^2 and round shaped items of 0.5 cm diameter, specifically designed for targeted characterization analyses. Photos of sample are provided in Figure 1.

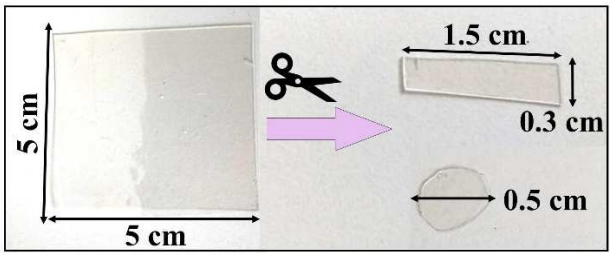


Figure 1. Photos of samples prepared in the formats of 5 × 5 cm^2 square sheets, rectangular strips of 1.5 × 0.3 cm^2 and round shaped items of 0.5 cm diameter.

B. Gamma irradiation tests

The irradiation tests were performed at the Calliope gamma irradiation facility (ENEA Casaccia R.C., Rome, Italy) equipped with a 60Co (mean energy of 1.25 MeV) radioisotopic source array [24, 25]. The samples were irradiated in air, at room temperature and humidity conditions, at absorbed doses of 10 and 25 kGy at a dose rate of around 1.5 kGy/h. The absorbed dose and dose rate values are referred to water. The dose rate was experimentally determined at the dosimetric laboratory of the Calliope facility, using Fricke and alanine-EPR dosimetric systems.

C. Characterization techniques

Raman spectra were recorded under the 785 nm laser excitation, a 50 mW laser power and a diffraction grating of 1200 gr/mm at the objective magnification of 100X. Before the analysis, Raman spectra were background subtracted and smoothed.

FTIR spectra were recorded in the range 4000-500 cm^{-1} by Spectrum 100 Perkin Elmer FT-IR spectrometer by 8 scans for each measurement with a scan resolution of 1 cm^{-1}. The spectra were analyzed in the range between 1800 and 1525 cm^{-1}. Before the analysis, the background (air) was subtracted to each spectrum, and a baseline correction was done. All spectra were deconvoluted using a multi-Gaussian fitting procedure to isolate overlapping contributions.

EPR spectra were obtained using an EPR Bruker *e*-scan spectrometer operating in the X-band, with a frequency of 9.4 GHz, microwave power of 0.14 mW and magnetic field in the range 3390–3580 G. For the measurement, 1.5 × 0.3 cm^2 rectangular strips of EC were located into a quartz tube to guarantee homogeneous exposure to the magnetic field. All the spectra and the EPR data were normalized to the sample mass (around 12 mg).

Thermogravimetric Analysis (TGA-DTG) was carried out using a TA Instruments Discovery TGA 55. EC round shaped samples (of 0.5 cm diameter) were placed in platinum crucibles and heated from 25 °C to 600 °C under a nitrogen atmosphere (flow rate: 40 mL/min). The heating rate was fixed at 5 °C/min.

Dynamic mechanical analysis (DMA) measurements were performed using a TA Instruments HR-20 rheometer in tension mode. Each sample was clamped between the grips with a constant preload of 2 N and heated from 40 °C to 160 °C under a nitrogen atmosphere. The oscillation frequency was set to 1 Hz with a strain amplitude of 0.1%, and the heating rate was maintained at 3 °C min^{-1}. For each irradiation condition, three independent measurements were carried out to ensure reproducibility.

For each sample type and irradiation condition, three independent replicates were produced and tested. The error bars shown in the figures, expressed as standard deviations, are calculated based on measurements performed on these three distinct samples for each condition. All the characterization measurements were conducted in air immediately after irradiation for all samples.

III. RESULTS AND DISCUSSION

Figure 2 shows the photos and representative deconvolved Raman spectra of EC samples before and after irradiation at absorbed doses of 10 and 25 kGy.

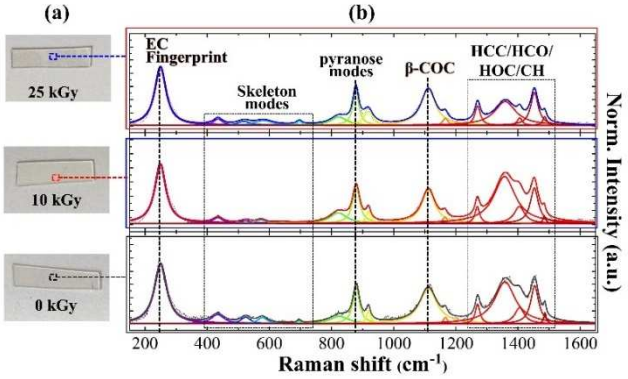


Figure 2. (a) Photos and (b) representative deconvolved Raman spectra of EC rectangular strips before irradiation (0 kGy) and after irradiation at 10 and 25 kGy.

As shown in Figure 2a, the samples exhibit no significant changes at macroscopic level or color variation after gamma exposure, indicating the absence of a significant number of newly formed chromophore groups, at least to the extent perceptible by the human eye.

Similarly, the Raman spectra reveal no substantial structural alterations upon irradiation. The main vibrational features remain consistent across all doses, with characteristic bands attributable to skeleton modes (~400–700 cm^{-1}), bands associated to distortions of the pyranose cycle conformation (~850 cm^{-1}), the β-COC band (~1100 cm^{-1}), and signals related to C–H and hydroxyl functional groups (HCC/HCO/HOC/CH) between 1200 and 1500 cm^{-1} [26-29]. The Raman band around 250 cm^{-1} is peculiar of ethyl cellulose. Considering that this signal is part of the low-frequency region (50–550 cm^{-1}), which is associated with skeletal bending and torsional modes involving CCC, COC,

OCC, OCO internal coordinates across multiple sugar rings, this band is assigned as the EC fingerprint.

To assess possible modifications at molecular level, we calculated the relative intensity (RI) between the cellulose fingerprint band and the β-COC band [30-33], using the equation:

$$RI = \frac{I_{EC\ fingerprint}}{I_{\beta COC}} \quad (1)$$

where $I_{EC\ fingerprint}$ and $I_{\beta COC}$ are the integrated intensity values of the EC fingerprint line at 250 cm^{-1} and βCOC glycosidic bonds band at 1100 cm^{-1}, respectively. The calculated RI values are 1.2, 1.5, and 1.3 for the samples irradiated at 0, 10, and 25 kGy, respectively. This trend suggests that irradiation at 10 kGy promotes a certain degree of crosslinking between polysaccharide chains, as evidenced by the increased molecular order [34]. At 25 kGy, a slight decrease in RI may indicate the onset of chain scission or minor degradation processes. However, the overall preservation of Raman spectral features and the RI values indicate that even at 25 kGy, the molecular structure of EC is not significantly compromised.

This is particularly promising for applications requiring gamma sterilization, as 25 kGy is the standard dose for ensuring sterility without inducing notable structural damage in the material.

To gain further insights into the chemical modifications induced by gamma irradiation, FTIR spectra were analyzed in the 1500-1800 cm^{-1} region, that is particularly sensitive to the presence of oxidized moieties and adsorbed water [35]. The representative deconvolved spectra and the variation of oxidized groups level for the samples before and after irradiation are reported in Figure 3.

As shown in Figure 3a, the spectra show two main features, such as a broad band around 1630–1650 cm^{-1} attributed to adsorbed water, and sharper peaks near 1740–1760 cm^{-1} corresponding to C=O stretching vibrations. The presence of two carbonyl-related peaks likely arises from both ketonic and ester groups.

From a first glance to Figure 3a, the spectrum of samples irradiated at 10 kGy appears strictly close to that of the sample before irradiation (0 kGy), while the 25 kGy sample shows a significant increase in the intensity of both the water and C=O bands. Since the area under each peak is proportional to the concentration of the associated functional group, the oxidative changes after irradiation can be quantified by percentage increase of the carbonyl peaks area relative to the unirradiated sample [35, 36]. This parameter, defined as Δ(C=O)%, is calculated as the percentage increase in the total area of the C=O peaks in the irradiated samples, relative to the total C=O peak area of the unirradiated sample. The trend of Δ(C=O)% as a function of the absorbed dose is reported in Figure 2b.

The results in Figure 3b show a modest ~10% increase in carbonyl content at 10 kGy, while an increase over 200% is observed at 25 kGy. This behavior suggests that irradiation at 10 kGy promotes limited oxidation and is instead likely dominated by crosslinking processes between EC polysaccharide chains. At higher doses (25 kGy), oxidative degradation processes become more prominent, as evidenced by the marked increase in carbonyl groups and the stronger water adsorption band.

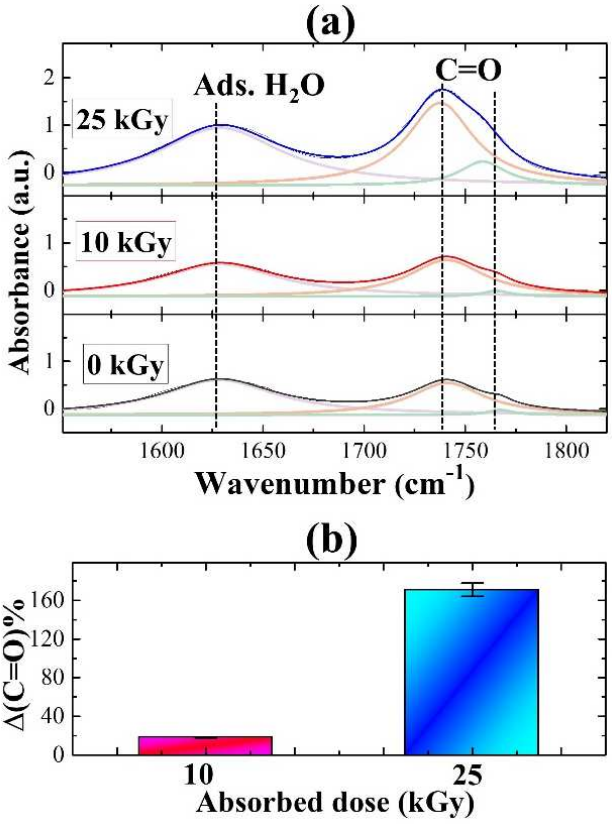


Figure 3. (a) Representative deconvolved FTIR spectra of EC samples before irradiation (0 kGy) and after irradiation at 10 and 25 kGy; (b) trend of Δ(C=O)% as a function of the absorbed dose for EC samples.

Combined with Raman analysis, these findings indicate that even at 25 kGy the molecular structure remains largely intact, with no major disruptions to the backbone network of the polymer. This supports the idea that gamma irradiation at sterilization-relevant doses (up to 25 kGy) does not compromise the structural integrity of EC films.

Interestingly, the increased intensity of the C=O and adsorbed water bands at higher doses suggests a change in the hygroscopic behavior of the material [37, 38, 14]. This tunable oxidation level could be exploited to modulate surface hydrophilicity, offering a promising route to tailor EC-based materials for specific applications such as sensing, packaging, or biomedical interfaces.

To investigate the behavior of radical species generated upon gamma irradiation, which are known to drive many of the post-irradiation chemical transformations, EPR spectroscopy was employed. EPR spectra (representing the first derivative of the absorption signal) of EC samples were acquired prior to irradiation and immediately after exposure to 10 and 25 kGy absorbed doses. The EPR data are shown in Figure 4.

As illustrated in Figure 4a, all spectra exhibit a weak and noisy signal, with poorly defined peaks. This observation suggests a relatively low concentration of paramagnetic (radical) species per unit mass in all samples, regardless of irradiation dose. Notably, even the signal from the unirradiated sample (0 kGy) shows a minor response, which can reasonably be attributed to mechanical stress, such as cutting or handling, applied to the material during the preparation of the strips.

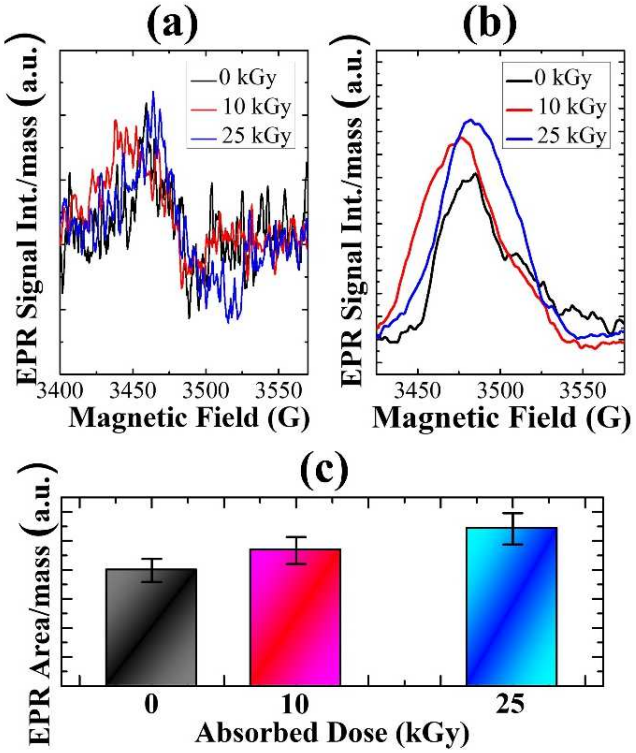


Figure 4. (a) Representative EPR spectra and (b) integrated EPR signal for EC samples before irradiation (0 kGy) and after irradiation at 10 and 25 kGy; (b) trend of integrated EPR area as a function of the absorbed dose for EC samples.

More importantly, the spectra of the irradiated samples (10 and 25 kGy) show no significant differences compared to the unirradiated one, indicating that gamma exposure does not lead to a pronounced accumulation of long-lived radicals in EC films. To better quantify this observation, the EPR signal was integrated (as shown in Figure 4b), and the resulting peak area was calculated by a further integration (Figure 4c). As depicted in Figure 4c, the integrated EPR area remains within the experimental error across all samples and shows minimal variation even at 25 kGy.

This result is particularly intriguing when compared to the behavior of conventional cellulose, such as Whatman filter paper, a material widely used as a benchmark in radiation chemistry studies [35, 39]. Whatman paper is composed of highly purified, hydrophilic α-cellulose fibers with a porous and open structure, which facilitates the diffusion and interaction of reactive species like oxygen and water-derived radicals. Upon gamma irradiation, this type of cellulose typically shows a significant and dose-dependent increase in radical concentration.

In contrast, the EC used in this work is structurally and chemically distinct. Due to its hydrophobic nature and the dense entanglement and packing of its polysaccharide chains, EC offers fewer accessible reactive sites for gamma-induced radicals [40]. This structural compactness likely hinders the penetration and mobility of oxidative species such as hydroxyl radicals or singlet oxygen generated during irradiation in the presence of moisture or air [21].

This hypothesis is supported by the FTIR results, which indicate that oxidation products (e.g., carbonyl groups) are present only in modest amounts even after exposure to 25 kGy. Interestingly, the increase in carbonyl content observed in EC at 25 kGy is comparable to that reported for conventional cellulose irradiated at only 8 kGy [35]. This suggests that the chemical reactivity and radical-driven degradation of EC are significantly suppressed relative to traditional cellulose materials.

Furthermore, it is worth emphasizing that the EPR measurements were carried out immediately after irradiation. Therefore, it is reasonable to assume that only a small number of radicals were formed and that those were rapidly quenched or reacted with accessible oxidizable groups within the bulk of the material. This behavior supports the idea that EC undergoes limited radical propagation or oxidative chain reactions under gamma irradiation, an advantageous feature for applications requiring radiation stability, such as in gamma-sterilized medical or electronic devices [41-45].

To further investigate how the observed structural and chemical modifications influence the functional performance of the material, thermogravimetric analysis (TGA) was performed, and data are reported in Figure 5.

The thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) curves provide valuable insight into the thermal behavior of ethyl cellulose (EC) films exposed to gamma irradiation at doses of 0, 10, and 25 kGy. All samples exhibit a stable thermal profile up to approximately 270 °C. The major weight loss associated with polymer decomposition occurs between ~300 °C and 400 °C across all samples. Notably, gamma irradiation slightly enhances the thermal stability of ethyl cellulose foils. Both irradiated samples (10 and 25 kGy) begin to degrade at slightly higher temperatures than the non-irradiated one, as seen in the small upward shift in the DTG peak temperatures. This perfectly corroborates Raman spectroscopy results, suggesting that irradiation induces mild structural modifications, such as crosslinking, that delay thermal decomposition. Additionally, while the non-irradiated sample shows almost complete mass loss above 500 °C, the irradiated samples retain a clear residual weight. This indicates the formation of more thermally stable degradation products or char-like residues, further supporting the conclusion that gamma irradiation alters the degradation pathway and improves the material's resistance to complete thermal breakdown.

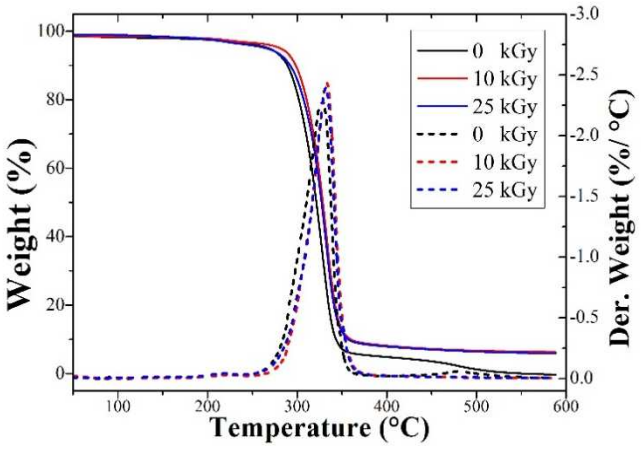


Figure 5: TGA and DTG curves of EC samples before irradiation (0 kGy) and after irradiation at 10 and 25 kGy.

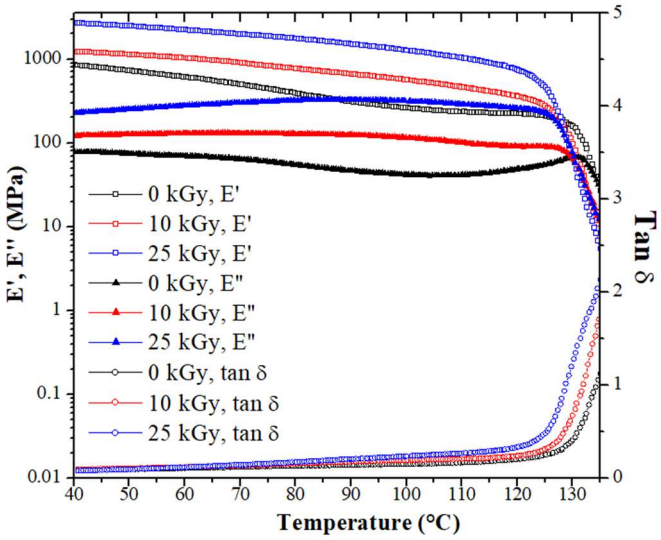


Figure 6. Dynamic mechanical analysis (DMA) of ethyl cellulose (EC) foils subjected to different gamma irradiation doses (0, 10, and 25 kGy), recorded at 1 Hz during a temperature ramp from 40 °C to 160 °C (data shown up to 140 °C). The storage modulus (E′, empty squares), loss modulus (E″, filled triangles), and loss factor (tan δ = E″/E′, empty circles) are plotted as functions of temperature. The curves illustrate the evolution of stiffness and viscoelastic behavior with increasing temperature and irradiation dose, highlighting the glass transition region and the modest yet discernible effect of gamma exposure on the viscoelastic properties of EC.

The storage modulus (E′), loss modulus (E″), and loss tangent (tan δ) derived from the dynamic mechanical analysis (DMA) of EC films irradiated at 0, 10, and 25 kGy are plotted in Figure 6 as functions of temperature. A DMA temperature ramp at 1 Hz provides a frequency-resolved mechanical spectroscopy of the material, in which E′ and E″E are the real and imaginary parts of the complex modulus, directly linked to the reversible elastic storage and irreversible viscous dissipation of mechanical energy as the material passes from its glassy to its rubbery state.

At lower temperatures, all samples exhibit a high and nearly constant E′, indicating a predominantly elastic, glassy behavior. As the temperature increases, E′ gradually decreases and drops sharply near the glass transition region (~130 – 140 ° C), consistent with the softening of the polymer matrix. The E″ curves display broad relaxation peaks in the same temperature range, while tan δ shows a corresponding increase, confirming the α-transition associated with the glass transition of ethyl cellulose.

Gamma irradiation slightly modifies the viscoelastic response. The irradiated samples (particularly 25 kGy) show a marginally higher E' and lower tan δ compared to the non-irradiated one, suggesting limited crosslinking or densification effects that enhance stiffness and reduce molecular mobility. Comparable effects have been reported for other polymers [46], although some materials exhibit a reduction in mechanical properties under similar conditions [47]. Overall, our data indicate that gamma irradiation up to 25 kGy does not significantly compromise the mechanical integrity of ethyl cellulose, maintaining its flexibility and thermomechanical stability.

CONCLUSIONS

This study examines the effects of gamma irradiation at sterilization-relevant doses on the structural and chemical stability of ethyl cellulose films, using Raman, FTIR, and EPR spectroscopy. EC maintained a high degree of molecular integrity up to 25 kGy. Raman spectroscopy showed no significant structural disruption, with an increased relative intensity (RI) at 10 kGy suggesting enhanced chain ordering, possibly due to crosslinking. A slight RI decrease at 25 kGy indicates the onset of mild degradation. FTIR analysis confirmed minimal changes at 10 kGy, while a marked increase in carbonyl content at 25 kGy (Δ(C=O)% > 200%) suggests oxidative modification. EPR spectroscopy revealed low radical concentrations across all doses, contrasting with the behavior of hydrophilic cellulose, and likely reflecting EC's hydrophobic and densely packed structure. The stability of EC after irradiation is also confirmed by TGA and DMA data. These results confirm the suitability of EC for sterilizable applications such as sustainable packaging, biomedical components, and flexible electronics, where both durability and environmental compatibility are critical. Beyond their robust irradiation resistance, the use of EC represents a meaningful advance toward greener material platforms, combining renewable sourcing, water resistance, processability, and biodegradability. While a full quantitative Life Cycle Assessment (LCA) is beyond the scope of this study, future work will systematically evaluate the carbon footprint, energy demand, and overall environmental impact of EC production and end-of-life pathways to numerically validate its sustainability advantages over conventional PET substrates. Additionally, since the fabrication process employs ethanol as the sole solvent, future optimization will include solvent recovery and reuse strategies to further minimize the net environmental impact.

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Cellulose nanocrystals as sustainable consolidant for fragile paper artworks: synthesis, characterization and application

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***Abstract*— Paper preservation is necessary because it has been entrusted with a large portion of humanity's recorded knowledge for centuries. This is because cellulose — the main component of these artifacts — tends to irreversibly degrade leading to color changes and an increase in paper acidity and fragility. To consolidate fragile paper, the common procedure is the employment of linings, but it necessary involve the use of adhesives, which accelerates paper degradation. To overcome these disadvantages a strategy is the application of cellulose nanocrystals (CNC) as fillers that enter and interact with cellulose fibers thus increasing mechanical properties and resistance. It is a sustainable approach, as it does not involve the use of other materials than the main paper component (cellulose) and organic solvents, potentially toxic for operators. Moreover, CNC can be prepared not only by acid hydrolysis (an aggressive treatment) on cellulose-enriched materials but also by a greener strategy involving enzymes. Here, the CNC synthesis, characterization and application on a drawing dated 1670 is briefly presented.**

Keywords*— *paper, cultural heritage, cellulose nanocrystals, conservation, nanotechnology

I. INTRODUCTION

Paper is present on tangible movable assets (like books, maps, drawings, historical documents) storing the history and way of life of Humanity. These objects with time often require preservation, conservation, and restoration treatments to slow down and repair the effects of irreversible degradation processes. They are caused by natural aging (due to oxidation and hydrolysis of cellulose, the main component of paper) and accelerated for example by exposure to pollutants like NO_x, SO_x, O_3, or metal ions (like $Fe^{2+,}$ Al^{3+}), by biological attacks (due for example, to rot, insects, etc.), as well as past improper conservation treatments [1]. These problems require the definition of protocols for paper deacidification, cleaning and consolidation [2-8]. Deacidification may be performed by a number of chemical treatments, like aqueous or non-aqueous application of alkaline chemical agents [2]. Moreover, dry (mechanical) and wet cleaning (washing) protocols may be used for removing pollutants, degraded material or residues of chemical agents previously used, for removing tape or glues from the surface of paper [3].

These methods nowadays often rely on the use of water-based hydrogels for the cleaning of paper [4-6]. As regards consolidation, it is performed usually by the use of suitable linings, for instance with Japanese paper of proper grammage to allows paper readibility [7,8, 9)]. This method could have some disadvantages because it involves the use a glue for the attachment of the reinforcing materials: the glue often interferes with the paper chemical stability [10, 11]. Nanocelluloses, and nanocellulose derivatives and specifically cellulose nanocrystals (CNCs), are innovative materials for the conservation of cultural heritage artworks as consolidate agent for textiles, wood, and paper materials [9,12,13]. This is because they present several advantages: first of all, CNCs are non-toxic materials, [14] and therefore safe for restorers; moreover they are sustainable as they can be in principle, obtained from suitable biomass. Finally, their physical and chemical properties offer effective solutions for consolidating materials without the use of traditional adhesives that can cause long term ageing on artworks [N10, N11]. Among nanocelluloses, cellulose nanocrystals (CNCs) are very suitable for consolidate paper materials [15]. Cellulose nanocrystals can be isolated from cellulose-rich pulps by acid hydrolysis [16, 17]. This process requires using concentrated acid in controlled conditions of reaction time and temperature. During the hydrolysis, the amorphous regions of cellulose are attacked by the acid, leading to the release of crystalline nanorods (CNCs). The typology of acid used has a dramatic influence on the surface chemistry of the nanocellulose [18]: the use of sulfuric acid produces surface sulfation of the nanocrystals, endowing them with a surface negative charge in neutral water that enables their dispersibility [19]. Conversely, applying hydrochloric acid hydrolysis produces neutral cellulose nanocrystals composed of pure cellulose (N-CNCs), presenting only surface alcohol groups, as schematically shown in Figure 1. In our previous work we have demonstrated the higher stability of CNCs produced by hydrochloric acid hydrolysis, with respect to sulfated ones: the former are composed of pure cellulose and do not introduce additional sources of acidity to paper; conversely, sulfated cellulose nanocrystals can eliminate sulfuric acid with aging, causing undesired degradation of paper [15]. In this work, we apply N-CNC to consolidate fragile and felt portion of a drawing, in a bad conservation status, dated 1670 and held in the Archivio di Stato of Rome, a cartographic documents attesting the ownership of lands in the area surrounding Terni at that time. Consolidation occurs effectively using N-CNCs without involving linings and adhesives. Furthermore, we introduce also the synthesis and characterization of neutral cellulose nanocrystals from a cellulose-rich source by mechano-enzymatic hydrolysis, as shown in Figure 1 (eN-CNC). The last one is a more sustainable and green approach avoiding the use of strong acids and preventing the release of corrosive hydrolysis waste; furthermore the reaction yield of the cellulose mechano-enzymatic hydrolysis, to produce CNCs is very high.

II. MATERIALS AND METHODS

A. Materials

Aspergillus niger endoglucanases (EC Number: 232-734-4) were from MP Biomedicals (Valiant Co. LTD, China). Pure cellulose paper samples (Whatman™ filter paper N°1) and all other reagents were acquired from Merck (Merck KGaA, Darmstadt, Germany). Avicel PH-101 (microcrystalline cellulose, derived from purified wood pulp, particle size of 50 µm, density 0.26 g/cm³; supplied by Merck KGaA, Darmstadt, Germany) was used as the cellulose source for the preparation of nanocrystals. This material consists of partially depolymerized cotton cellulose with high crystallinity and is widely used as a reference cellulose for the synthesis of nanocellulose particles.

To prepare all the solutions, bi-distilled water (Millipore, Billerica, MA, USA) was used. All reagents used were analytical grade and used without further purification.

B. N-CNCs synthesis

75 mL of deionized water in a 250 mL three-necked round-bottomed flask was cooled in an ice bath and 75 mL of concentrated HCl was added. After that, 7.50 g of Avicel PH-101 was added and the suspension was warmed to 105 °C for 6 h. The system was cooled to room temperature and diluted with 75 mL of distilled water and the mixture Centrifuged at 4000 rpm for four times, replacing the supernatant liquid with fresh deionized water until the pH was approximately 3. Then, the precipitate was suspended in deionized water with the aid of a Dr. Hielscher sonicator equipped with an ultrasonic horn with a 3.5 mm diameter (micro-tip) operated in pulsed mode, with a power of 40 W. It was subject to 0.6 s pulses for 10 min and dialyzed against distilled water until neutrality to eliminate acid residues using a cellulose nitrate membrane with a molecular weight cut-off of 12400 Da. The resulting suspension was centrifuged at 1000 rpm for 10 min. The supernatant suspension was lyophilized, yielding 1.54 g of CNCs (21% yield)

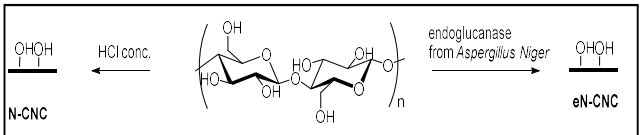


Fig. 1. Synthesis of N-CNCs (left) or eN-CNC by Avicel PH-101

C. eN-CNCs synthesis

Avicel PH-101 pretreatment was conducted using a ball mill with horizontal oscillation (BM500, Anton Paar) equipped with two 50 mL stainless steel jars and one 2.5 cm diameter ball for each jar. Each jar was loaded with 5 g of Avicel. The pretreatment involved a frequency of 3 Hz for 50 minutes without breaks. 5.04 g of Avicel was combined with 50 mL of 50 mM phosphate buffer at pH=5.0 and homogenized using a tissue master. Subsequently, *Aspergillus niger* endoglucanase (516 mg, 6000 U/g of Avicel) was introduced into the suspension. The reaction mixture was then placed in an orbital shaker at 55°C for 96 hours, operating at 150 rpm. Then, it was transferred to a beaker and heated from 55°C to 95°C for 15 minutes to deactivate the enzyme. The resultant mixture underwent centrifugation at 4000 rpm for 10 minutes. This was followed by a washing step with 20 mL of 0.1 M HCl, followed by another round of centrifugation at 4000 rpm for 10 minutes.To remove the HCl, the solution underwent multiple centrifugations with deionized H_2O (20 mL) at 4000 rpm for 10 minutes, discarding the supernatant each time, until neutrality. Then, the reaction underwent a 24-hour dialysis period. Subsequently, the suspension underwent sonication with a Dr. Hielscher 400 W tip sonicator with a power of 40 W, impulses of 0.6 seconds, for 10 minutes. A final centrifugation at 1000 rpm for 10 minutes was conducted, and the supernatant containing nanocrystals was collected and lyophilized.

D. Paper samples

Used drawing (no. 116-17/1) dated 1670 belongs to the "First Collection of drawings and maps" held in *Archivio di Stato* in Rome. Fragile, non-replaceable fragments of XVII century paper samples were from private collections (Figure 2). N-CNC has been applied on paper samples using a 1% (w:v) deionized water solution. An adequate volume of the CNC solution was uniformly spread with the help of a Japanese goat hairbrush (da Vinci, Künstlerpinselfabrik DEFET GmbH) on the selected area. Before CNC application, the drawing has previously wetted by nebulization of a hydro alcoholic solution (50:50, v:v).

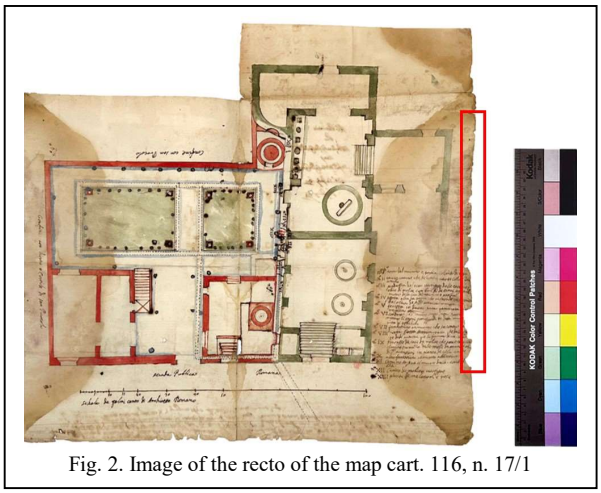


Fig. 2. Image of the recto of the map cart. 116, n. 17/1

E. Paper Characterization

Paper characterization has been performed before and after CNCs application. Images on 116-17/1sample have been obtained by using a stereomicroscope Leica mod. MZ7.5 with a 2.5x or 3.2 magnification size. FTIR spectra on samples in Attenuated Total Reflectance (ATR) mode were performed using a Thermo Scientific instrument (model Nicolet is5) (Thermo Scientific Inc., Madison WI, USA) equipped with a single reflection diamond ATR cell (Everest Diamond ATR accessory). Spectra were recorded in the wavenumbers region from 4000 to 550 cm^{-1}, averaging over 32 scans with a resolution of 4 cm^{-1}. pH measurements were performed on paper samples surface, before and after every cleaning treatment, using a Crison Instrument (mod. Basic-20, Crison Instrument s.a., Alella, Barcelona, Spain) and a flat tipped symmetry glass electrode (Hanna Instrument., Woonsocket, RI, USA). Colorimetry measurements to evaluate the variation of optical quality of paper samples due to treatment were performed using an Eoptis Digital Handheld Colorimeter (mod. CLM-194, Eoptics srl, Trento, Italy). The coordinates in the CIELAB 1976 color space (L∗=brightness, a∗= red/green color component, b∗ = blue/yellow color component) were obtained using a D65 illuminant and a 10° observer. For each sample, at least three measurements were carried out. Chromatic variation data before and after CNCs addition were reported in terms of $\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$, which is the distance between two points in the CIELAB color space. Eyes are not able to visualize color differences if $\Delta E < 2$. Small, significant, and large differences are visible by eyes if $2<\Delta E<3$ $3<\Delta E<6$, $\Delta E>6$ respectively [20, 21].

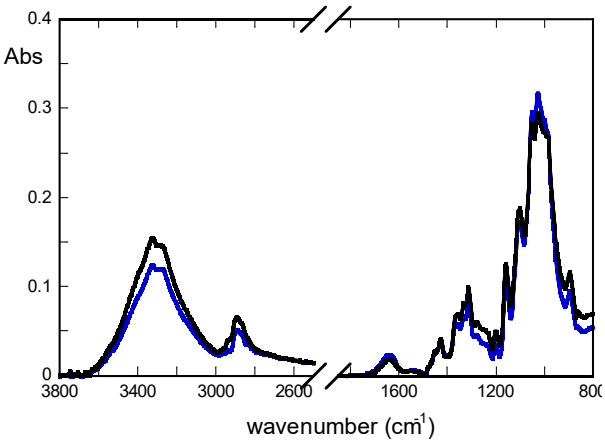


Fig. 3. ATR-FTIR spectra of N-CNCs obtained by acid (black) and eN-CNCs (blue).

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III. RESULTS AND DISCUSSIONS

A. *Nanocellulose crystals synthesis and characterizaion*

Cellulose nanocrystals under investigation were prepared from Avicel PH101 using two different hydrolytic approaches as schematically shown in Figure 1.

N-CNCs were obtained by hydrochloric acid hydrolysis, which involves treatment at 105 °C for 6 hours. However, this method yielded relatively low amounts of CNCs (21% yield for the batch used in this work) and showed some variability depending on reaction conditions. In contrast, eN-CNCs were prepared using a mechano-enzymatic hydrolysis, a more sustainable and reproducible approach that avoids the use of concentrated mineral acids and the associated disposal of toxic or corrosive waste. In this case, Avicel was first subjected to a mild mechanical pretreatment using a horizontal ball mill equipped with stainless steel jars to enhance enzyme accessibility. The enzymatic hydrolysis was then carried out using endoglucanase from *Aspergillus niger* in a phosphate buffer at pH 5.0, yielding nanocrystals with favorable morphological and structural characteristics with 76% yield. Both N-CNC and eN-CNC samples were characterized by elemental analysis and ATR-FTIR (Figure 3). ATR-FTIR spectra show the characteristic vibrational bands of cellulose are clearly visible, including the O–H stretching at 3325 cm^{-1}, the C–OH and C-C stretching, as well as the typical cellulose band pattern due to CCH and OCH bending in the 900 cm^{-1}-1100 cm^{-1} range, and a weak deformation signal of the anomeric C–H at 896 cm^{-1} [22, 23]. The band at 1646 cm^{-1} corresponds to the bending mode of crystallized water. No distinct protein-related signals were detected by FTIR, confirming the successful purification of the materials [24, 25].

Elemental analysis results indicate that the carbon content in both samples is slightly lower than the theoretical value for cellulose (44.45%), consistent with the presence of crystallized water. Notably, a nitrogen content of 0.25% was observed in the eN-CNCs, attributed to residual traces of enzyme in the final product. This point at the importance of the purification step applied to enzymatic nanocrystals to remove any trace of contamination from residual protein. Sulfur levels were negligible, as expected given the absence of sulfuric acid in the preparation. The XRD pattern of both the CNCs shows the typical peaks corresponding to cellulose I (CrI), the crystalline allomorph naturally found in plant-derived cellulose (data not shown). Crystallinity indices were determined using the Segal method, a semi-quantitative and simplified approach based on the ratio between crystalline and amorphous diffraction intensities. This method was employed here for comparative purposes, to confirm that the neutral and enzymatic CNCs feature similar crystallinity. Therefore, the CI values reported in this work are intended to provide relative comparisons between the two preparation routes rather than absolute crystallinity measurements. The determination yielded values of 76.3% for N-CNC and 76.9% for eN-CNC (errors are below 5%). These results confirm that both hydrolysis methods effectively preserve the crystalline domains of cellulose, while efficiently removing amorphous regions. The close crystallinity values also underscore the viability of the mechano-enzymatic route for CNC production.

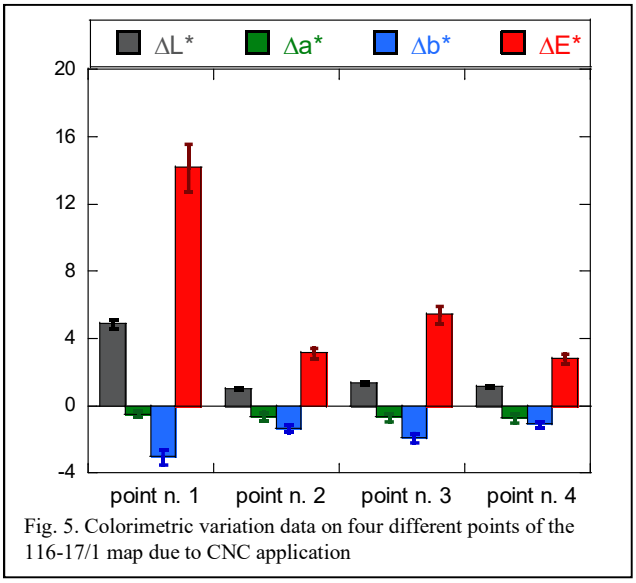


Fig. 5. Colorimetric variation data on four different points of the 116-17/1 map due to CNC application

B. *Compatibility studies*

Before applying the CNC on a naturally aged artwork, preliminary compatibility studies on not aged or artificially aged Whatman™ n.1 paper (considered reference paper material for restorers) were performed. Experiments on these samples have demonstrated the compatibility of CNC treatments with paper. Reference

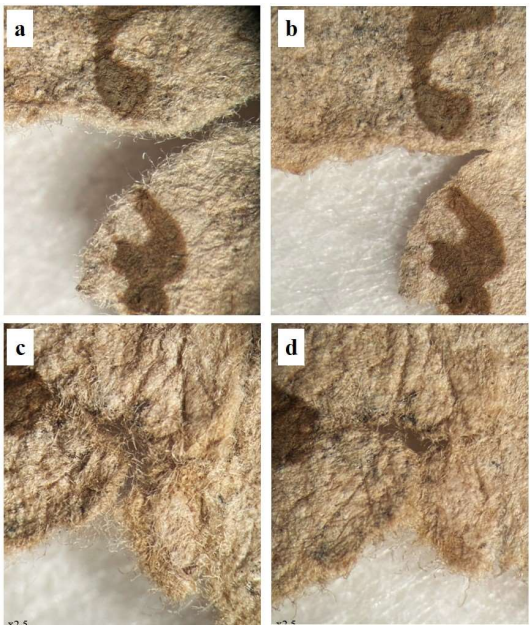


Fig.7. optical microscope images of two different points (a and b) of the right margin of 116-17/1 before (a, b) and after (c,d,) the CNC application

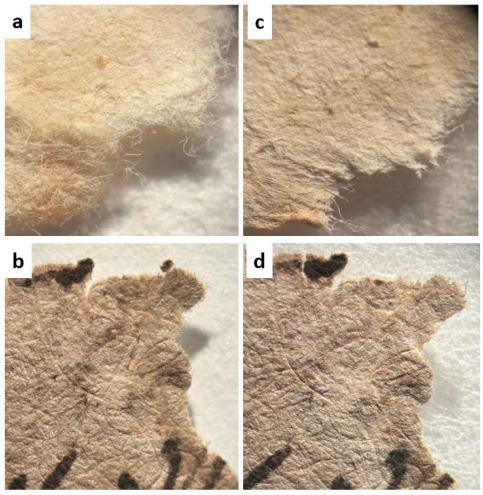


Fig. 4. Optical microscope images of two fragments before (a, b) and after (c, d) the N-CNC application

[15] shows that treatment does not alter pH, optical quality, as well as crystallinity index, while increase significantly the mechanical property of paper. Moreover, further experiments on fragile, non-replaceable fragments of XVII century paper samples whose stereomicroscope images obtained before and after CNC application, presented in Figure 4, indicate that treatment reduces significantly felting without reducing the optical quality (the colorimetry variation ΔE is less than 1.5 in both cases) and readability of samples.

C. *Application of cellulose nanocrystals on a naturally aged paper sample.*

As reported earlier, the no.116-17/1 drawing (Figure 2) belongs to the "First Collection of drawings and maps" kept in "Archivio di Stato" in Rome. It is approximatively 49.6x 54.6 cm, is dated 1670 and is signed by A. Vitale. As shown in Figure 2, it is a map depicting grain and oil mills in the Terni area (Italy). Probably it is one of the cartographic documents used during territorial disputes among landowners. Before restorations, the drawing is in bad conservation state, with incrustations, stains and foxes. Deteriorations due to humidity has led to map fragility with felting along the right and left margins. FTIR spectrum, reported in Figure 6, indicate in the 1900-1500 cm^{-1} region, the presence of bands attributable to cellulose degradation products [26,27]; the pH value of 6.2 suggests that degradation is not, up to now, severe, even if the optical quality due to yellowing is not good. After a complex and delicate wet cleaning, that is not reported because out of the scope of this paper, N-CNC has been applied on the right margin of the drawing as outlined by a red rectangle in Figure 2. The effectiveness of the treatment can be easily visualized in images reported in Figure 7, in which also the assessment that readability is not altered is shown. To evaluate the effect on readability and optical quality of N-CNC treatment, colorimetric variation on several point of the treated area has been performed before and after the N-CNC application. In

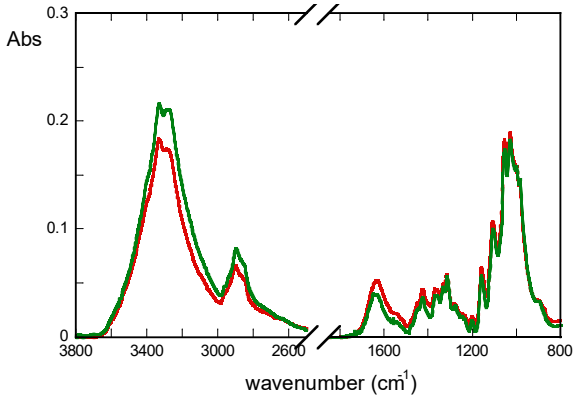


Fig. 6. FTIR spectrum of a point on the 116-17/1 map before (red) and after (green) CNCs application

several measurement areas, only negligible changes in colorimetric variation, is observed as shown in Figure 5, indicating that treatment does not alter the optical quality of paper. In the case of one point, a modest color difference (ΔE* = 5.8) is obtained. In this case, the difference values in brightness and in a* and b* color components, suggests a cleaning process induced by the aqueous CNC solution, that has removed dirt and cellulose byproducts eventually remained on map surface despite the previous wet cleaning processes. As reported in the materials and methods section, these data are in CIELAB 1976. However, recently a new, more precise colorimetric scale CIELAB00 is presented [28]. Future perspectives involves the use of this new instrument to determine colorimetric changes. Moreover, the FTIR spectrum of the sample after treatment (Figure 6) indicate that N-CNC application does not induce damages, and, on contrary, a slight decrease of intensity of bands attributable to cellulose degradation is evidenced, confirming the slight cleaning action as a secondary effect of CNC application.

IV. CONCLUSION

In this work, a sustainable procedure to consolidate paper artworks is presented. It is based on the use of cellulose nanocrystals in water suspensions and therefore does not imply the use of organic solvents (that could be toxic for operators) or adhesives, which could induce degradation on time. We have demonstrated the synthesis of neutral cellulose nanocrystals both by hydrochloric acid hydrolysis (N-CNC) and by mechano-enzymatic approach (eN-CNC). The second is more sustainable, producing less toxic waste and yielding eN-CNCs in high yield (76%). We have assess the consolidation properties of N-CNC and considering the very good properties possessed by eN-CNCs, we expect excellent consolidation properties also from these materials, combined with the better accessibility given by the mechano-enzymatic synthetic approach.

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Eco-Friendly Restoration of Parchment Using Nanodiamond-Enhanced Materials

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***Abstract*— The need for sustainable, biocompatible restoration strategies has driven growing interest in nanomaterials for cultural heritage conservation. This study investigates the use of nanodiamonds (NDs) for cleaning and consolidating degraded parchment, a collagen-based material prone to structural damage. ND-based dispersions and nanocomposites, particularly those combined with hydroxypropyl cellulose, were applied to deteriorated samples and evaluated before and after artificial aging using Light Transmission Analysis (LTA) and ATR-FTIR spectroscopy. The results demonstrate that NDs can enhance collagen stabilization while offering a low-impact, effective alternative to conventional treatments.**

Keywords—parchment restoration, nanodiamond composite, biopolymers, green chemistry, hydrothermal aging

I. INTRODUCTION

In recent years, the development of innovative approaches in conservation science has made this field increasingly complex and compelling within materials science. Restoration processes must account for the fragility, uniqueness, and historical significance of each cultural heritage (CH) item, necessitating treatments that are effective, minimally invasive, and reversible. An ideal restoration material must not alter the mechanical properties or visual appearance of the artefact, must prevent further deterioration, and should be easy to apply in a professional setting. Moreover, in light of growing environmental and health concerns, it must be safe for both the object and the conservator. Among the materials commonly used, many polysaccharide-based polymers, such as Hydroxypropyl Cellulose (HPC) [1-5], Polyvinyl Alcohol (PVA) [6-9], Methyl Cellulose (MC) [10-11], and Funori [12-16], are frequently employed in the conservation of paper, parchment, paintings, and other CH items [17–19].

Within this framework, the integration of nanomaterials into restoration treatments offers promising possibilities.

Nanoparticles, when added to traditional polymers, can significantly alter their physicochemical properties, including viscosity, hydrophobicity, thermal stability, and mechanical performance, thereby enhancing the effectiveness and adaptability of these formulations [20-22]. However, such improvements must be carefully tailored to each application, as the concentration of nanoparticles and their interactions with the polymeric matrix can affect the transparency, flexibility, or aging behavior of the composite. Thus, while nanomaterials open new avenues for the creation of multifunctional coatings and cleaning systems, their formulation must be application-specific. To date, various nanomaterials have been tested in CH conservation, especially for consolidation and antimicrobial purposes or as cleaning aids [22–25]. These include metal oxides, silica, carbon nanotubes, and nanoclays, each offering specific advantages. Compared to conventional restoration techniques, nanoparticle-based treatments can reduce the reliance on harmful solvents and reactive chemicals, aligning with the ongoing transition toward greener, more sustainable methodologies. Their nano-scale size allows for deeper penetration into degraded substrates, while their high surface area increases reactivity and efficiency, key features in delicate operations like cleaning or strengthening aged surfaces.

Nanodiamond (ND), in particular, stands out due to its exceptional physical and chemical properties. It is biocompatible, non-toxic, and exhibits high thermal and chemical stability. Its surface can be easily functionalized, which allows fine-tuning of its dispersibility and interaction with other compounds. These attributes make ND highly suitable for integration into polymeric matrices used in conservation. For instance, ND has shown the ability to mitigate UV-induced degradation, helping protect substrates such as paper and parchment from photochemical damage [25–26]. Its compatibility with collagen-rich materials and dermal tissues [27–30] makes it especially attractive for applications in parchment restoration, where sensitivity to treatment is paramount. By enhancing the mechanical stability of treated materials and potentially imparting deacidifying

effects, ND-based treatments may offer a safer and more effective alternative to conventional methods.

This work investigates the use of ND-based composites for the treatment of degraded parchment, a historical writing material derived from animal skin and rich in collagen. Parchment is highly susceptible to environmental degradation, which can lead to gelatinization and a subsequent loss of structural integrity [31]. To address this, we formulated and tested ND dispersions both in alcohol-based media and in combination with common conservation polymers (HPC, PVA, MC, and Funori) [1-17]. Preliminary screening suggested that HPC-ND composites, along with the Funori composites, offered the best combination of stability, applicability, and compatibility with parchment substrates.

In particular, the use of HPC as a carrier is particularly suitable due to its known transparency, film-forming properties, and stability. The interaction between ND and HPC has already been studied in the literature and proven viable for related applications [21, 33-34]. Therefore, the HPC-ND effects were further investigated. To assess the performance of these composites, we conducted Light Transmission Analysis (LTA) and Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy before and after artificial aging (80 °C and 80% RH). LTA allows for the monitoring of collagen denaturation by measuring changes in light transmission, which correlate with the mechanical integrity of the protein matrix. ATR-FTIR provides insight into chemical changes within the collagen, such as hydrolysis or gelatinization, by analyzing the vibrational signatures of functional groups. TGA was also perfomed to assess the effect of the composites on the thermal stability of the parchment material. In this context, the incorporation of nanodiamond into established conservation polymers aligns with current trends in sustainable restoration practices. The proposed ND-based treatments show promising results in restoring partially deteriorated parchment substrates, offering a non-toxic, effective, and environmentally conscious alternative to traditional methods.

II. MATERIALS AND METHODS

A. Restoration materials preparation and preliminary tests

Several composites based on restoration materials such as Hydroxypropyl cellulose (HPC), Methylcellulose (MC), polyvinyl alcohol (PVA) and Funori algae, were prepared with the addition of ND at different concentration (0%, 0.01%, 0.05%, 0.1% in weight).

HPC with a MW of 370kDa (commercially known as Klucel G), Methyl cellulose (commercially know as Culminal MC 2000), PVA, and Funori algae were purchased from CTS, Italy. ND powder was obtained from International Technology Center (ITC, USA).

ND (at different concentrations) was dispersed in ethanol and placed in ultrasonic bath for 30 minutes to prevent the formation of aggregates, and then HPC, PVA, MC or Funori were added to the ND dispersion to obtain the composites.

More specifically, composites were prepared at 2% HPC in ethanol; 2% PVA in an hydroalcoholic solution 40:60 (water: alcohol) and 2% MC in an hydroalcoholic solution 40:60 (water: alcohol).

For Funori, two preparation methods were employed: heat extraction (denoted as T_{high}) and room-temperature extraction (denoted as T_{low}). The extractions were performed in water at 60 °C (T_{high}) and 25 °C (T_{low}), by dispersing the algae for 30 minutes and 12 hours, respectively. The resulting dispersions were then purified by filtration. After the extraction procedure, Funori was also used at a 2% weight.

A series of parchment samples was cut-off from a commercial parchment derived from sheep skin. Parchment samples were treated with the different composites with two methods: by immersion and by brushing (*Fig. 1*). The immersion method was used solely to enhance the observable effects of the treatment; however, in restoration practice, the standard application protocol involves brush application. From a piece of sheepskin parchment, about 80 samples (1×1 cm) were prepared. For each consolidant type (HPC, PVA, MC, Funori T_{high}, Funori T_{low}, each tested with four different nanodiamond concentrations, from 0 to 0.1%$_w$), 4 samples were treated, 2 by immersion and 2 by brush, totaling 80 treated samples. The list of samples tested is reported in Table 1.

Table 1. Consolidants tested in the preliminary tests

Consolidant	*ND%$_w$*	*Restoration method*
HPC (2%$_w$)	0, 0.01, 0.05, 0.1	Immersion, brushing
PVA(2%$_w$)	0, 0.01, 0.05, 0.1	Immersion, brushing
MC (2%$_w$)	0, 0.01, 0.05, 0.1	Immersion, brushing
Funori (2%$_w$) – T_{high}	0, 0.01, 0.05, 0.1	Immersion, brushing
Funori (2%$_w$) – T_{low}	0, 0.01, 0.05, 0.1	Immersion, brushing

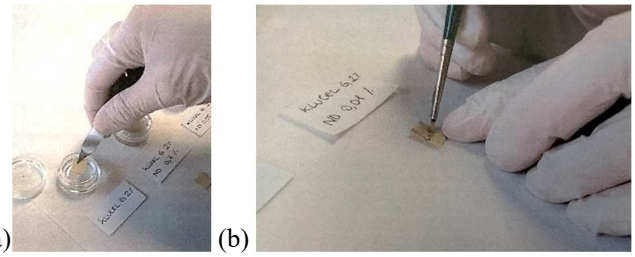


Fig. 1 Application of the ND composites (a) by immersion and (b) by brushing.

B. Sample preparation and treatment with HPC composites

After the preliminary tests, parchment samples were treated with the HPC based composites at different ND concentrations (0%, 0.01%, 0.05%, 0.1% in weight) (*Fig. 2*) by immersion. The immersion was performed to grant penetration of the compound through the entire sample thickness so as to increase the effect of the treatment, even though it is not the standard restoration procedure. The parchment samples were immersed in the obtained viscous solution for 1 hour.

After the immersion the samples were pressed between two absorbing paper leaves to dry out. In order to distinguish between eventual effects induced by the ND and those related HPC alone, an additional series of samples of the same parchment were treated with a dispersion of the same ND concentrations in ethanol only.

While the immersion time for parchment samples in the HPC-ND composite was 30 minutes, samples treated with ethanol-based dispersions were immersed for only 20 minutes, as the ethanol medium allows for faster sample hydration compared to the viscous HPC composite.

Finally, some of the samples have been artificially aged at 80 °C and 80% relative humidity for 32 days. For each treatment tested, three samples were examined.

C. Light Transmission Analysis

The LTA is a technique able to determine the deterioration degree of a parchment sample by the characterization of the so-called denaturation temperature (T_d).

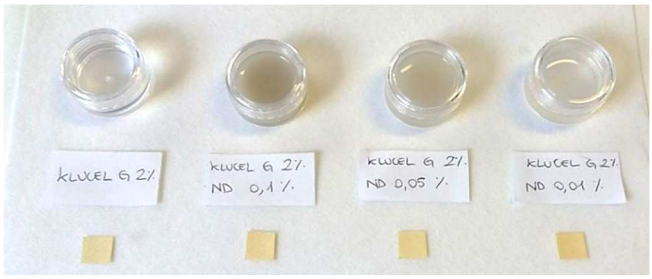


Fig. 2. HPC-ND composites prepared for the parchment treatment.

This parameter described the hydrothermal denaturation process of collagen fibers when they are heated in water determining the hydrothermal stability of the investigated sample. More specifically, LTA allows to analyze the variation in the light scattering capability of the material that occurs during the induced hydrothermal denaturation process of the specimen, in this case a suspension of parchment fibers in water. In particular, due to changes in the collagen molecular structure induced by the combined action of water and heat, during the temperature increase a reduction in the light scattering capability of the material occurs with a consequent increase in the light unscattered component transmitted through the specimen. Thus, the variation of the transmittance signal can be obtained as a function of the sample temperature to determine the T_d of the specific parchment sample. The lower is the recorded temperature the more is deteriorated the sample, since in an already partially deteriorated sample it is easier to induce the breaking of the hydrogen bonds of the collagen molecule and thus to convert the triple helical structure of the molecule into a disordered one. In the LTA experimental setup, the light is provided by a He-Ne laser beam crossing a sample suspension of parchment fibers (0.1 mm in thickness). The recorded signal is generated by a photodiode onto which the emerging light is collected and focused by a lens. The temperature of the sample is varied between room temperature up to 90°C with a constant rate (1°C/min). The variations in the sample appearance during the entire process can be monitored through a polarization microscope, included in the setup [35-37].

D. ATR-FTIR spectroscopy

In this study a Thermo-Scientific instrument (model Is50) (Thermo Scientific Inc., Madison WI, USA) in Attenuated Total Reflectance (ATR) mode using a single reflection diamond cell was used. The spectra were recorded from 4000 to 750 cm^{-1}, with a resolution of 2 cm^{-1} and averaging over 32 scans. In particular, we investigated the intensities and relative displacement of the Amide I (AI) and Amide II bands (AII) (located at about 1650 cm^{-1} and 1540 cm^{-1}), which are related to the molecular conformation of proteins, collagen in this case. This allows for the evaluation of denaturation, hydrolysis, or oxidation phenomena that alter the protein secondary structure simply by evaluating the AI/AII intensity ratio [38, 39].

E. Thermogravimetric analysis (TGA)

Thermogravimetric Analysis (TGA-DTG) was carried out using a TA Instruments Discovery TGA 55. Parchment samples were placed in platinum crucibles and heated from 40 °C to 500 °C under a nitrogen atmosphere (flow rate: 40 mL/min). The heating rate was fixed at 10 °C/min. Three runs were conducted for each sample, under the same experimental conditions [40].

III. Results and Discussion

A. Preliminary test results

One the most crucial aspect to be evaluated while performing consolidation work is the effect of the applied restoration material on the aspect of the substrate, with must not be altered, and that the material should have a consistency such as to ensure an easy application without mechanically stressing the substrate and assuring a homogenous treatment.

Moreover, it is important to consider the dispersion quality of the nanomaterial used, in this case ND. The nanoparticles must be well dispersed and prevented from aggregating; otherwise, there is a risk of nanomaterial accumulation on the surface of the material to be consolidated. Such aggregation could lead to color variations and irregular modifications in the mechanical properties of the material. Images of parchment samples treated with the different consolidant with different ND concentrations are reported in *Fig. 3*.

In the case of HPC and its ND composites, good results were obtained both in the case of treatment by immersion and brushing. The ND dispersed homogeneously in the consolidant and the samples showed no variation in colour. As for PVA, the ND dispersion was not as homogeneous as the one in HPC. The low viscosity of the composites allowed a good application of the material, however the parchment after both immersion and application by brush results visibly altered, more opaque and darker.

As for MC, the composite resulted more viscous, thus less easy to apply on the parchment substrate. Moreover, through observation at the optical microscope, an alteration of the parchment support was visible.

In the case of both types of Funori no alteration of the parchment is observed, and the application was easy to perform, given the low viscosity of the material.

From these preliminary results, it was possible to rule out the use of PVA-ND and MC-ND composite as restoration materials for parchment. The best results were obtained with Funori and HPC consolidants.

In this work, HPC was chosen to be further tested mainly because it is commonly employed in the restoration of book materials as a fixing agent for inks and pigments.

B. Results of the treatment with HPC-based composites

Parchment samples treated with HPC-based composites, as well as those treated with an ethanol-only dispersion containing ND, were selected for further investigation.

A preliminary analysis on the non-aged samples was performed via TGA. The TGA and DTG curves for the non-aged parchment samples treated with HPC, HPC–ND 0.1%, EtOH, and EtOH–ND 0.1% are shown in Fig. 4, with untreated parchment included as a reference. All samples exhibit the typical two-step weight-loss behavior of collagen-based materials: an initial mass loss below ~150 °C corresponding to the evaporation of adsorbed and bound water, followed by the main degradation event between 250 °C and 350 °C associated with the thermal decomposition of collagen.

Overall, the treated and untreated parchments display very similar decomposition profiles, indicating that the treatments do not substantially modify the thermal stability of the substrate.

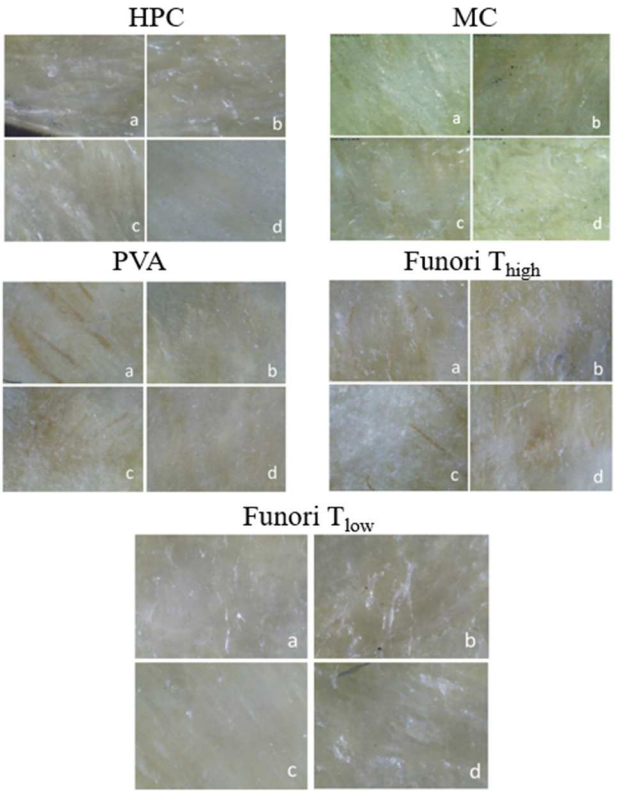


Fig. 3. Parchment samples treated with the various consolidants tested: (a) 0% ND (b) 0.01% ND (c) 0.05 % ND (d) 0.1 % ND. Only pictures of the brushing treatment are reported.

Notably, samples treated with HPC (with or without nanodiamonds) show more defined DTG peaks compared to untreated or EtOH-treated samples. This sharpening of the main degradation peak is attributed to the contribution of the HPC component, which in its pure form (not shown here) exhibits a distinct degradation event around 360 °C±3. When HPC is applied to the parchment, this degradation feature appears broadened and slightly shifted toward lower temperatures, likely due to interactions between the HPC coating and the collagen network of the substrate. These interactions result in a combined thermal response rather than independent degradation events. The residual weight at 500 °C is also marginally higher for the ND-containing samples, consistent with the presence of thermally stable nanocarbon species. Overall, the data confirm that the treatments preserve the characteristic thermal behavior of parchment, while the presence of HPC introduces additional, well-defined features in the derivative curves due to its intrinsic thermal decomposition profile.

LTA investigation was performed on both aged and non-aged samples, in the case of the parchment samples treated with HPC composites, the results show that, for the non-aged samples, the obtained value of T_d is not altered by the use of the different mixtures, both with or without the addition of ND (T_d~52°C). On the contrary, after the artificially ageing process, all the samples treated with pure HPC or with HPC with addition of ND, show a substantial decrease of T_d with ageing apart from the untreated sample where the decrease of T_d with ageing is moderate. Quite interesting, the maximum decrease of T_d is ~8/9 °C with respect to the non-aged samples is recorded for the sample treated with the HPC only with a down shift considerably larger than the one recorded for the untreated sample (ΔT_d=1.6±1.2 °C).

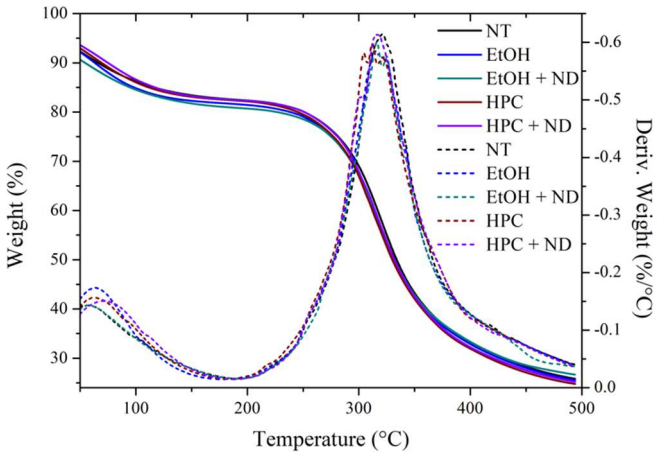


Fig. 4: Thermogravimetric (TGA, solid lines) and derivative (DTG, dotted lines) curves of non-treated parchment (NT) and samples treated with ethanol (EtOH), ethanol with nanodiamond (EtOH + ND), hydroxypropyl cellulose (HPC), and hydroxypropyl cellulose with nanodiamond (HPC + ND).

The other samples treated with ND composites show a smaller decrease in T_d, after the ageing, with respect to sample treated with HPC alone. In particular, the better results seem to be obtained by the sample treated with the ND concentration of 0.05% and 0.1%, where a temperature decrease of ΔT_d=3.5/3 °C respectively is observed. By these results, it appears that the presence of ND in the composites acts as a protective agent in particular in the aged samples treated with the above-mentioned concentration, while the HPC alone induced the most severe deterioration with the worst behavior as a function of ageing. It must be remarked that normally, parchment is not subject to wet treatments through immersion, but it has been performed to evaluate eventually induced deterioration factors in the sample bulk.

To better discriminate the effects on ageing played by the various components of the applied composites it has been necessary to also evaluate the effects of the ND application on the parchment substrate samples without the presence of HPC, and thus with only ethanol. In the case of the non-aged samples, the T_d values seem to be slightly larger in the samples treated with ND with respect to the untreated one with the maximum value obtained for a ND concentration of 0.01% and 0.05% (from 51.8°C of the untreated sample to the ~54.2°C of the mentioned concentrations). Moreover, at the concentration of 0.05%, a smaller negative T_d shift is observed also in the 32 days aged samples (ΔT_d = 0.3±1.2 °C) with respect to the untreated one (ΔT_d = 1.6±1.2 °C) suggesting a protective action of the ND on the long-term deterioration process of the collagen molecule (Fig. 5).

The ATR-FTIR analysis (Fig. 6) seems to complete and confirm the results obtained by LTA. For the samples treated with ethanol only and before the artificially ageing process, the AI/AII bands intensity ratio remains almost constant revealing not significant evidence that the treatment affects the structural characteristics of the parchment.

Some variations are visible, instead, after the ageing, when can be recorded an increase, although very slight, in the values of the AI/AII bands intensity ratio.

The hydrolysis processes have thus started in the aged samples but, being smaller in the samples treated with the ND suspensions in ethanol (best results for the sample treated with the concentration of 0.1%) they only seem to be due to the artificially ageing process.

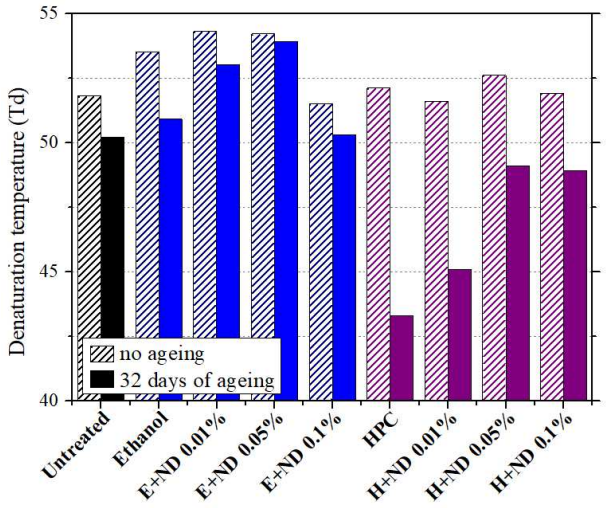


Fig. 5. LTA denaturation temperatures of modern parchment samples treated with ethanol dispersions, ethanol-ND composites, HPC, and HPC-ND composites. Striped bars represent non-aged samples, while solid bars indicate aged ones.

No significant evidence of eventual gelatinization processes can be deduced. Very slight shift of the two Amide bands and a general broadening of the Amide II bands after ageing suggests that some secondary structure changes are present but contrasted and prevent by the treatment with ND (Fig. 6). Similar results have been obtained for the sample treated with HPC based composites. A small increase in the AI/AII ratio can be recorded in this series of samples and it can be probably due to a slight hydration effect induced in the sample by the HPC itself. As for the LTA results, also in this case the analysis shows the smallest increase for the sample treated with HPC and ND 0.05% reflecting the protective effect of the ND in the treatment.

Regarding the aged samples, the ATR-FTIR spectroscopy results show a minor broadening of the Amide I and II bands. This peculiar feature of the spectrum reflects an eventual incoming of gelatinization in the protein conformation as well as the separation of Amide I and II bands position (Δν) that, although very slightly, increases [41] (Fig. 6).

The mechanism behind the effect of the ND on the preservation of both collagen and HPC is yet to be studied and understood. However, some explanation could be found in the thermal properties of the ND, that somehow could diminish the effect of heat by dissipating it, and in the reinforcement effect that the nanoparticles have when dispersed into a polymeric matrix. In fact, nanofillers have the capability of increasing the stability and the rigidity of the polymeric entanglement, making polymeric chains more resistant to deterioration by stabilizing their structure [42].

IV. Conclusion

In this work, the effects of the application of nanodiamond (ND) composites as restoration agent for parchment supports has been explored. Different increasing concentrations of ND have been dispersed in a commonly used wet cleaning media (ethanol) and in polymeric materials, commonly employed in the field of restoration. The suitability for application of the obtained composites was preliminarily evaluated based on the color and morphological alteration of the parchment substrate after treatment. Among the materials tested, Funori-ND based composites and HPC-ND based composites were proven not to alter parchment appearance and to be easily applicable.

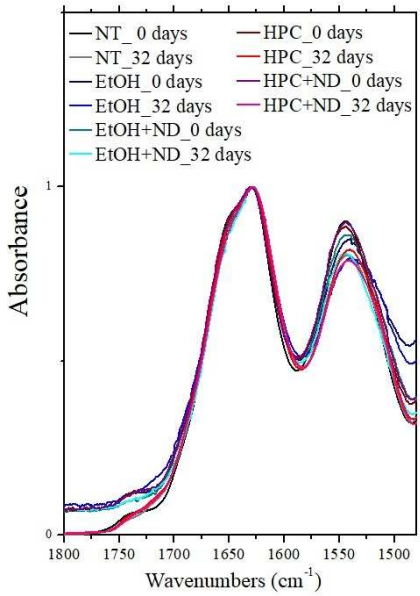


Fig. 6: FTIR-ATR spectra (Amide I and Amide II bands) of non-aged and aged parchment samples, untreated (NT, black and grey); treated with Ethanol alone (navy blue and blue); Ethanol dispersions with ND at 0.05% (dark cyan and cyan); HPC alone (wine red and red); HPC with ND at 0.05% (pink and purple).

Among these two treatments, the HPC-ND was further investigated. The results were evaluated using two techniques, the Light Transmission Analysis (LTA) and Attenuated-Total-Reflectance Fourier Transformed Infrared (ATR-FTIR) analysis, showing that ND based composites are able to contrast the negative effect of the artificial ageing process on the collagen molecule. Both the techniques have highlighted the capability of the ND dispersion in ethanol to work as a protective treatment, in particular in the concentration of 0.05%. Although the research is still ongoing with the aim of finding a better procedure to perform the restoration treatment and to explore further eventual application of the composites in the consolidation/preservation of parchment substrate, ND-based treatments have showed interesting and promising results. Concrete possibility in their future possible application has been shown making ND a valid "green" candidate to develop new approaches in the restoration of cultural heritage goods. The next step would be the investigation of the Funori-ND based composite, which seems promising giving the successful applications and results obtained using the Funori alone in parchment, and mostly in paper restoration [43].

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Development of Polyaniline-Based Polysaccharide Composite for Biomedical Applications

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***Abstract*— Electrically conductive hydrogels (ECHs) represent an emerging class of sustainable materials for tissue engineering, capable of coupling biocompatibility with electroactivity. Here we report xanthan gum/locust bean gum–polyaniline (XG/LBG-PANI) hydrogels synthesized via oxidative polymerization of aniline within a natural polysaccharide matrix. The composites exhibit stable redox behavior and electrical signal transmission comparable to cardiac muscle tissue, highlighting their biomimetic performance. Structural analysis confirmed the incorporation of the conductive structural form of PANI, i.e. emeraldine salt (ES), while preliminary in vitro cell tests demonstrated good cellular adhesion. These results demonstrate that XG/LBG–PANI composites are promising candidates as eco-friendly, electroactive scaffolds for next-generation bioelectronic interfaces and tissue regeneration applications.**

Keywords—Xanthan gum, Locust bean gum, Polyaniline, conductive composite

I. INTRODUCTION

Composite biomaterials have gained growing attention in the biomedical field due to their ability to integrate versatile properties with the capacity to interact with biological tissues and stimulate specific cellular responses [1]. These materials can be employed in the development of systems for controlled drug delivery, biosensing applications, and scaffolds for tissue engineering [2]. Among the various classes of biomaterials, natural and synthetic polymers are of particular relevance due to their versatility. They can be processed into two-dimensional structures, such as thin films, or into three-dimensional architectures, which can be easily functionalized to suit specific application requirements [3]. In this context, electrically conductive hydrogels (ECHs) have recently emerged as a new class of electroactive and multifunctional biomaterials. By combining soft, hydrated polymer networks with electrical conductivity, ECHs can transmit bioelectrical signals while maintaining mechanical properties similar to biological tissues. This unique combination enables applications in tissue regeneration, biosensing, and neural or cardiac repair, where electrical communication between cells is crucial [4]–[6]. To achieve these properties, a common strategy is to combine conducting polymers (CPs) with polysaccharides [7]. CPs such as polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT) have recently been applied in biomedical contexts and are considered highly promising candidates. They effectively bridge the gap between organic compounds and inorganic conductors by combining favorable chemical physical characteristics with intrinsic electrical conductivity. A distinctive property of CPs is their ability to modulate electrical conductivity through reversible redox reactions, which promote charge generation and counterion migration within the polymer matrix [8], [9]. These distinctive features, particularly their tunable charge transport properties, make CPs particularly attractive for applications in electronic devices, including the development of organic light-emitting diodes and organic transistors. [10]–[12]. In the biomedical fields, the dual ionic/electronic conduction makes CP-based composites particularly suitable for scaffolds aimed at regenerating electrically excitable tissues, including neural, cardiac, muscular, and bone tissues [13]. Among CPs, PANI is one of the most widely studied due to its unique properties, such as redox activity and ease of synthesis. PANI can exist in three oxidation states: leucoemeraldine (LE, fully reduced), emeraldine (E, semioxidized), and pernigraniline (P, fully oxidized) [14]. These forms can be protonated in acidic media and deprotonated in basic media. Each state exhibits different levels of conductivity and electrochemical behavior [14]. The ability of PANI to reversibly switch between these forms under applied potentials, and to vary the electrochemical properties upon protonation, candidate this CP to a vast class of electrochemical, sensing, and memory applications [14]. However, PANI's range of applications is limited due to its poor solubility in most aqueous environments. One strategy to overcome these limitations is to combine PANI with stabilizing agents such as natural polymers, colloids, or nanoparticles [15]. Moreover, integrating PANI within biopolymer matrices

enables the development of environmentally friendly, low-cost, and sustainable materials. In particular, numerous studies have demonstrated that blending PANI with natural polymers, such as polysaccharides, is an effective strategy for developing scaffolds that promote cell proliferation and influence cell morphology, thus showing a strong potential for cardiac tissue regeneration applications [16], [17]. Our previous works [18]–[21] have demonstrated that PANI can be synthesized through different approaches and employed in both biological and sensing applications. In particular, an our recent study [22] demonstrated that PANI can be successfully combined with natural polymeric systems, specifically xanthan gum (XG), to produce the final composite materials (XG-PANI). The resulting composites exhibit morphological, structural, and functional properties that couple the electrical and electroactive performance of PANI with the unique rheological characteristics of XG. In this study, we propose the introduction of a second polysaccharide, locust bean gum (LBG), into the previously developed system [22]. LBG is well known for its ability to interact with XG through electrostatic forces and hydrogen bonding. Under specific conditions, these interactions produce a synergistic effect, leading to the formation of a heat-reversible, gel-like composite material [23], [24]. The resulting XG/LBG–PANI ECHs were synthesized, similarly to that reported in [22], via oxidative polymerization of aniline (ANI) within the polysaccharide matrix and characterized by chemical compositional (FT-IR) and electrochemical (CV) analyses. The produced material exhibited stable redox response and electrical signal transmission comparable to cardiac muscle tissue, highlighting their biomimetic electrical performance. Preliminary in vitro viability tests demonstrated good cell adhesion on the ECH surfaces, supporting their potential use as bioelectronic interfaces. Beyond their functional performance, the use of renewable and biodegradable polysaccharides, such as XG and LGB, points out the sustainability and green chemistry principles guiding this approach. Altogether, these results position XG/LBG–PANI as sustainable, electroactive ECHs with strong potential for tissue engineering, bioelectronic interfaces, and regenerative medicine, particularly in applications where electrical conductivity and biological compatibility are essential for functional tissue restoration.

II. Materials and Methods

A. Chemicals

Analytical-grade reagents were used throughout this study without further purification. Xanthan gum (XG), locust bean gum (LBG), aniline (ANI), ammonium peroxydisulfate (APS), sodium chloride (NaCl), phosphate-buffered saline (PBS, without calcium and magnesium), 6-diamidino-2-phenylindole (DAPI), were obtained from Merck KGaA (Darmstadt, Germany). Dulbecco's Modified Eagle Medium (DMEM) and fetal bovine serum (FBS) were supplied by Euroclone (Milan, Italyocust bean gum (LBG), Dialysis tubing cellulose membranes were obtained from Merck KGaA (Darmstadt, Germany) and purified according to the supplier's instructions

B. XG/LBG-PANI composites preparation

The synthesis of XG/LBG–PANI composite was achieved through chemical oxidative polymerization of the ANI monomer, employing APS as the oxidizing agent in the XG/LBG polysaccharide matrix, as illustrated in Fig. 1.

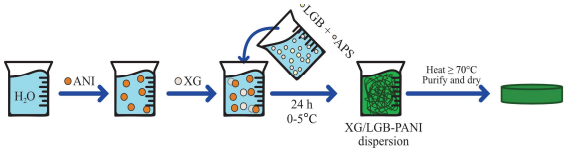


Fig. 1: Schematic representation of the synthetic route for XG/LBG–PANI composite.

The reported synthetic route is analogous to those reported in our recent work [22]. The procedure is as follows: ANI precursor was dissolved in distilled water (0.1 M) and sonicated for 30 min at room temperature. Subsequently, an appropriate amount of XG powder was gradually added to the ANI dispersion under continuous magnetic stirring until complete dissolution. Separately, LBG powder was gradually introduced into a 0.1 M APS solution under constant stirring. The resulting LBG–APS dispersion was then slowly added to the XG–ANI to start the ANI oxidative polymerization. The reaction was maintained at 0–5 °C in an ice bath for 24 h. The resulting dispersion was subsequently heated above 70 °C for 5 min to promote intermolecular interactions between the XG and LBG polysaccharide chains. The final composite was purified by dialysis in hydroalcoholic solution for 7 days, casted into circular silicone molds, and dried at room temperature. The name and experimental conditions of all samples produced are summarized in Table 1.

A reference XG/LBG sample was also produced by mixing aqueous solutions of XG and LBG without ANI and APS.

Table 1: Composite names, reference sample names, and experimental condition.

Sample name	XG percentage (wt%)	LBG percentage (wt%)	ANI concentration [M]	ANI:APS
XG/LBG	1%	1%	-	-
XG/LBG-PANI	1%	1%	0.1	1:1

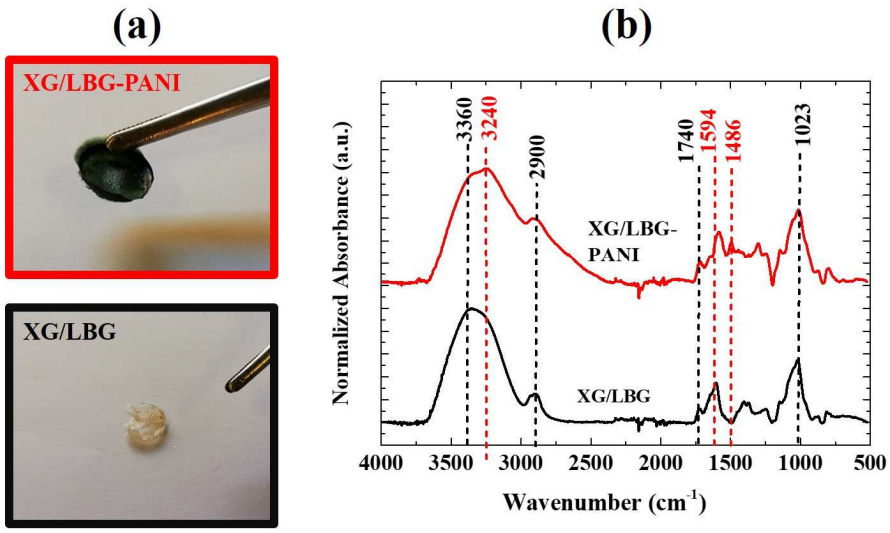


Fig. 2: a) images of XG/LBG and XG/LBG-PANI composites; b) FTIR-ATR spectra of XG/LBG (Black line) and XG/LBG-PANI (Red line).

C. *Characterizations*

The structural features of the XG/LBG–PANI samples were examined by FT-IR spectroscopy. Spectra were collected using a Thermo Fisher Scientific IS50 spectrophotometer equipped with a single-reflection ATR diamond crystal, in the range of 4000–500 cm^{-1}.
The electrical conductivity of the sample was assessed using a four-point measurement at room temperature. A custom apparatus was employed to collect the I-V curves, with external probes delivering current (Keithley 6221) and measuring the voltage difference (Keithley 2700) between internal probes. Measurements were carried out on three independent samples, exhibiting an average thickness of 0.68 mm.

Cyclic voltammetry (CV) was employed to assess the electrochemical performance in a standard one-compartment, three-electrode cell using a PalmSense compact workstation. Measurements were conducted within the potential window of +0.3–+0.7 V at scan rates between 10 and 120 mV s^{-1}. The reference and counter electrodes were a saturated calomel electrode (SCE) and a Pt foil, respectively. The working electrode was prepared by applying a platinum contact to the backside of the composite samples.
The cell viability of the ECHs was evaluated as reported in [22], using the PC-3 human prostate cancer cell line (ATCC, Rockville, MD, USA). In detail, the Cells were grown in Dulbecco's Modified Eagle Medium (DMEM) supplemented with 10% fetal bovine serum (FBS), penicillin (1×10^5 U/L), streptomycin (50 mg/L), and glutamine (200 mM) (Euroclone, Milan, Italy). Cultures were incubated at 37 °C in a humidified atmosphere containing 5% CO_2 and routinely subcultured by enzymatic detachment using Trypsin-EDTA (Euroclone, Milan, Italy).

Prior to seeding, ECH specimens were sterilized by immersion in 70% ethanol for 30 min, rinsed with sterile phosphate-buffered saline (PBS), and preconditioned with FBS for 24 h under aseptic conditions. PC-3 cells (2×10^4 cells for sample) were then seeded onto the samples positioned in 24-well culture plates and incubated for 72 h in DMEM supplemented with 10% FBS at 37 °C and 5% CO_2.
Following incubation, the samples were fixed in 4% paraformaldehyde at 25 °C for 15 min, permeabilized with 0.1% Triton X-100 for 2 min, washed with PBS, and stained with a 1 mg/mL DAPI solution to visualize cell nuclei. Fluorescence images were captured at 20× magnification using a ZEISS Axio Observer microscope and analyzed with ZEN software (Carl Zeiss Microscopy GmbH)

III. Results and Discussion

Fig. 2 shows the dried XG/LBG and XG/LBG-PANI composites (a) and their FT-IR spectra (b).
The dried XG/LBG–PANI composites exhibited self-standing behavior, in contrast to the XG/PANI composites reported in previous work [22]. This enhanced mechanical stability can be attributed to the incorporation of LBG within the polymer network. Probably, LBG interacts with XG, reinforcing the structural integrity and modulating the mechanical and physicochemical properties of the resulting materials. Incorporation of PANI into the XG/LBG matrix resulted in the emergence of the characteristic green coloration associated with the protonated emeraldine form (E) of PANI. This suggests that the synthesis of PANI occurs successfully within the polysaccharide matrix [19].
These findings were further supported by FT-IR spectra shown in Fig. 2b. The signals corresponding to the XG/LBG phase (dashed black line) are attributed to the characteristic vibrational modes of the polysaccharides.

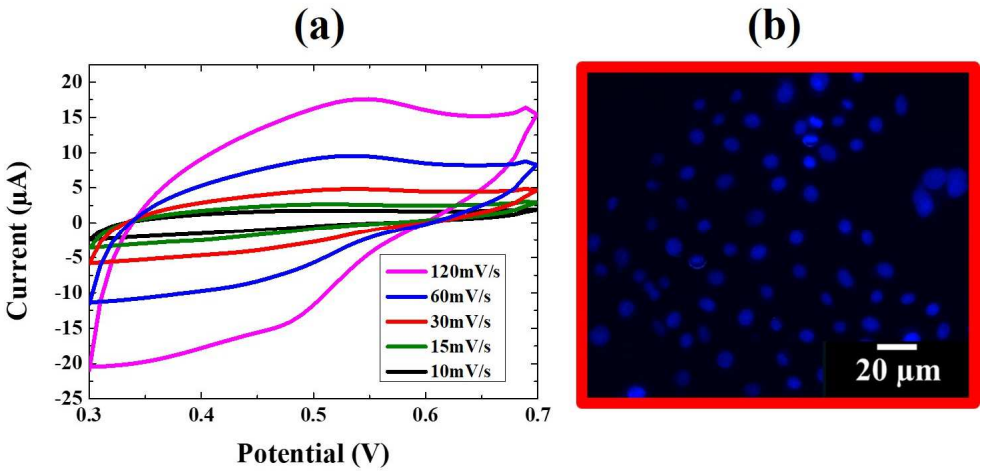


Fig. 3: a) CV analysis of XG/LBG-PANI in saline solution (1M of Nacl) collected at different scan rates (120, 60, 30, 15, 10 mV/s). b) fluorescence microscope image of PC-3 cell line on the XG/LBG-PANI 0.1 composite, after 3 days of incubation.

In particular, the bands observed at 3360, 2900, and 1023 cm^{-1} are assigned to –OH stretching, aliphatic C–H stretching, and C–O stretching of the glycosidic ether bond (C–O–C), respectively, which are inherent to the chemical structures of both LBG and XG [22], [25], [26]. The signal at 1740 cm^{-1} is assigned to the C=O stretching of the acetate groups of the XG chains [27].
The FT-IR spectra of XG/LBG-PANI (dashed red line) composites show a series of further peaks related to the XG/LBG and PANI phases. The peaks at 3240, 1578, and 1489 cm^{-1} are characteristic of PANI and are assigned to N–H stretching and the stretching vibrations of the quinoid (Q) and benzenoid (B) rings, respectively [14], [28]. The presence of the quinoid (Q) and benzenoid (B) peaks confirms that the PANI chains are present in the semioxidized, protonated (E) form. This observation further validates the successful formation of conductive PANI within the XG/LBG matrix [22].

The electrical conductivity (σ), determined by I–V characterization, was found to be $2.3 \pm 0.1 \times 10^{-4}$ S m^{-1} for the XG/LBG–PANI composite. This value is relatively low, even compared to that reported for the XG–PANI system [22]. The lower conductivity likely originates from the insulating nature of the XG and LBG matrices, which form a compact polymer network that hinders efficient charge transport between PANI chains. Nevertheless, the measured conductivity remains sufficient to promote the proliferation of cardiomyocyte and neural stem cells [29], [30].
Cyclic voltammetry (CV) was employed to assess the electrochemical behavior of the XG/LBG–PANI composites in 1 M NaCl solution at scan rates of 10, 15, 30, 60, and 120 $mV \cdot s^{-1}$. The corresponding voltammograms are shown in Fig. 3a, together with a fluorescence microscopy image of PC-3 cells cultured on the composites after three days of incubation (Fig. 3b). As illustrated in Fig. 3a, the XG/LBG–PANI system exhibits a distinct anodic peak at approximately +500 mV and a corresponding cathodic peak near +450 mV. These redox features are characteristic of the transition between the semioxidized emeraldine (E) and fully oxidized pernigraniline (P) forms of PANI [18], [31].
Although the two redox peaks are broad and of modest intensity due to the presence of XG/LBG insulant system, the inclusion of PANI induces the fabrication of a final composite with electrochemical activity in neutral pH environment.
As shown in Fig. 3a), the current peaks increase with scan rate. Moreover, the intensity ratio between the anodic and cathodic peaks deviates from 1, suggesting a quasi-reversible redox process. This behavior is analogous to that observed for XG/PANI composites [22], and can be attributed to complex kinetics involving chemical and structural modifications of PANI chains within the XG/LBG matrix. As previously observed for XG–PANI composites, the electrochemical behavior of conducting polymers involves ion and solvent exchange with the surrounding medium to preserve charge neutrality and osmotic equilibrium. In XG/LBG–PANI systems, the redox transition between the E and P forms of PANI is compensated by cations and water exchange. During oxidation, cations and water are released from the polymer matrix, whereas reduction induces their reuptake, leading to swelling/deswelling and conformational rearrangements. These structural variations alter polymer interactions and contribute to the observed quasi-reversible electrochemical behavior of the ECH. Based on the electrical and electrochemical results, the charge transport properties of produced

XG/LBG–PANI ECH are suitable for supporting bioelectrical signaling, making these composites promising candidates for the fabrication of scaffolds in cardiac tissue engineering. In agreement with our previous work [22], the electrochemical activity of the produced materials is sufficient to sustain microcurrent fluxes associated with cellular communication, proliferation, and differentiation in electrically excitable tissues [29], [30].

Cellular assays were carried out to assess the viability and adhesion of PC-3 cells on the synthesized composite biomaterials. As illustrated in Fig. 3b, PC-3 cells displayed normal morphology and well-defined nuclei, indicative of preserved metabolic activity. Nevertheless, owing to the limited optical transparency of the samples, a slight underestimation of the DAPI signal cannot be excluded, consistent with observations previously reported for XG–PANI composites. Overall, these findings demonstrate that the XG/LBG–PANI composites support good adhesion and viability of PC-3 cells, in agreement with our earlier work [22]. Additional viability tests involving different cell lines will be necessary to more comprehensively evaluate the suitability of these substrates for tissue engineering applications. These findings are consistent with our previous work on XG/PANI composites. The incorporation of LBG into the matrix appears to improve biocompatibility and may also contribute to enhanced mechanical properties of the composites. Overall, these findings indicate that XG/LBG–PANI composite biomaterials possess suitable characteristics for integration within physiological environments.

IV. Conclusions

In this work, we successfully synthesized XG/LBG–PANI ECHs biomaterials via oxidative polymerization of aniline in a XG/LBG matrix. The coupling of chemical compositional analysis with electrochemical characterization confirmed the incorporation of PANI in its conductive emeraldine form, able to retain redox activity in a neutral environment. The redox behavior is consistent with the swelling/deswelling mechanisms previously reported for XG/PANI systems. Preliminary studies with PC-3 cells indicate good adhesion and normal morphology, suggesting that the composite has good in vitro biocompatibility. The inclusion of LBG appears to improve both the mechanical and biological properties of the material, allowing the formation of self-standing samples without freeze-drying. Taken together, these findings demonstrate that XG/LBG–PANI composites are promising candidates for biomedical applications requiring electroactive materials, including tissue engineering scaffolds and interfaces with electrogenic cells. Importantly, the synthetic procedure employs naturally derived polysaccharides, highlighting the potential for sustainable and biocompatible electroactive biomaterials.

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Experimental Study and Affordable Instrumentation of a Piezo-Thermoelectric Hybrid Road Energy Harvester: Field Implementation

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***Abstract*—Road infrastructure presents a compelling opportunity for energy self-generation by harvesting thermal energy (solar radiation) and mechanical vibrations (traffic). The design, fabrication, and real-world implementation of a hybrid thermo-piezoelectric energy harvester for roads are presented. Arduino-based instrumentation was developed and validated, exhibiting a relative error of 4.97%. Real-world testing confirmed an output of 2.4 V without material optimization. The experimental data allowed for the establishment of an empirical model that reinforces a previously proposed electronic model. The feasibility of this hybrid approach is demonstrated. Future work must prioritize material optimization for enhanced efficiency and include an in-depth study of road surface mechanical integrity following installation.**

***Index Terms*—energy harvester, hybrid, piezoelectric, thermoelectric, Arduino sensors, IoT**

I. Introduction

The necessity to reduce fossil fuel consumption has driven research into sustainable energy sources. Road infrastructure, a contributor to CO_2 emissions, presents a substantial, underutilized energy-harvesting potential due to its constant exposure to ambient energy streams [1]–[3].

Previous research has predominantly concentrated on single-source harvesting [4]. Piezoelectric devices convert mechanical stress into electrical energy but are highly susceptible to traffic frequency fluctuations [5]. Thermoelectric solutions harness temperature gradients, particularly solar radiation, but suffer from low conversion efficiencies [6]. To mitigate these intrinsic drawbacks, research interest in hybrid energy harvesters has

increased [7].

Literature includes hybrid prototypes demonstrating outputs such as 1.55 mW and 9.83 V (Mujahiid *et al.* [8]), and 2.75 W to 4.33 W (Pacis *et al.* [9]). Lower output, such as 1.75 μW, has also been reported without material optimization [10].

This work moves beyond laboratory investigations by implementing and validating a functional prototype under real-world operating conditions. A cost-effective, Arduino-based measurement system was validated for reliable data acquisition. The resulting experimental dataset facilitated the development of a novel empirical model that reinforces the validity of an existing theoretical electronic model [10].

II. Materials and Methods

This work primarily aims to design and fabricate a hybrid road energy harvesting system, implement it in a real-world environment, and evaluate its energy output using Arduino-based instrumentation.

A. System Design and Components

1) Piezoelectric Harvester Design: This system is designed to convert the mechanical energy from vehicle traffic into electrical energy. As illustrated in Fig.1, the harvester consists of piezoelectric transducers (KPGS100) positioned beneath 350 g seismic masses and calibrated springs. This configuration is tuned to achieve resonance conditions, maximizing energy harvesting efficiency.

The transducers are embedded in the pavement using an optimized spatial layout. Vehicle passage applies force, deforming the piezoelectric discs and generating voltage. Key design considerations included:

- Optimized sensor placement under the road surface;
- Component dimensions (e.g., 35 mm piezo disc);
- Electrical connections to a rectifying circuit and an energy storage device.

2) Thermoelectric Harvester Design: This system utilizes TEC1 − 12706 thermoelectric modules to convert temperature gradients between the road surface and a heat sink into electrical energy via the Seebeck effect. As illustrated in Fig.2, aluminum bars transfer and direct heat flow from the road surface to the modules, optimizing the thermal gradient. Insulating materials are incorporated to minimize energy losses and improve overall system efficiency.

The output voltage is measured using digital multimeters and directed to an energy storage device. System

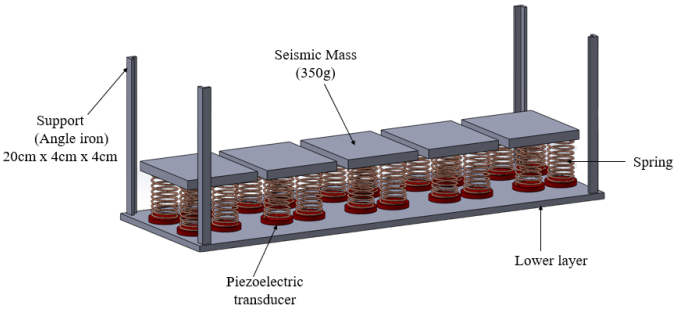


Fig. 1. Piezoelectric Harvester Design.

performance is assessed under varying thermal and cooling conditions. The design model addresses:

- Arrangement of TEC modules on the pavement;
- Cooling system structure (heat sinks);
- Voltage generation through the Seebeck effect;
- Precise component dimensions (aluminum bars, TEC modules, etc.).

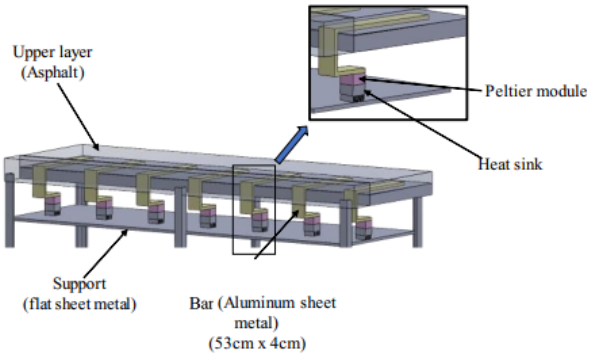


Fig. 2. Thermoelectric Harvester Design.

3) Hybrid Harvester Design: This system integrates piezoelectric and thermoelectric technologies to enhance energy harvesting by capturing both mechanical vibrations and thermal gradients. The two subsystems can be connected in either series or parallel configurations, depending on the energy management strategy (Fig. 3).

The voltages generated by each source are collected, compared, and combined to evaluate the overall efficiency of the hybrid configuration. The system is designed for operation under diverse environmental conditions, including day-night cycles and temperature fluctuations.

Piezoelectric and thermoelectric modules are co-located and structurally integrated to form a compact, multifunctional energy harvesting unit.

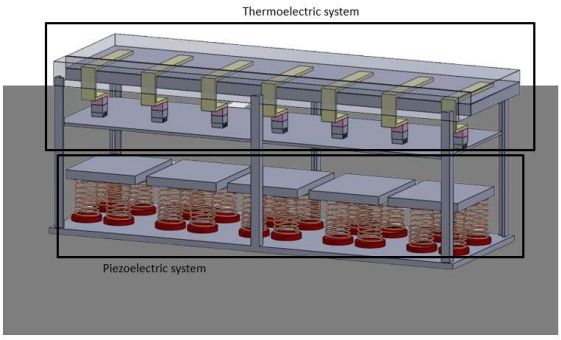


Fig. 3. Hybrid Harvester Design.

The modeling demonstrates the feasibility of simultaneous operation, harnessing solar heat absorbed by the asphalt and vibrations generated by vehicular traffic. The prototype hybrid energy harvester will be implemented by embedding the entire system within the asphalt surface in a real-world setting.

B. Instrumentation and Data Acquisition

1) Data Acquisition and Processing: Voltage and temperature data are acquired using Arduino microcontrollers (Uno and Mega models), connected to MAX6675 thermocouples and voltage sensors. Vibration data are analyzed using Fast Fourier Transform (FFT) techniques to identify dominant traffic-induced frequency components. Results are transmitted via an ESP8266 Wi-Fi module to a computer for remote monitoring and processing. Figure 4 illustrates the acquisition setup structure.

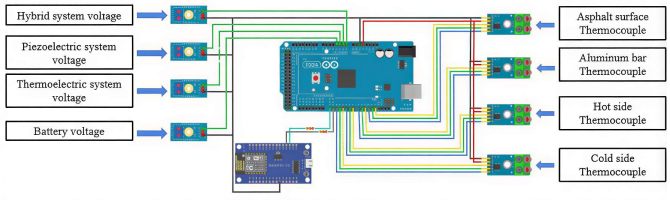


Fig. 4. Data acquisition Design.

2) Piezoelectric Transducer Specifications: The proposed piezoelectric harvester employs KPSG100 transducers, selected primarily for their affordability. While higher energy conversion performance may be achievable with other transducers, the KPSG100 provides a cost-effective solution suitable for practical implementation. Specifications are detailed in Table I.

TABLE I
SPECIFICATIONS OF THE KPSG100 PIEZOELECTRIC TRANSDUCERS

Description (unit)	Value
Device	Piezoelectric speaker
Manufacturer	Kingstate Electronic
Model number	KPSG100
Dimension (mm)	50 × 2.2
V_{max} input (V)	30
Operating Temperature (°C)	-20 to +70
Resonant frequency (Hz)	1200
Resonant impedance (Ohm)	3500
Weight (g)	3

3) Thermoelectric Generator Specifications: The thermoelectric component utilizes TEC1 − 12706 modules, selected for their balance of performance, availability, and cost. These modules are frequently employed in low-grade thermal energy harvesting due to their reliability and commercial accessibility. Module specifications are provided in Table II.

TABLE II
SPECIFICATIONS OF THE TEC1-12706 THERMOELECTRIC MODULE

Description (unit)	Value
Device	Thermoelectric cooler
Manufacturer	Hebei I.T
Model number	TEC1-12706
Dimension (mm)	40 × 40 × 3.9
ΔT_{max} (°C)	75
Max. Operating Temperature (°C)	138
Life expectancy (hours)	200,000
I_{max} (A)	6.4
V_{max} (V)	16.4

III. RESULTS AND DISCUSSION

A. Instrumentation Validation and Reliability

Given the use of low-cost sensors, validating reliability is essential for ensuring data accuracy and credibility. Error analysis was conducted by comparing the outputs of the data acquisition sensors with high-precision reference instruments (thermocouple and calibrated digital multimeter). This verified the accuracy and consistency of the temperature and voltage measurements obtained. Fig. 5 illustrates the setup used for this comparison.

A comparison was conducted between the low-cost sensors and reference instruments to evaluate measurement accuracy (temperature and voltage). The sensors

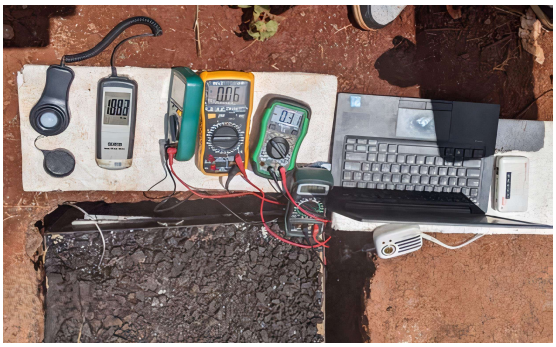


Fig. 5. Calibration setup for comparing low-cost sensors with reference instruments.

exhibited acceptable performance, showing minor deviations from reference values. Table III summarizes the mean absolute error and relative error observed.

TABLE III
ERROR ANALYSIS OF THE LOW-COST SENSORS

Parameters	Absolute error	Relative error
Voltage	0.15 V	7.14 %
Temperature	0.4°C	4.1 %

B. Results of the Real-World Experimentation

The prototype was installed at the Polytechnic University of Antananarivo, Madagascar (longitude: 47.410215, latitude: −18.9720009) for real-world experimentation (Fig. 6). This section details the relationships observed between key operational parameters (vibration frequency, vehicle speed, temperature difference) and the electrical output.



Fig. 6. Operational setup of the device on site with a passing vehicle.

1) Piezoelectric System Performance: To investigate the relationship between vehicle speed and output voltage, tests were conducted at speeds ranging from 0 to 30 km/h. The results indicate a linear increase in output voltage with vehicle speed (Fig. 7). This correlation is consistent with the linear relationship between speed and induced vibration frequency (Fig. 8), as supported by Song *et al.* [11]. A maximum output voltage of 2 V was recorded at 28 km/h, corresponding to a vibration frequency of 7.21 Hz.

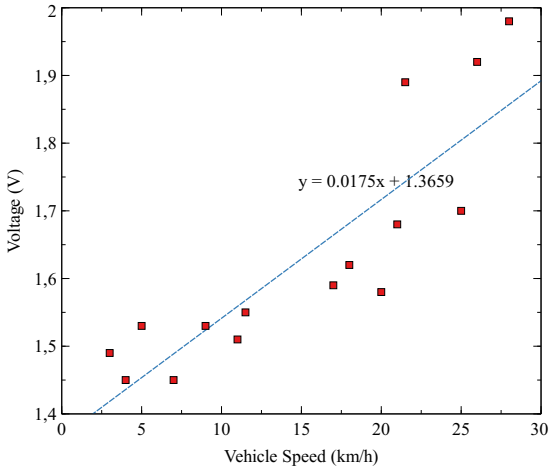


Fig. 7. Relation between vehicle speed and output voltage.

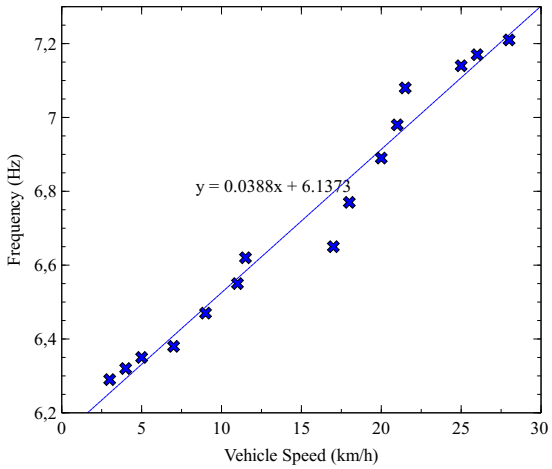


Fig. 8. Relation between vehicle speed and vibration frequency.

2) Thermoelectric System Performance: To evaluate measurement repeatability, data were collected over several days. Peak solar radiation occurred between 12:00 p.m. and 1:00 p.m. Maximum recorded temperatures for asphalt, aluminum, and the Peltier module sides were 69.75°C, 61°C, 50°C, and 39°C, respectively. The temperature evolution is shown in Fig. 9.

Observations indicated that as the asphalt temperature increased, heat losses during transfer to the metal bar

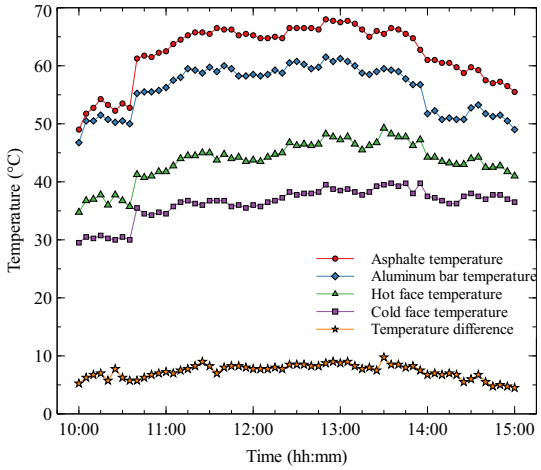


Fig. 9. Evolution of temperatures for various components of the thermoelectric harvester.

also increased, attributed to the bar's decreasing thermal conductivity. This suggests the need for optimized cooling, which falls outside the scope of the current work.

The relationship between output voltage and temperature difference is shown in Fig. 10. A total Seebeck coefficient of 0.09754 V/°C was determined, yielding a maximum open-circuit voltage of 0.87 V at a 9°C difference (March 4, 2025).

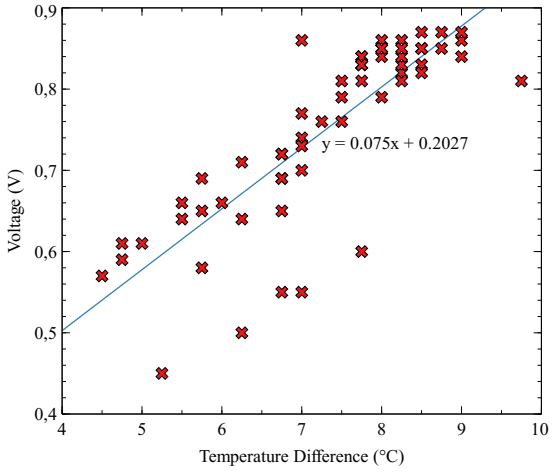


Fig. 10. Relationship between temperature difference and output voltage for the thermoelectric system.

3) Hybrid System Performance: Following independent characterization, the systems were integrated into a series hybrid configuration, chosen to maximize harvested energy by leveraging both mechanical vibrations and thermal gradients. Fig. 11 illustrates the combined power output as a function of vehicle speed and temperature difference. The curve was generated using a thin plate spline approach in MATLAB.

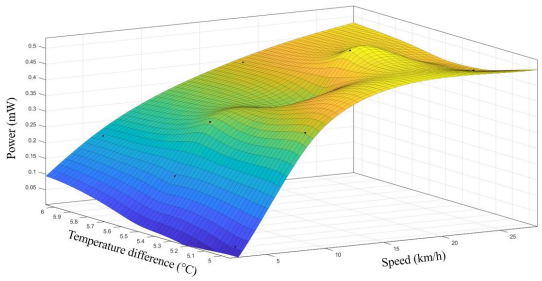


Fig. 11. Combined performance of the Piezo-Thermoelectric system: Power output as a function of vehicle speed and temperature difference.

Results indicate that generated power is a function of both vehicle speed and temperature difference, showing a synergistic increase in overall energy production. A maximum power output of 0.5 mW was achieved with the series-connected hybrid system, demonstrating the power density achieved under tested conditions.

Using polynomial fitting in MATLAB, an empirical relationship was established:

$$z = 0.0148x + 0.0357y - 0.0713 \tag{1}$$

Where z, x, and y represent output power (W), temperature difference (ΔT in °C), and vehicle speed (km/h), respectively. The R^2 and RMSE were 0.75 and 0.08, demonstrating a satisfactory correlation. Scaling analysis indicates that $12,500$ devices distributed over a 1 km road section could yield $\mathbf{2.5}$ kWh per day under specific conditions (110 km/h, ΔT of 20°C).

The present findings align with established literature [4], [8], confirming that traffic volume and vehicle weight significantly influence power output, suggesting installation on high-traffic, sun-exposed roads maximizes energy harvested. The hybrid configuration provides a tangible improvement in output power over individual systems, consistent with Seung-Bum *et al.* [7].

Overall efficiency remains modest due to intrinsic energy losses, frequency mismatch limiting piezoelectric conversion, and the low temperature gradient constraining thermoelectric performance. Improvements in structural design, frequency tuning, and thermoelectric materials are necessary to enhance overall efficiency. Optimization could yield a 26% increase in output power, consistent with findings by Seung-Bum *et al.* [7].

IV. Conclusion

Addressing global climate change, this research successfully designed and implemented a system for harvesting electrical energy from roads.

The hybrid device integrates KPGS100 piezoelectric transducers and $TEC1-12706$ Peltier modules. Maximum subsystem outputs were 2 V (7.21 Hz) and 0.87 V ($\Delta T = 9°C$). A maximum power output of 0.5 mW was achieved in the series configuration. Extrapolation indicates a 1 km road section could produce 2.5 kWh per day under specific conditions, confirming the system's potential for road energy recovery.

The developed hybrid device presents a viable road energy recovery system. Future work will focus on enhancing power density through the integration of power-boosting circuits and material optimization. Copper will be explored in the thermoelectric subsystem for improved heat transfer, and phase change materials/aerogels will be investigated to maintain a lower cold-side temperature and reduce thermal losses.

To improve efficiency, plans include designing a transducer with a resonance frequency between 7 and 15 Hz, addressing the current transducer's limitation.

Finally, studying the system's mechanical reliability and resistivity under cyclic loads and thermal variations is necessary. Fatigue and multi-season trials will be required to validate long-term robustness.

Acknowledgment

This work resulted from collaboration between the University of Lorraine, France; the Higher Institute of Technology of Antananarivo (IST-T), Madagascar; and the Higher Polytechnic School of Antananarivo (ESPA), Madagascar. The research was carried out at the Research Laboratory of Material, Process, and Civil Engineering (LRMPGC), Madagascar. Financial support from the LERMAB laboratory at the University of Lorraine is gratefully acknowledged.

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Signal Time-Advance Measurement with LP-NGD Circuit

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***Abstract*—This paper investigates on the time-advance test method of arbitrary waveform signal generated by a low-pass (LP) type negative group delay (NGD) circuit. The considered active topology is constituted by RL-network circuit. The design theory of LP-NGD function is recalled for the basic comprehension by expressing the NGD value at very low frequency and the NGD cut-off frequency. The LP-NGD circuit design methodology including the design equations enabling to choose the resistors and inductor constituting components of the proof-of-concept from the targeted time-advance specifications is shortly addressed. The proof-of-concept implemented as a printed circuit board (PCB) prototype is designed by considering the desired time-advance of about -300 ns. Frequency domain simulations confirm the relevance of the LP-NGD theory. After the prototype description, the experimental setup is explained. Despite the noise effect, measured time-advances of about -255 ns in good agreement with simulation were observed. Potential applications of LP-NGD circuit are proposed.**

Keywords—negative group delay (NGD), RL-network, measurement method, frequency domain analysis, time-advance

I. INTRODUCTION

Over the age, the history of engineering science progresses naturally with emergency of successive new ideas upsetting the common and familiar ones. Behind the wonderful history, the experimental works constitute the decisive steps to bring the uncommon idea to the application area as a popular knowledge. Today, this historical process still happens when we have a close look about the sign of time status. Therefore, the study of negative delay attracts a particular attention of researchers notably in the electronic engineering. In 1980s, after theoretical intuitive postulate, the negative group delay (NGD) phenomenon was physically observed by experimentation with negative group velocity media in the optical area [1]. The existence and characterization of abnormal NGD function have attracted the attention of electronic engineering researchers since 1990s [2]. Thanks to the equivalence of transfer function (TF), NGD electronic topologies constituted by classical components as resistor, inductor, capacitor and operational amplifier were identified [2]. The particularity of NGD function is its possibility to propagate voltage signals with output detected in time-advance of its input [2-7]. Despite its counterintuitive behavior, it was emphasized that the NGD function does not contradict the causality [2]. However, so far, due to the plenty diversity of electronic topologies enabling to verify the possibility to demonstrate it, the meaning of NGD phenomenon remains an open question for non-specialist researchers. For this reason, a fundamental basic NGD circuit theory inspired from the filter was initiated in the mid-2010s [3]. Even the topological structure can be exactly the same, the main difference between the NGD and filter circuit theory is the main function to be characterized. The filter circuits are essentially specified from the TF magnitude frequency response. However, the NGD circuits are elaborated from the group delay (GD) response. There may have confusion for non-specialists because the same electronic circuit topology can behave as both filter and NGD function. It was pointed out from the developed fundamental theory that all NGD circuits can be innovatively identified as either low-pass (LP) or high-pass (HP) or bandpass (BP) or stop-band (SB) or all-pass (AP) type topologies [4]. The present research work proposes a close look on the experimentation of LP type NGD function [4-7]. The LP-NGD topology under study is constituted by an RC-network [5-6]. We would like to popularize the possibility to analyze, characterize, study and experiment this LP type NGD topology. To do this, an experimental demonstration of negative time ($t<0$) effect like the RC-network based prototype considered in [8] constitutes the main focus of the present work but by using an RL-network [9-10] based LP-NGD circuit. The paper is mainly organized in three main sections:

- Section II describes the theory of the LP-NGD circuit constituted by considering on the topology of RL-network. The theoretical investigation is elaborated by means of TF analysis.

- Section III examines the experimental work from the LP-NGD RL-network based proof-of-concept and prototype dedicated to the $t<0$ metrology. After discussion on the frequency domain simulation results, the time-domain outcomes will be analyzed to validate the time-advance concept.
- And Section IV is the final conclusion by point out some potential applications of LP-NGD electronic function [11-16].

II. LP-NGD Circuit Theory with RL-Network Cell

A recall on the basic circuit theory necessary to understand the LP-NGD circuit design is elaborated in this section. Then, the design methodology of LP-NGD structure constituted by RL-network in function of the targeted time-advance $t_a<0$ is described.

A. LP-NGD Function Signature

The theory of electrical and electronic circuits exhibiting $t<0$ behavior is explored under the same approach as the classical one (filters, amplifier, oscillator, energy converter …). Based on the circuit and system theory, the linear time-invariant (LTI) TF approach represents the most pragmatic strategy to build an electronic engineering analytical investigation. We proceed under the same tradition for the present research work. Doing this, let represent the LP-NGD function as a two-port black box interacting with a t-time-dependent input signal $x(t)$ to generate the corresponding output $y(t)$ as illustrated in Fig. 1(a).

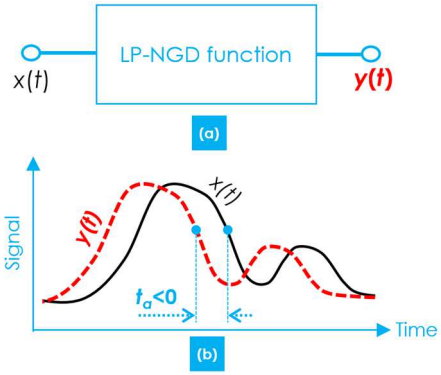


Fig. 1. Two-port system (a) black box and (b) LP-NGD ideal response.

The analytical expression of $t<0$ concept studied in this work can be understood from the input and output signal transient relationship:

$$y(t) \approx x(t + t_a) . \qquad (1)$$

by taking $t_a<0$ as the time-advance parameter which represents a delay with negative sign. To study this intriguing function in the frequency domain, the frequency variable is denoted by f. The LP-NGD TF $T(j2\pi f)$ can be expressed via the Fourier transform of input $X(j2\pi f)$ and output $Y(j2\pi f)$ which is traditionally expressed by the transmittance:

$$T(2j\pi f) = Y(2j\pi f) / X(2j\pi f) . \qquad (2)$$

The LP-NGD function basic definitions yielding from this TF are described in the next subsection.

B. Specifications of LP-NGD Function

To materialize the LP-NGD function, we need an electrical circuit in order to make us to be able to intelligibly experiment the $t<0$ effect. Doing this, one considers the RC-network based LP-NGD topology having input $x(t)$ and generating output $y(t)$ represented in Fig. 2.

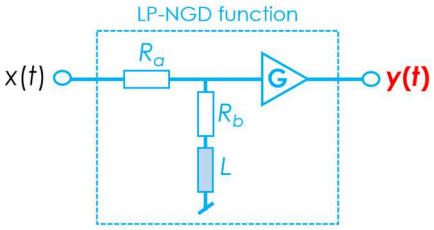


Fig. 2. Topology of RL-network based LP-NGD function.

The LTI topology under study is constituted by a series resistor R_a and R_bL-shunt passive network to an active cell with gain G. The LP-NGD analysis of this topology consists in calculating the frequency responses following the circuit and system theory traditional approach.

C. LP-NGD Function Frequency Response

The main parameters of the frequency domain analysis of LP-NGD function are the magnitude and phase which are classically expressed as:

$$T(f) = |T(2j\pi f)| = \sqrt{real[T(2j\pi f)]^2 + imaginary[T(2j\pi f)]^2} \qquad (3)$$

$$\varphi(f) = \arg[T(2j\pi f)] = \arctan\left\{\frac{imaginary[T(2j\pi f)]}{real[T(2j\pi f)]}\right\} . \qquad (4)$$

It yields from the latter one that the corresponding GD parameter is defined by:

$$GD(f) = \frac{1}{2\pi} \times \frac{-\partial\varphi(f)}{\partial f} . \qquad (5)$$

To reach the time-advance expressed in equation (1), as depicted in Fig. 3(a), we should have a magnitude at low frequency for example, approximately close to unity:

$$T(f \approx 0) \approx 1 . \qquad (6)$$

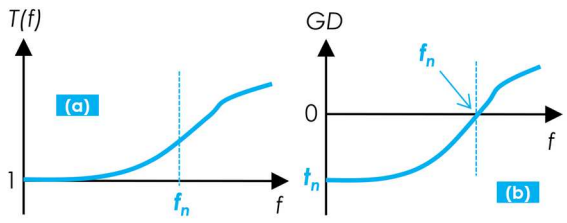


Fig. 3. Typical behaviors of LP-NGD (a) magnitude and (b) GD frequency responses.

It is more importantly to keep in mind that the LP-NGD function specifications are defined by:

- As illustrated in Fig. 3(b), the GD value t_n at very low frequencies (f≈0) which must be negative:

$$t_n = GD(f \approx 0) < 0 . \quad (7)$$

- And the NGD value f_n which is the root of equation:

$$GD(f = f_n) = 0 . \quad (8)$$

Meanwhile, the LP-NGD function can be also analytically represented by the GD diagram drawn in Fig. 3(b) is spectrally negative:

$$\begin{cases} GD(f < f_n) < 0 \\ GD(f > f_n) > 0 \end{cases} . \quad (9)$$

The exploitation of these two last equations permits to construct the LP-NGD theory of the topology introduced in Fig. 2.

D. LP-NGD Analysis of the Considered RL-Cell

The passive cell is composed of a series resistor R_a shunted at the output by a series RL-network with parameters R_b and L. The TF between x and y versus the passive cell parameters is written as:

$$T_p(s) = Y(s) / X(s) = (R_b + Ls) / (R_a + R_b + Ls) . \quad (10)$$

The frequency domain derivation of magnitude and GD enables to express the considered LP-NGD cell values at very low frequencies (LFs). The DC attenuation of the LP-NGD passive cell defined as:

$$\alpha = T_p(f \approx 0) < 1 . \quad (11)$$

in function of the parameters R_a, R_b and L is given by:

$$\alpha = R_b / (R_a + R_b) . \quad (12)$$

The GD expressed in equation (1) at very LFs (f≈0) defined in equation (7) is equal to:

$$t_n = -R_a L / [R_b (R_a + R_b)] . \quad (13)$$

Moreover, the LP-NGD cut-off frequency defined as the root of equation (8) is expressed as:

$$f_n = \sqrt{R_b (R_a + R_b)} / (2\pi L) . \quad (14)$$

Based on these analytical characterization expressions, design formulas of resistor and inductor components are established in the following subsection.

E. Design Equations of the RL-Network Based LP-NGD Function

The concrete LP-NGD circuit diagram adopted in this work is represented in Fig. 4. It is terminated by a non-inverter amplifier with an operational amplifier associated to resistors R_f and R_d. The LP-NGD design aims to determine the component values of resistors R_a, R_b and inductor L as functions of the amplifier gain G>1 constituting the topology proposed in Fig. 4.

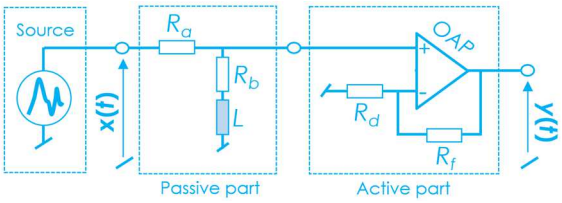


Fig. 4. LP-NGD active circuit to be explored in the present work.

To do this, for the case of unity DC gain (T_0=1) NGD circuit, the input parameter of the design equation is the desired time-advance t_n<0. As a matter of fact, the LP-NGD synthesis equations are formulated as:

$$R_a = -(G-1)^2 L / (t_n G) \quad (15)$$

$$R_b = R_a / (G-1) \quad (16)$$

by fixing L. When assuming the active part resistors as $R_d/R_f \approx R_a/R_b$, the NGD cut-off frequency formulated in equation (8) is simplified as:

$$f_n = (1-G) / (2\pi t_n \sqrt{G}) \quad (17)$$

This last term is always positive because we are dealing with t_n<0. It is noteworthy that to experiment t<0, the bandwidth of input signal spectrum must belong to the base band spectrum f<f_n. This condition is also linked to the causality effect. It means that maximum bandwidth of considered input signal must be inversely proportional to the desired time-advance.

F. LP-NGD Circuit Design Methodology

The design phases of LP-NGD circuit are generally similar to classical electronic system functions, such as filters, phase shifters, oscillators, and amplifiers. However, in this study, only the targeted specifications, particularly the NGD parameters, differ. Ensuring that non-specialist system designers and manufacturers are familiar with the LP-NGD circuit remains one of the biggest challenges NGD researchers face today. The six basic steps for the design method of the LP-NGD circuit shown in Fig. 4 are summarized in Table I.

TABLE I. DESIGN METHOD STEPS OF LP-NGD RL-NETWORK BASED CIRCUIT

Step	Action
Step1	Input parameter definition: - desired time-advance - available resistor and inductor component value limits - then, considered test signal bandwidth and amplitude
Step2	Choice of LP-NGD topology parameters R_a, L_b, L and G by using for example the design formulas
Step3	Design of the LP-NGD circuit schematic in the available tool
Step4	Verification of the LP-NGD specifications with frequency domain simulation of GD and magnitude
Step5	Validation of signal advance by comparison of time-domain simulation and measurement in function of the considered input signals
Step6	LP-NGD characterization by comparing the input and output signal integrity

To verify the feasibility of the established LP-NGD circuit theory, a proof-of-concept design is described in the following section. To do this, after frequency domain analysis, the verification results from the time domain experimentation will also be discussed.

III. Experimental Study of RL-Network Based LP-NGD Prototype

This section focuses on the feasibility study of the LP-NGD function by experimentation of $t<0$ effect with a printed circuit board (PCB) prototype.

A. LP-NGD Prototype Description

The LP-NGD circuit proof-of-concept considered in this work is targeted to operate with t_a and amplifier gain G given in Table II. After optimization and choice of nominal values, we utilized the components R_a, R_b and L having +/-5% tolerances. Therefore, the LP-NGD cut-off frequency expressed in equation (17) is equal to f_n. The targeted design specifications and the proof-of-concept parameters are indicated in Table II.

TABLE II. Specifications of the LP-NGD Circuit Proof-of-Concepts

Objective	Nature	Name	Value
Targeted specifications	Time-advance	t_a	-316 ns
	Amplifier gain	G	10 dB
LP-NGD circuit parameters	Resistor	R_a	500 Ω
		R_b	220 Ω
	Inductor	L	100 µH
NGD cut-off frequency	Frequency	f_n	63.3 MHz
Amplifier	Resistor	R_f	2.2 kΩ
		R_d	1 kΩ
	Op. Amp.	-	TL081

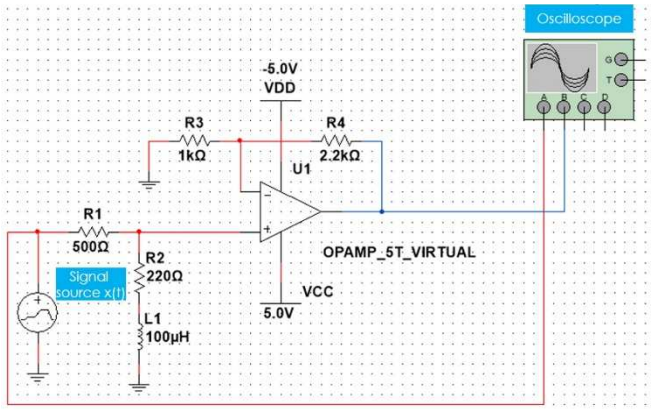


Fig. 5. MULTISIM® schematic design of LP-NGD circuit.

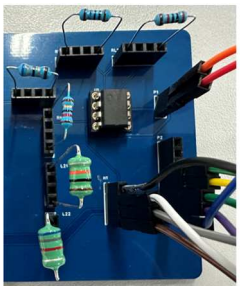


Fig. 6. Photo of the LP-NGD PCB prototype.

The proof-of-concept of LP-NGD active prototype was designed in the SPICE environment of MULTISIM® as proposed in Fig. 5. The proof-of-concept and the test circuit prototype were fed by DC power supply V_{CC}=5 V_{DC} and V_{DD}=-V_{CC}. The corresponding prototype was designed and implemented as PCB seen in Fig. 6. The validation results in the time domain are discussed in the next subsection.

B. NGD Frequency Results

Before the time-domain analysis of the tested prototype, a frequency domain analysis was performed in the range delimited by f_{min}=1 kHz and f_{max}=100 MHz. The frequency domain analysis enables to highlight the NGD response behavior and the relevance of the circuit theory developed in the previous section. The theoretical calculation was carried out by means of the TF expressed in equation (10) by using the magnitude and GD defined in equation (3) and equation (5), respectively. The parameters of the considered proof-of-concept circuit are addressed in Table II.

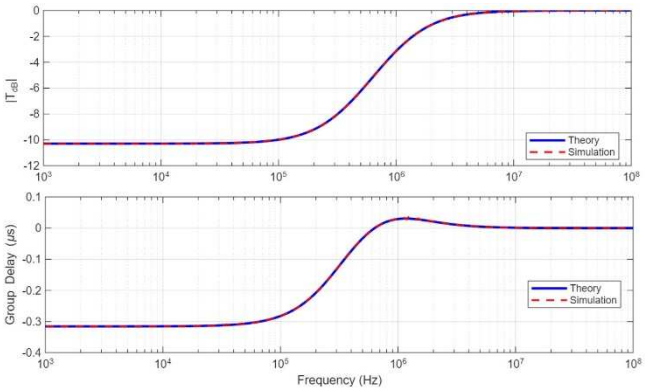


Fig. 7. Frequency domain result magnitude (in top) and GD (in bottom) of the LP-NGD circuit proof-of-concept.

The frequency domain analysis is based on the comparison between the calculated and MULTSIM AC simulated magnitude and GD as plotted in top and in bottom of Fig. 7, respectively. We can see that the theory (solid blue curve) and simulation (dashed red curve) results are in excellent agreement in the considered frequency band. As can be seen in Fig. 7, an NGD behavior is obtained with GD value about -310 ns from very low frequencies up to NGD cut-off frequency f_n=63 MHz. To perform the LP-NGD metrology, the experimental setup of the time-domain measurement is described in the next subsection.

C. $t<0$ Experimental Setup

The present $t<0$ metrology was realized by simultaneous visualization of signals representing the input x and the output y of LP-NGD circuit prototype.

The performed experimentation is illustrated by the synoptic diagram illustrated in Fig. 8. During the test, the LP-NGD active circuit prototype was fed by +/-5 V_{DC} power supply. The references of the test instruments used during the experimentation are indicated in Table III. As photographed in Fig. 9, the experimental test is based on the input x provided from the arbitrary waveform signal generator with the visualization of the input and output signals by a digital oscilloscope.

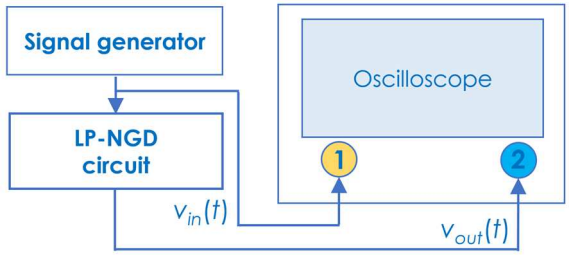


Fig. 8. Synoptic diagram of negative time testing with LP-NGD circuit.

TABLE III. TEST INSTRUMENT SPECIFICATIONS

Instrument	Reference	Specifications
Digital oscilloscope	NDS102	Precision: 12 bits Bandwidth: 100-MHz Sampling rate: 1 GSa/s
Signal generator	Siglent® SDG1062X	Bandwidth: 60-MHz Sampling rate: 150 MSa/s

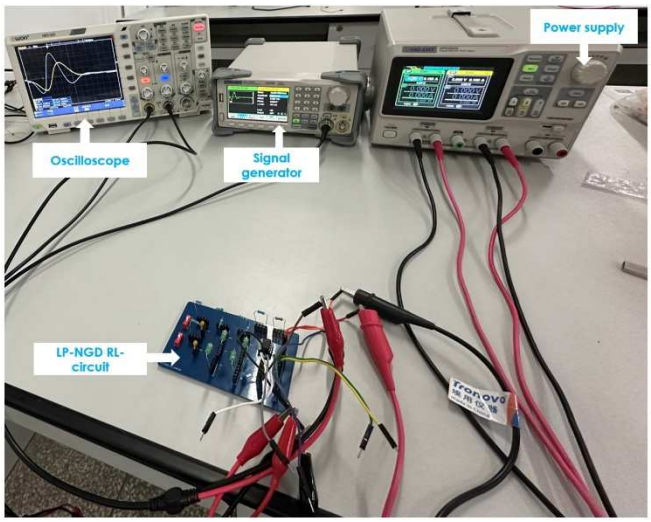


Fig. 9. Photo of negative time testing with LP-NGD circuit prototype shown in Fig. 6.

The performed LP-NGD metrology of the counterintuitive effect $t<0$ is confirmed by the results discussed in the next subsection.

D. Discussion on t<0 Validation Results

To highlight the relevant of the intriguing effect $t<0$ metrology, two-different input signals x_1 and x_2 having Gaussian pulse and arbitrary waveforms are considered as seen in Figs. 10 and in Figs. 11, respectively. These test signals were chosen with time duration t_{max}=4.35 µs. The experimentation was done by controlling the arbitrary wave form signal generator with CSV-format files containing the date of two-different input signals x_1 and x_2. The comparisons between time-domain results of x_1 from the MULTISIM® simulation with the circuit designed Fig. 5 and measurement test prototype photographed in Fig. 6 are plotted in Figs. 10. Moreover, the time domain validation results with arbitrary waveform input x_2 can be seen in Figs. 11. The time-domain experimental results were performed with input signals $x_{1,2}$ plotted in black solid curves.

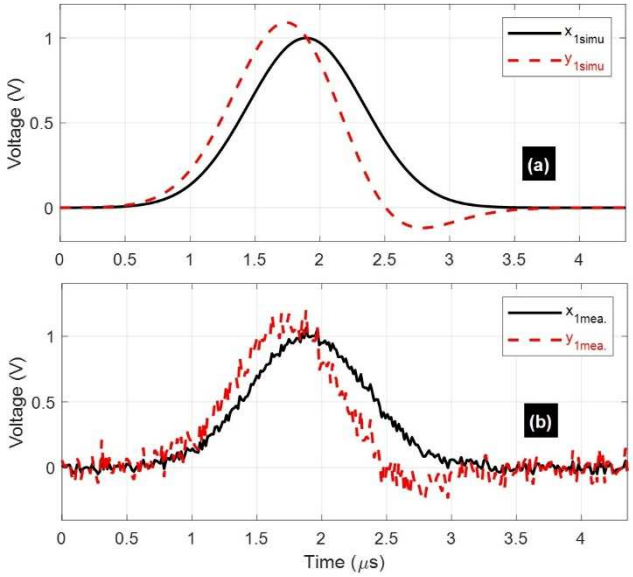


Fig. 10. Time-domain responses of (a) simulated and (b) measured signal x_1.

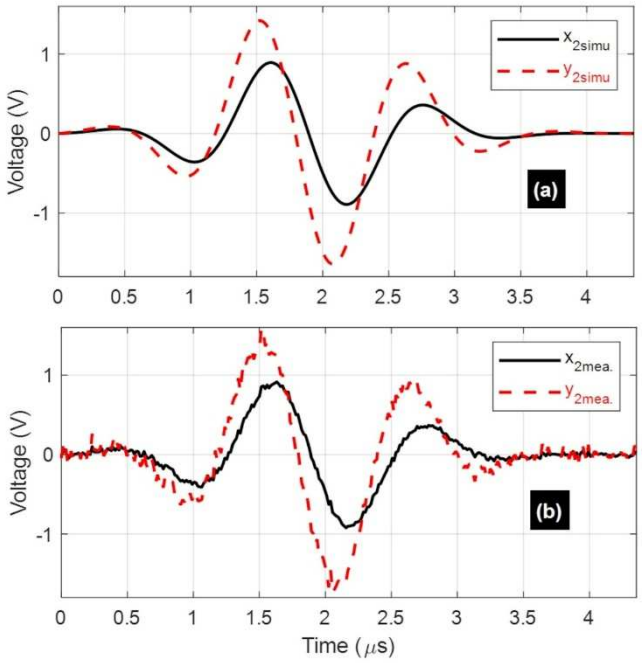


Fig. 11. Time-domain responses of (a) simulated and (b) measured signal x_2.

The output signals $y_{1,2}$ in apparent advance of input ones $x_{1,2}$ without violating the causality are plotted in red dashed curves. We can observe from Figs. 10 and Figs. 11 that the simulated and measured results are in good correlation. As expected, the output signals plotted in red dashed curves present raising and falling edges in

time-advance corresponding to (t<0) effect. The transient outputs approximately expressed by:

$$\begin{cases} y_1(t) \approx x_1(t+t_{a1}) \\ y_2(t) \approx x_2(t+t_{a2}) \end{cases} \quad (18)$$

with t_{a1}=t_{a2}≈-255 ns are observed.

IV. Conclusion

An investigation on the experimentation of negative time metrology with LP-NGD topology is proposed in the present work. The design equation of LP-NGD circuit by using an RL-network topology is recalled. The t<0 effect is innovatively studies with NGD circuit. The fundamental LP-NGD circuit theory enabling to explore the counterintuitive t<0 effect is developed. The basic specifications of the LP-NGD function are defined. Then, a concrete LP-NGD topology is studied from the TF examination. The mathematical demonstration showing why the circuit emanates the t<0 effect is established. The design equations of LP-NGD circuit resistor and inductor in function of the desired value of time-advance and the amplifier gain are formulated.

The metrology is based on the LP-NGD circuit experimentation by using an RL-network based topology. The NGD test technique is described. The simulation and measurement results confirm the LP-NGD effect. The t<0 effect of about -255 ns is observed.

The time-advance property related to LP-NGD function can be exploited in term of prediction for very interesting potential applications especially in sensor [11-16], industrial, robotic, environmental, biologic and health medical areas where mostly using slow signals. The innovative idea can be understood with equation (1). By supposing, for example, we have LP-NGD circuit with any time-advance as t_a=-1 minute, the output $y(t)$=$x(t$-1 minute) represents the information about input with 1 minute in advance. Nowadays, according to recent research work results, the LP-NGD function application idea was validated with:

- LP-NGD analog circuit prototypes for:
  - Reconstruction of sensor signal distorted by unwanted perturbations [11],
  - Anticipating actuator with arbitrary mechanical actioning [12],
  - And temporally advanced detection of physiological medical signals [13],
- LP-NGD digital circuit prototypes for:
  - Luminosity sensing prediction [14],
  - CO2 gas concentration prediction in real-time [15],
  - And real-time prediction of greenhouse temperature with a LP-NGD digital circuit [16].

Acknowledgment

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Data-Driven Diagnosis of Building-Envelope Thermal Behavior in Real Time

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Abstract*— This work presents a data-driven methodology to identify the thermo-physical properties of building envelope components and to perform real-time diagnosis under realistic, time-varying boundary conditions. The approach combines a dedicated state-space heat-transfer model with a non-dimensional reformulation that replaces classical RC coefficients by compact parameter sets $(\boldsymbol{p},\boldsymbol{q})$ that separate internal conduction from surface exchange. Treating identification as an inverse problem, we adapt Dynamic Mode Decomposition with control (DMDc) to estimate discrete-time state and input matrices directly from temperature and heat-flux snapshots. The resulting low-order models are fast to identify, suitable for in-situ characterization and model calibration of single- and multi-layer walls and remain physically interpretable. On top of the identified model, we define two complementary diagnostic indicators: (i) a residual-based score that tracks persistent inconsistencies between model predictions and measurements, and (ii) a parameter-drift score that exploits the $(\boldsymbol{p},\boldsymbol{q})$ structure to distinguish internal wall alterations from changes in boundary exchange. The framework is assessed on a single-wall assembly under dynamic climatic excitations, using both numerically simulated data and experimental measurements. Results show that the proposed methodology accurately reconstructs surface temperatures and heat fluxes and yields compact state-space models that are well adapted to real-time envelope monitoring, model calibration, and energy-aware operation of buildings.

Keywords*— Building envelope, Thermal characterization, Data-driven system identification, Dynamic Mode Decomposition, DMDc, drift parameter.

I. INTRODUCTION

In the current energy context, marked by growing awareness of the challenges related to decarbonizing the building sector, European and French policy continues to implement ambitious new regulations. European buildings are expected to reduce their greenhouse gas emissions by 90% by 2050, thus requiring a larger number of nearly zero-energy buildings (nZEB).

This regulation embodies the willingness to reduce the building sector's carbon footprint and to encourage innovation in the energy design of new constructions. To achieve zero net Carbon emissions, energy conservation measures should be adopted in existing buildings to reduce their energy demand. These measures are understood as any type of modification made to a building to improve its energy performance [1], [2], [3], [4],. The envelope is closely linked to energy demand; therefore, envelope elements are generally the main target for intervention. The effectiveness of applying energy conservation measures to the building envelope has been extensively studied, mainly analyzing energy improvements for buildings located in cold climate zones.

Accurate characterization of building envelopes plays a key role in this process. It is essential both for the retrofit of existing dwellings and the design of new constructions, aiming to improve energy efficiency and thermal comfort. In this regard, several approaches have been developed, distinguishing primarily between in situ methods, carried out under real conditions, and laboratory methods, which are more controlled but potentially less representative of in situ complexity. Among these, the hot-box technique allows precise identification of heat exchange fluxes, while the enclosure method offers an effective alternative for assessing the thermal performance of materials. In addition, approaches such as that proposed by Juricic et al.[5] enrich the diagnosis of existing buildings, contributing to an overall understanding of thermal challenges.

Data-driven processing enables more precise identification and thermal characterization of building components. Identifying the thermo-physical properties of building envelopes through modeling emerges as an effective strategy for real-time analysis. The thermal performance of walls is deficient due to their design and the aging of materials. Improving the thermal performance of walls would reduce building heat losses by 10 to 45%. Consequently, energy consumption would also decrease. Three main types of models can be identified in the literature: deterministic or "white-box" models, based on explicit physical principles; non-deterministic or "black-box" models, which rely on statistical and machine learning methods to establish correlations from large datasets; and hybrid models, which combine these approaches to optimize the accuracy and relevance of predictions.

Thermal modeling of buildings stands at the heart of this approach, offering crucial tools for optimizing energy performance from the design phase through to operation. It is in this context that our contribution introduces the Dynamic Mode Decomposition (DMD) technique[6], [7]. This method, emerging in the field of thermal characterization of buildings, promises to offer a finer understanding of the dynamic phenomena at play, enabling precise, real-time analysis of the thermal behavior of envelopes. The DMD approach appears particularly promising for overcoming certain limitations of traditional methods, opening new perspectives for energy optimization of buildings in an era marked by climate urgency and sustainability imperatives.

In this work, diagnosis is used in the sense of thermal state assessment: the identified non-dimensional parameters (p, q) act as interpretable state indicators, and we monitor model–data **residuals** and **parameter drift** to flag persistent deviations from nominal behavior such as insulation degradation, sensor fault or altered surface exchange.

II. Dynamic Mode Decomposition

Dynamic Mode Decomposition (DMD) is a data-driven method that identifies low-rank spatio-temporal structures "modes" directly from high-dimensional snapshots collected numerically or experimentally. Originally introduced by Schmid [6] and subsequently popularized across disciplines [7], [8], DMD approximates the evolution of the state by a linear map acting on successive snapshots.

The DMD algorithm for the building wall to estimate the temperatures is defined as following:

- **We collect state and input snapshots at uniform sampling:**

$$X = [\theta_1 \quad \cdots \quad \theta_{m-1}], X' = [\theta_2 \quad \cdots \quad \theta_m], U = [u_1 \quad \cdots \quad u_{m-1}], \Omega = \begin{bmatrix} X \\ U \end{bmatrix}.$$

- **Compute reduced SVDs $\Omega \approx \widetilde{U}\widetilde{\Sigma}\widetilde{V}^*$ (partition $\widetilde{U} = [U_1 \; U_2]$) and $X' \approx \widehat{U}\widehat{\Sigma}\widehat{V}^*$. The least-squares, projected operators are**

$$\tilde{A} = \widehat{U}^* X' \tilde{V} \tilde{\Sigma}^{-1} U_1^* \widehat{U}, \tilde{B} = \widehat{U}^* X' \tilde{V} \tilde{\Sigma}^{-1} U_2^*.$$

- **Eigen-decompose $\widetilde{A}W = W\Lambda$ and form full-state modes**

$$\Phi = X' \tilde{V} \tilde{\Sigma}^{-1} U_1^* \widehat{U} \, W.$$

- **Set $(A_d, B_d) = (\widetilde{A}, \widetilde{B})$; continuous recovery uses the matrix logarithm. Rank r is chosen by energy or cross-validation.**

III. Methodology

A. Modelling

The used model has been inspired from the earlier works [9], [10] . The method transforms the physical space into a mathematical, dimensionless form using a discrete version of equation (3). The characteristic time for the wall case is expressed as follows:

$$t_c = \frac{kL}{a(h_0 + h_L)} \tag{1}$$

where $a = \frac{k}{C}$ represents the thermal diffusivity, $C = \rho c$ denotes the thermal mass, L is the characteristic length, and $\sum h_{ext} = h_0 + h_L$ correspond to the external heat transfer coefficients by convection. By substituting the diffusivity term into equation (1), the expression for the characteristic time is obtained as follows:

$$t_c = C \frac{L}{\sum h_{ext}} \tag{2}$$

The obtained t_c in equation (3) can be extended to the local formula as follows.

$$t_c = \frac{C}{\sum U_{ext}} \tag{3}$$

The dimensionless states and parameters

- $\theta = (T - T_i)/(T_{max} - T_i)$: dimensionless temperature,
- $\tau = t/t_c$: dimensionless time,
- $\zeta = x/l$: dimensionless spatial coordinates,
- $\alpha = l^2/t_c$ thermal diffusivity,

:

where $\sum U_{ext}$ represents the external global heat transfer coefficient of the local thermal body. Applying dimensionless techniques to the simplified (1+time) D heat transfer equation. the dimensionless heat transfer equation with source terms is:

$$C\frac{\partial T}{\partial t} = U_{ein}(T_0 - T) - U_p(T - T_L) + S \tag{4}$$

$$\frac{\partial \theta}{\partial \tau} = q(\theta_0 - \theta) - p(\theta - \theta_L) + \text{ß}\bar{S} \tag{5}$$

where $q = \frac{U_{ein}}{\sum_i^N U_{ein} + \sum_i^N U_{eout}}$ and $p = \frac{U_p}{\sum_i^N U_{ein} + \sum_i^N U_{eout}}$ refer respectively to the named external inputs and proper parameters. $\bar{S} = \frac{S}{S_{max}}$, $\theta = \frac{T - T_{ref}}{T_{max} - T_{ref}}$, and $\tau = \frac{t}{t_c}$. The local formula for a linear model can be expressed by equation (6):

$$\frac{\partial \theta}{\partial \tau} = r\Delta\theta + \text{ß}\bar{S} \tag{6}$$

A state-space representation is used to describe heat transfer through the building envelope. The wall is modeled as an -state RC network; let $\theta(\tau) \in \mathbb{R}^n$ denote the internal node temperatures at continuous time τ. Boundary condition inputs are grouped in $u(\tau)$ (for example, outdoor air temperature θ_e, solar heat flux ϕ_s, and indoor setpoint/disturbances). The continuous-time dynamics follow from this framework.

$$\dot{\theta}(\tau) = A(r)\theta(\tau) + B_{u1}\bar{P}(\tau) + B_{w1}(r)\theta_e(\tau) + B_{w2}(\bar{s})\bar{\varphi}_s(\tau) \tag{7}$$

The dimensionless formulation for two nodes without internal gains and

$$\begin{pmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{pmatrix} = \begin{bmatrix} -(p_1 + q_1) & p_1 \\ p_2 & -(p_2 + q_2) \end{bmatrix} \begin{pmatrix} \theta_1 \\ \theta_2 \end{pmatrix} + \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix} \begin{pmatrix} \theta_{a1} \\ \theta_{a2} \end{pmatrix} \tag{8}$$

B. Characterised states

The characterized states are classified into two dimensionless parameters, q and p, which contains the global heat transfer coefficient and the convective transfer coefficient.

The $r(q, p)$ parameters of the matrices A fall into two groups: proper parameters $p = \frac{U_p}{\sum U_e}$, found in the upper triangular part, and external input parameters $q = \frac{U_{ein}}{\sum U_e}$, located in the lower triangular part. The algebraic model replaces the RC method with a single dimensionless impedance $r(q, p)$. The network can be viewed as a

substitutive impedance network (Fig. 1), since thermal balance at the nodes dynamically adapts to impedance changes and heat fluxes during the substitution process.

C. Real-time diagnostic indicators

We derive two simple indicators from the identified DMDc model (A_d, B_d) and the (p, q) parametrization.

- **Residual score: model–data consistency**

The residual score quantifies, at each step k, the mismatch between the observed output y_k such as surface temperature, heat flux in our case and the model prediction $\hat{y}_k = C\,\hat{\theta}_k + D\,u_k$ produced by the identified pair (A_d, B_d). The residual $r_k = y_k - \hat{y}_k$ aggregates in a single quantity all mechanisms that temporarily make the model inaccurate: sensor noise, unmodeled wind gusts, specular solar spikes, or slow parameter drift caused, for instance, by moisture uptake in the insulation. To emphasize persistent inconsistencies (not just isolated outliers), we accumulate a CUSUM-like score:

$$S_k = \lambda S_{k-1} + \frac{\|r_k\|_2}{\hat{\sigma}_\tau}, \qquad S_0 = 0, \qquad \lambda \in (0,1) \tag{9}$$

where $\hat{\sigma}_r$ is a robust dispersion estimate computed in nominal conditions. The forgetting factor λ controls the memory horizon: larger λ integrates evidence over longer periods and is sensitive to slow drifts; smaller λ reacts to abrupt changes. When $S_k > \tau_r$, we flag a sustained anomaly either a model-coherence failure (inputs outside the design envelope) or the onset of a physical drift, which we then seek to confirm using the parameter-based indicator below.

- **Parameter-drift score (p, q) : physical interpretation**

The second indicator leverages the non-dimensional parameterization to separate internal wall alterations (captured by p) from boundary-exchange changes (captured by q). From the state matrix A, we extract $(\hat{p}_k, \hat{q}_k)$ via the upper/lower-triangular mapping and track their **sliding deviation** relative to nominal references $(\bar{p}, \bar{q})$ obtained from a healthy period the DMDc algorithm:

$$D_{pq}(k) = \frac{\| \hat{p}_k - \bar{p} \|_2}{\| \bar{p} \|_2} + \frac{\| \hat{q}_k - \bar{q} \|_2}{\| \bar{q} \|_2}. \tag{10}$$

Where

$$p = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix}, \quad q = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$$

A threshold crossing $D_{pq}(k) > \tau_{pq}$ suggests a structural modification:

- Change in $p \rightarrow$ altered internal coupling and time constants (e.g., insulation wetting/settlement, thermal discontinuities, active thermal bridges). One typically observes shorter time constants (faster poles).
- Change in $q \rightarrow$ modified surface exchanges (such as wind-driven convection, surface condition/fouling, infiltration/ventilation effects).

This indicator is interpretable: it ties the alert to an actionable physical hypothesis (internal vs. boundary). As with S_k, set τ_{pq} from nominal data (high quantile), and consider adding hysteresis to avoid chatter near the threshold.

D. Diagnosis scenarios

To illustrate the behavior of the two indicators, four diagnosis scenarios are considered on the measured wall. In all cases, a "healthy" reference model is first identified directly from the experimental data using DMDc. This provides:

- Nominal discrete-time matrices $\mathrm{A}_d, \mathrm{B}_d$,
- A baseline residual score $S_r^{(0)}(k)$ and its threshold γ_r,
- and the nominal continuous-time parameters p_0, q_0 extracted from the matrix A .

Starting from this baseline, we emulate different types of degradations either by modifying the p–q parameters and re-simulating the wall response, or by corrupting the measurements, and we recompute $S_r(k)$ and S_p.

Scenario S0: healthy reference case

In scenario S0, the DMDc model identified from the first 6 h of data is used without modification. The model reproduces the inner and outer surface temperatures with low RMSE and high NSE, indicating an accurate description of the wall dynamics.

The residual score $S_r^{(0)}(k)$ exhibits a transient peak at the beginning of the sequence, attributed to a mismatch between the initial state of the model and the true thermal state of the wall, and then stabilizes within a narrow band. The threshold γ_r is computed from this reference sequence according to (X.6). As expected, the parameter–drift index is $S_p = 0$ in this scenario.

Scenario S1: internal wall degradation

In this scenario, a mild internal degradation of the wall is emulated by slightly increasing the internal coupling parameters:

$$p_1 = 1.03\,p_{1,0}, p_2 = 1.03\,p_{2,0},$$

while keeping the surface exchange parameters unchanged:

$$q_1 = q_{1,0}, q_2 = q_{2,0}.$$

The modified continuous-time matrix $\mathrm{A}_b(p, q)$ is then re-discretized, and the resulting $\mathrm{A}_d^{(1)}, \mathrm{B}_d^{(1)}$ are used to propagate the wall states under the same boundary conditions. This scenario mimics a small increase in effective conduction between the two surfaces, for example due to moisture accumulation or ageing of the insulation.

Under S1, the residual score $S_r^{(1)}(k)$ shows a clear departure from the healthy pattern and exceeds γ_r for a significant portion of the horizon, revealing a persistent inconsistency between the perturbed model and the measured temperatures. The parameter–drift index increases to a small but non-zero value (around $S_p \approx 0.03$ in the case study), dominated by the change in p. This "high S_r, moderate S_p with drift in p"

signature is consistent with a physical change in the internal wall behavior.

Scenario S2: change in surface heat-transfer conditions
In S2, the internal coupling is kept at its healthy value, $p_1 = p_{1,0}$, $p_2 = p_{2,0}$, and a change in surface heat-transfer conditions is emulated by modifying the exchange parameters:

$$q_1 = 1.05\, q_{1,0}, q_2 = 1.05\, q_{2,0}.$$

This reflects, for instance, a slight change in the convective environment on both sides of the wall (altered air movement, obstruction, or modified radiative exchange).
As in S1, the residual score $S_r^{(2)}(k)$departs from its healthy baseline and crosses $\gamma_r$more often than in S0, indicating that the modified p–q model no longer matches the experimental data. However, the growth of $S_r(k)$is less pronounced than in S1 due to the smaller impact of the change on the wall dynamics. The parameter–drift index increases to a value around $S_p \approx 0.02$, this time dominated by the drift in the q components. The combination of "high S_r, moderate $S_p$with drift in q" thus points towards a change in surface heat-transfer conditions rather than a degradation of the wall fabric.

Scenario S3: sensor fault on the outer surface
Finally, S3 represents a pure measurement fault. The healthy DMDc model from S0 is kept unchanged, so that $p = p_0$and $q = q_0$, but a bias of +1 °C is artificially added to the measured outer surface temperature. The inner surface measurement is left unchanged.
In this scenario, the residual score r(k) contains a nearly constant offset on the outer surface channel. Therefore, $S_r^{(3)}(k)$ rapidly increases and then remains at a level significantly above γ_r over the whole horizon, clearly indicating an anomaly. In contrast, the parameter–drift score remains essentially equal to zero, since the underlying matrices $\mathbf{A}, \mathbf{B}$ are identical to those of the healthy scenario. This "high S_r, low S_p" signature is characteristic of a sensor fault: the model structure remains valid, but the measurements are no longer coherent with the model predictions.

IV. Case Study

We tested the building wall for dynamic climatic conditions, simulated with suing direct finite difference numerical method.
Data-driven framework based on Dynamic Mode Decomposition with control (DMDc) to identify low-order state-space models of single-wall assemblies from temperature and boundary-condition snapshots. We combine a dimensionless (p, q)parameterization with rank-truncated DMDc to estimate discrete matrices (A_d, B_d) and recover continuous counterparts (A, B). The pipeline accommodates simulated datasets. Results show that the method yields compact, interpretable dynamics suitable for real-time forecasting and control, while requiring only routine sensing and minimal assumptions on the underlying physics. The approach is readily extensible to multi-layer walls settings through lifting and input design, offering a practical route to scalable envelope diagnostics and energy-aware operation.

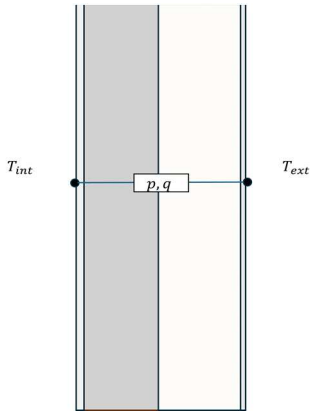


Figure 1: Multi-layer building envelope

The following assumptions are considered.

- Heat transfer in the absence of an internal heat generation source is governed and presented by Equation (8). This transfer occurs solely through diffusion within a heat transfer in the boundaries of the building wall, as illustrated in Figure 1-a.
- Heat transfer is assumed to be unidirectional (one-dimensional).
- Internal heat sources are neglected.
- The building wall is in contact with two distinct environmental media, denoted as (a_1) and (a_2), each characterized by average heat transfer coefficients h_1 and h_2, which are considered equivalent.
- The wall material is assumed to be isotropic and homogeneous.

V. Results and Discussion

A. Numerical simulation setup

The DMD algorithm yields thermo-physical parameters that we validate using a numerical simulation model. As shown in Fig. 1, the DMD inverse algorithm in 1D snapshots agree closely with the direct simulated model. The identified parameters (p,q) agree also with those obtained from the introduced in the simulation model.

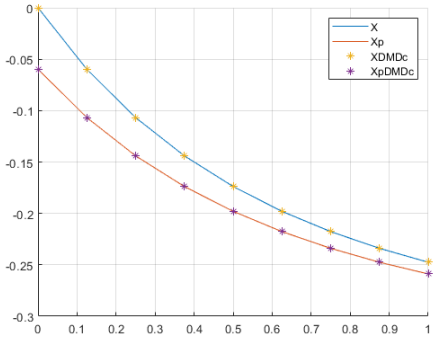


Figure 2: Simulated dimensionless external and internal temperatures vs. calculated temperature with DMDc-based identification algorithm

For direct simulation method, the discrete finite difference method has been applied and resolved for flexible resolution from low to high resolution, in time dynamics, compared with full order dynamic simulation, and stationary mode.

B. Dynamic mode decomposition identification results

The experimental data from the study of Shen et al.[11] has been used to and to identify the parameters. The schematic of the experimental setup used can be summarised by figure 1.

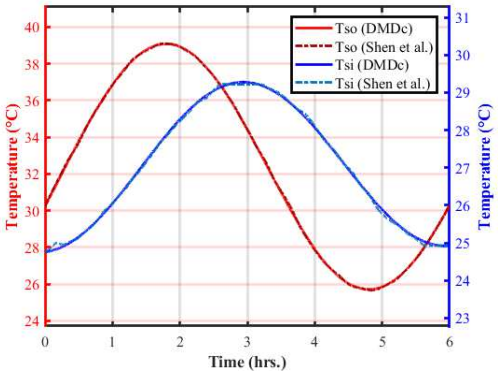


Figure 3: Comparison of DMDc Model Against Experimental Surface Temperatures of multi-layred wall from Shen et al. [11]

We fit (A_d, B_d)using DMDc with rank truncation. Accuracy is reported using RMSE on interior surface temperature and heat-flux, normalized by the dynamic range (NRMSE):

,

$$\mathrm{RMSE}(y) = \sqrt{\frac{1}{M}\sum_{k=1}^{M}(y_k - \hat{y}_k)^2}$$

$$\text{and NRMSE} = 1 - \frac{\| y - \hat{y} \|_2}{\| y - \bar{y}\,\mathbf{1} \|_2}$$

Residual-based indicator. Figure 4 shows the evolution of the residual score $S_r(k)$over the 6 h identification window for the healthy reference case. A pronounced peak, with $S_r$close to 4, is observed at the beginning of the sequence. This initial transient is attributed to the mismatch between the initial state of the DMDc model and the measured wall temperatures. After this short transient, the score oscillates between approximately 0.5 and 2, with occasional peaks in the range 2.5–3.5, but without any long-term drift. This behaviour indicates that the DMDc-based model remains globally consistent with the experimental data, and that the residuals, normalized by σ_r, remain of order one for most of the simulation.

The empirical distribution of $S_r(k)$in this healthy case is used to define a detection threshold γ_r. In the following, $\gamma_r$is chosen as a high quantile of $S_r(k)$, so that isolated peaks are tolerated while sustained increases above $\gamma_r$are interpreted as evidence of a model–data inconsistency or the onset of a physical change in the wall or its boundary conditions.

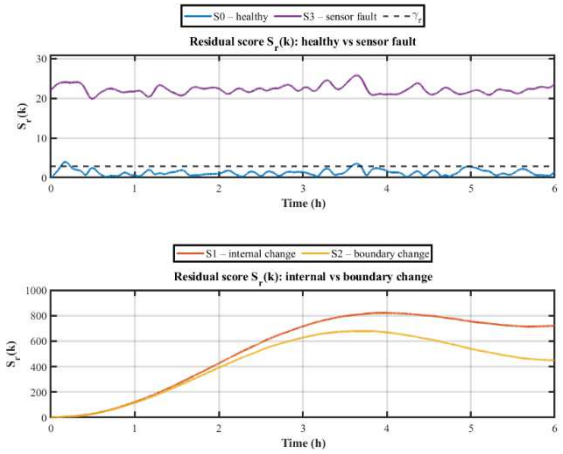


Figure 4: Residual-based indicator S_r(k) for all scenarios (S0–S3)

The parameter–drift index $S_p$is defined with respect to the DMDc–based healthy wall model (scenario S0). As expected, $S_p$remains zero for S0 and S3, since the latter only involves a biased temperature sensor and does not modify the dynamical model. When a small internal degradation is introduced (S1, +3% on the internal coupling coefficient), $S_p$increases to about 0.03. A slightly smaller drift, around 0.02, is obtained for a 5% change in the surface heat transfer parameter (S2). These values confirm that the parameter drift index is sensitive to physical changes in the wall model, while remaining insensitive to pure sensor faults.

CONCLUSION

This paper presented a real-time, data-driven framework for diagnosing the thermal behaviour of building envelopes under dynamic boundary conditions. The approach combines a compact two-state wall model, expressed in a non-dimensional p–q parameterization, with DMDc-based identification from temperature snapshots. This combination yields low-order, physically interpretable models that can be identified directly from routine sensing without requiring full knowledge of the wall's thermophysical properties.

The proposed residual-based score $S_r(k)$and parameter–drift index $S_p$provide complementary diagnostic information. The residual score quantifies the consistency between model predictions and measurements, and a simple threshold γ_r derived from healthy operation effectively detects persistent anomalies. The parameter–drift index exploits the p–q structure to distinguish between internal wall changes (affecting the coupling parameters p_1, p_2) and modifications of surface heat-transfer conditions (affecting q_1, q_2), while remaining insensitive to pure sensor faults.

The framework was evaluated on a single-wall assembly subjected to dynamic excitations, using both numerically simulated data and experimental measurements from a calibrated hot-box setup. The DMDc-identified model accurately reconstructed inner and outer surface temperatures, and the diagnostic indicators successfully differentiated between an internally degraded wall, altered boundary conditions, and a biased surface-temperature sensor. These results confirm the potential of the proposed method for real-time envelope monitoring, model calibration, and fault detection.

Future work will focus on extending the approach to multi-layer and multi-zone envelopes, incorporating additional

measurements such as heat flux and solar gains, and integrating the diagnostic indicators with model-predictive control strategies for energy-aware operation of buildings.
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Air Quality Prediction in Indoor Environments: A Review of Methods and Limitations

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***Abstract*—The majority of our lives are spent in indoor environments (buildings). Therefore, the quality of indoor air has a direct impact on our daily lives and health. Most studies concentrate on thermal and lighting comfort in buildings, and it seems there is a huge lack of work regarding the role of indoor air quality (IAQ) in building management systems and their impact on our daily lives. Within this paper, we conducted a structured review on this domain using PRISMA methodology and shed light on challenges, investigation shortages, and upcoming futures. Modelling IAQ permits us to extend our knowledge about the air quality of the place we are living in and, consequently, enhance the ambient conditions. It will allow deeper analysis in this area and, as a result, it will lead to involving IAQ parameters in control loops of building management systems to boost indoor ambient conditions. The results of the review illustrate that most of the focus in this area is limited to residential buildings and black box modeling approaches. It also indicates the modelling is narrow to specific indoor parameters like CO_2 concentration and a few types of particles.**

***Index Terms*—Air pollution; Air quality; Environmental monitoring; Forecasting; Machine learning; Sensor systems**

I. Introduction

Taking into account up to 90% of our time spent inside the building [1], and air quality in indoor spaces has a direct influence on our daily life, and more importantly, our health. Therefore, studying and optimizing indoor air quality (IAQ) is essential and it's becoming crucial and challenging. The IAQ factors, like Voltaic Organic Compounds (VOC), or particulate matters regularly exceed the threshold in indoor spaces recommended by the World Health Organization (WHO) [2]. Maintaining IAQ to a high standard, and while reducing the energy consumption by ventilation systems, is highly complex. Most of the studies in this area are focusing on thermal comfort and energy consumption, and there is a huge lack of work on IAQ factors.

Modelling IAQ factors, whether with classification, estimation or prediction approaches, permits to analysis of their behavior in indoor spaces and to detect their influential parameters. It finally leads to considering them in the control loop of ventilation systems in order to improve their functionalities in terms of energy consumption and standard IAQ.

In this domain, numerous studies have demonstrated the effectiveness of white-box approaches using Computational Fluid Dynamics (CFD) [3], black-box modeling using artificial intelligence algorithms like Long Short Term Memory (LSTM), Multi-layer perceptron (MLP) [4], or hybrid approaches (grey-box modeling) [5]. However, the main part of the investigations is limited to certain IAQ indicators like CO_2, VOC, and $PM_{2.5}$. It also illustrates as well that the main focus of each investigation is on a single family. It shows a lack of investigation into the impact of one on the other, and vice versa. And furthermore, there is a lack of a comprehensive study that focuses on the how different types models are used to estimate/predict different type of indoor pollutant, nor how the prediction horizon influences the performance of these models. To address this gap, this paper presents a systematic review of recent IAQ modeling developments, covering applications, modeling approaches, target buildings and sectors, pollutant types and objectives, prediction horizons, and available datasets.

II. Methodology for papers selection

The bibliographic search for the review was carried out using the PRISMA [6] (Preferred Reporting Items for Systematic Review and Meta-Analysis) methodology. This standardized method aims to make the rigor of the search transparent, so that the results of the review are easier to understand and evaluate.

The literature search was conducted to cover studies published from 2012 to 2025 on IAQ modelling. Two databases were used to search for articles: Scopus [7] and OpenAlex [8]. Fig. 1 presents the PRISMA flow for study selection, with four stages: identification, screening, eligibility, and final selection. In the identification stage, general keywords were used to retrieve papers on IAQ modelling, subsequent stages applied relevance-based filtering. At the end of this filtering, we selected a total of 34 papers.

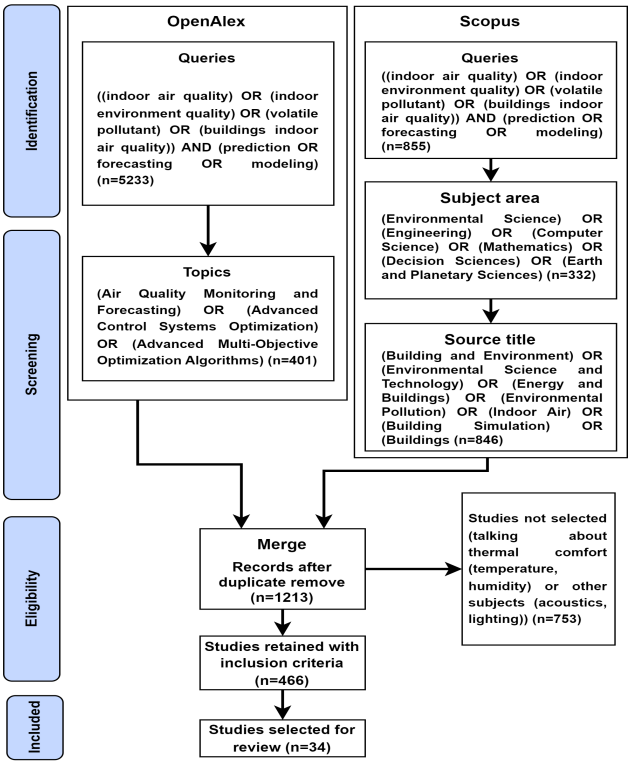


Fig. 1. PRISMA flow of studies included in the review.

III. Indoor air quality modeling technics

The studies were grouped into five types of environment: industrial, transportation, controlled environment, commercial and residential. Figure 2 shows the relationship between the environments and the type of model, pollutants, and application of the studies. For clarity, we define short ($\leq$ 30min), medium (30min–8h), and long ($\geq$ 8h) horizons. In the following subsections, different approaches for modelling are explained, which are principally white box and black box modelling.

A. White and grey box

The white-box models refer to all methods based on the use of physical laws, mathematical equations, or mechanical principles. Developing them is computationally expensive and time-consuming. While grey box models, adjusting physical models using data-driven methods, or vice versa.

Across commercial and laboratory environments, white-box models have been applied to predict pollutant dynamics under controlled conditions. In the work of [9], in test chambers, indoor particles' mass balance formulations showed strong agreement for $PM_{1,\ 2.5,\ \text{and}\ 10}$ concentrations, enabling real-time estimation of air exchange rates with normalized mean errors around 2–3%. In the work of [10], for a ventilated laboratory, CFD simulations using RANS with k-ω turbulence closure captured the emission kinetics of major VOCs such as acetone, hexanal, formaldehyde, and terpenes. The results show the consistency of the formaldehyde prediction. Although in the case of VOCs, for a longer horizon, the error increases. In a controlled chamber experiment, URANS SST k-ω simulations combined with stochastic Euler-Lagrange tracking are compared with turbulence models (RNG k-ϵ, realizable k-ϵ, SST k-ω) and highlighted significant variability in particle suspension, deposition, and near-wall turbulence levels, indicating the sensitivity of aerosol's predictions to turbulence modeling choices [11].

In residential contexts, white-box approaches have been used to link air quality and energy performance. In work of [12], a differential equation model coupled with MERV-13 filtration is used to predict $PM_{2.5}$ reduction efficiency and has shown improved efficiency for up to 60 minutes . In a penthouse apartment, building energy models calibrated with EnergyPlus and ELA (Effective Leakage Area) regulation achieved a better balance between thermal comfort, simulated energy consumption, and CO_2 concentrations, with $R^2 = 0.92$, surpassing conventional and reference infiltration models [13]. In the long term prediction, the simulation of work of [14] (up to 2100), seeks to model the evolution of several pollutants in the indoor environment. They used IAQCC model to simulate indoor particles based on climate change scenarios.

All studies conducted using white-box modelling methods generally make multi-family predictions or estimates, but focus heavily on $PM_{2.5}$ for particles and limonene in almost exclusively residential environments. Furthermore, the computational complexity of white boxes means that predictions focus mainly on the short term.

Research work of [15] uses grey-box modeling. The researcher used mass-balance aerosol concentration equations for predicting incidental nanoparticle and calibrated the model using an experimental dataset.

B. Black box models

Black box models are developed based on experimental data. They are efficient, and rapidly can be developed comparing to white box models.

Across the literature, ANN approaches are compared with tree-based and linear baselines. Short-to-medium horizons are common for operational decisions, and several studies focus on estimation without an explicit prediction step. In a residential building, a time-segmented MLR approach for $PM_{2.5}$ is applied, where hourly segmentation and regularization capture diurnal patterns without overfitting [16]. The use of CatBoost as a classifier has shown strong discrimination for $PM_{2.5}$ threshold events rather than predicting exact concentrations [17]. Multi-site hourly estimation indicates that Random Forest (RF) has shown better performance accuracy compared to linear baselines when data from offices, primary and secondary schools, kindergartens, shopping malls, and restaurants are combined, showing the benefit of nonlinear models under mixed-use variability [18]. Similarly, operating-room experiments add position-sensitive, submicron prediction, and lack of accuracy of CFD-based simulations in the dynamic environments, an experimental control and model choice is proposed and shown that these should be aligned in critical environments

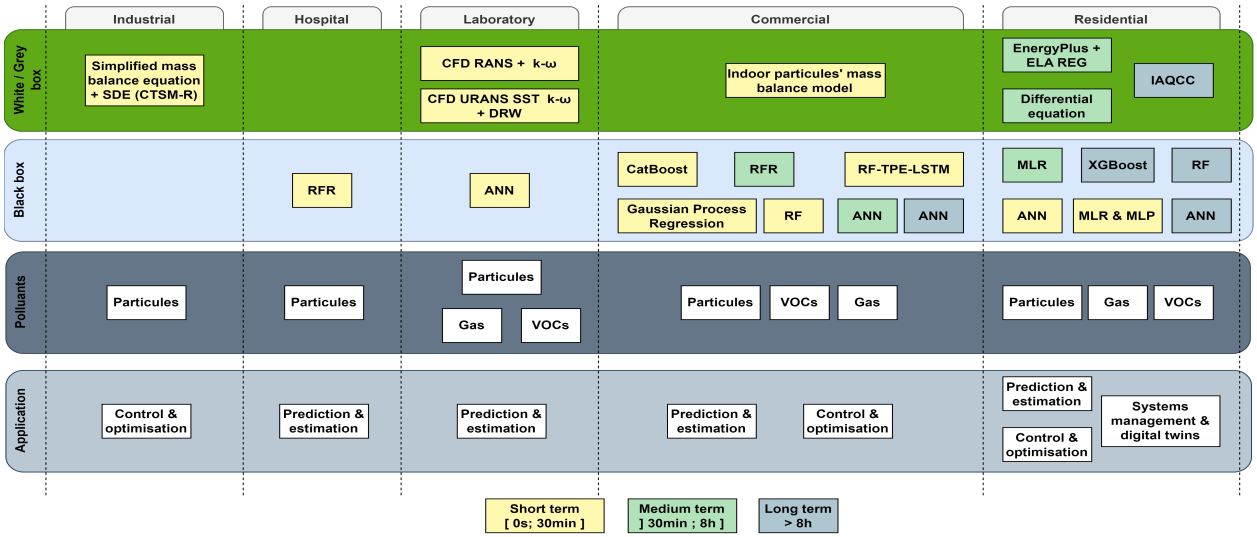


Fig. 2. Summary of modeling methods considering the objective, time horizon, and environment.

[19]. The study also showed how different ML and DL-based algorithms performed for different positions. In addition to generic PM, bioaerosol estimation from common IAQ sensors suggests that learned surrogates can substitute for fluorescence instruments at short-medium term horizons [20].

In university classrooms, cleaner-air operation must balance IAQ and energy. With the objective of keeping $PM_{2.5}$ below a target under changing occupancy, a daily-retrained ANN is integrated in an MPC controller and it showed that IAQ is maintained below the threshold while reducing energy use relative to a rule based controller [21]. In similar school environment where CO_2 predictions were used to decide the lessons and ventilation windows. In this regard, a comparative study conducted showed that modern deep temporal models and boosted trees trade accuracy for speed, so model choice should match operational needs [22]. Whereas, a short-term CO_2 prediction with Hierarchical Model for CO_2 Variation Predictions (HMCOVP) based on a two-step method that predicts direction and magnitude of change provides more actionable signals for control and shows short-horizon error than direct level prediction [23]. Furthermore, classrooms with multi-sensor inputs used for short-term CO_2, was predicted through the LSTM with a combination of features that were selected through tree-based methods (RF-TPE-LSTM: Random forest, Tree-structured Parzen estimator, LSTM) [24].

In a high-density metro/subway platform where insufficient ventilation influences rush-hour pollution spikes, a probabilistic transformer was applied for the sustainable management of fine particulate matter-related health risks [25]. In the same environment, Kim et al. [26] presented the HiFi-IAQ model, integrating GCN and GRU, and predicted IAQ with the OAQ interpolation. At the city scale, in which policy questions depend on sparse indoor sensing, the inference problem is to generalize across homes with minimal instrumentation, and an RF model trained on surveys and ambient fields produces daily indoor $PM_{2.5}$ maps with strong test performance [27]. Furthermore, at the national scale where communication of risk requires quantified uncertainty, a Bayesian NN is used to produce distributional daily $PM_{2.5}$ predictions for many urban areas [28].

The Gaussian Process Regression (GPR) framework used to reconstruct spatiotemporal representations of physical measurements associated with IEQ variables, through a short-term spatiotemporal measurements of TVOC and $PM_{2.5}$ collected by a mobile sensing platform, the presented GPR model showed better performance compared to traditional ML approaches [1]. In office environments, reactive hourly $PM_{2.5}$ control signals are required, in this regard, a lightweight hybrid LSTM with an adaptive GRU was applied and was shown to improve single-step accuracy over a vanilla LSTM, while transfer depends on input design and site representativeness [36]. Miao et al. [37] developed a data-driven algorithm for predicting the degree of IAQ and thermal comfort in naturally ventilated educational facilities. The model was constructed via the class-weighted RF approach, incorporating data from an extensive measurement effort. The created model exhibited high accuracy, the capacity to generalize well, and strong robustness. The investigation determined that occupancy, the operation of windows and doors, and exterior environmental conditions are crucial aspects that must be considered. Sha et al. [38] developed a data-driven MPC strategy integrated encoder-decoder LSTM to optimize a net-zero house HVAC energy consumption, thermal comfort, and IAQ, but the resulting control law is solved online and can be computationally intensive for large-scale systems. In an apartment with data collection at 2-second resolution, an investigation of cross-room prediction evaluated multi-output learning and found that linear baselines can match more complex models for temperature and humidity, but CO_2 remains harder to generalize at ultra-short horizons [39]. On multi-pollutant sick building

TABLE I
SUMMARY OF AVAILABLE OPEN-SOURCE DATA

Ref	Year	Type of building	Collection duration	Collection frequency	Pollutants
[29]	2023	Commercial and Residential	3 months	2s	Particles ($PM_{1;\,2.5;\,10}$, Nano-particules), gases (O_2, CO, CO_2, SO_2, NO_2, O_3) and VOCs (TVOC)
[30]	2024	-	24 hours	1s	gases (CO, eCO_2, NH_3, NO_x, C_6H_6) and VOCs (TVOC)
[31]	2025	Residential	1 year	7min	Particles ($PM_{2.5}$, PM_{10})
[32]	2025	Residential and Commercial	6 months	0.5s	Particulates (PM_1, $PM_{2.5}$, PM_{10}), gases (CO_2, NO_2, CO), and VOCs (VOC, C_2H_5OH)
[33]	2025	-	3 months	1min	gas (CO_2, CO, NO_2, O_3, SO_2), particulates ($PM_{10;\,2.5}$), and VOCs
[34]	2024	Laboratory	6 days	15s	Particles ($PM_{2.5;\,10}$) and gases (CO_2)
[35]	2023	Residential	1 day	10min	gases (CO_2)

datasets, a broad comparative analysis evaluated fair cross-model comparisons and found that winners vary by target, motivating transparent, multi-metric summaries [40].

In a naturally ventilated home, a low-computational-cost metamodel coupled with multi-objective optimization balances comfort and energy, maps actionable trade-off frontiers aligned with residential practice, and reduces optimization time by about 80 % [41]. Linking measurements with occupant feedback, an optimization study reframes indoor quality targets for classrooms and labs and shows how satisfaction and seasonal effects interact with physical limits [42]. To provide day-ahead guidance for operators, a hybrid LSTM–CNN is applied to daily CO_2 prediction in campus buildings and shows that accuracy varies by variable as much as by architecture [43]. In a large library, a graph-based encoder with calendar and interaction features used to capture movement and layout effects, this resulted is delivering multi-step gains due to the learned structure rather than deeper sequences alone [44].

All studies conducted using black box modeling methods perform either predictions, estimates, or control and optimization of IAQ. The studies are mainly modeled on a single family of pollutants with CO_2 or $PM_{2.5}$ in primarily commercial and residential environments. Here, computational complexity is less of an issue, but these models are heavily dependent on historical data for input, and there is still a shortage of studies that thoroughly investigate the interactions among various features and also addressing the saturation of developed models performance over a period of time.

IV. DISCUSSION

The majority of studies focus on the IAQ of residential and commercial buildings. Surprisingly, solely one of the aforesaid investigations concentrates on the health sector. However, it is expected that the health center should be among the buildings with a high standard of IAQ. This can be explained by taking into account confidentiality and the restriction of data accessibility in such buildings. However, the visible research gap is undeniable. Due to the high accuracy of black-box modeling, it remains the preferred method in this domain. The most commonly used metrics are R^2, RMSE, and MAE. The combination of these three metrics is systematically reported in articles proposing black-box models in table II.

Despite the open source online available data (as it is illustrated in table I), the proper dataset that represents the dynamics of the spaces is not easy to collect. Due to this difficulty, we can observe many investigations that rely on data generated by CFD approaches. It is a smart choice, especially in buildings with data collection restrictions like health buildings, however, as the CFD modeling also has an error compared with the real world, using generated data for black-box modeling will reinforce the final error. As a result, it is still preferable to do data collection for developing a black-box model or to validate the CFD models with real-world data in order to be able to measure the final error. Apart from data collection challenges, the black-box models have other shortcomings as well. Applicability of a model developed on one building to another one is challenging. Or even in the same building, the accuracy of a model will drop over time. It is due to the unique properties of buildings in the first case and characteristic changes over time in the second case. One solution is to develop one model, one building for each individual case. Or, regarding maintaining the accuracy of the model over time, one solution is to regularly do the data collection and develop a model from scratch. In both cases, it is almost an impossible task, as collecting representative data for each case is time-consuming and impractical.

TABLE II
SUMMARY OF BLACK BOX STUDY RESULTS

Metric	[16]	[24]	[25]	[26]	[27]	[28]	[40]	[43]
R^2	0.25	0.98	-	0.89	0.89	0.70	0.09	0.38
RMSE	4.86	5.54	9.7	5.96	9.13	13.3	$<$0.01	-
MAE	3.66	2.96	7.2	3.02	-	9.45	$<$0.01	0.04

As described in Table I, the data comes from residential and commercial environments, except for one laboratory. Other environments such as industrial, medical, or transportation are not represented. This represents a significant bias, as the models cannot develop aspects and characteristics that are only observable in residential and commercial environments. The lack of information, linked to the measurement methodology, also represents a transparency issue: lack of information related to location, information on buildings, etc.

Knowledge transfer is a promising solution in this context. It allows models trained on data from one building to be adapted to another using limited new data, reducing the need for costly data collection. Techniques such as fine-tuning used

in different domain, however, there is few works in this domain (IAQ) using this approach.

V. Conclusion and research perspectives

Two key approaches emerge to overcome the identified limitations. First, models must simultaneously predict air quality (CO_2, PM, VOC), thermal comfort, and energy consumption. Architectures such as Informer or Autoformer, which can manage multiple time horizons, provide a solid basis for structuring this multi-objective framework. Combined with exogenous data (occupancy, weather, window opening), they provide a better understanding of the interactions between the environment and usage. The goal is to move from simple prediction to contextualized control, where each result feeds into a decision.

There is an urgent need to develop models that can be transferred from one building to another. Currently, most models remain limited to a single site. Other approaches, such as federated learning or domain adaptation (i.e., aligning distributions across buildings), could also reduce dependence on local data. With these tools, we can aim for more robust predictors that are less costly to deploy and truly adaptable to real-world constraints.

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Influence of CO_2 Sampling Techniques on ^{14}C-Based Biogenic Carbon Quantification in Waste-to-Energy Emission

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Abstract— The alteration of the carbon (C) cycle by fossil fuel burning has climatic implications, requiring accurate partitioning of the fluxes of fossil vs biogenic (=renewable) carbon in various applications (eg: Carbon in bioplastics, Carbon Dioxide (CO_2) emitted by waste to energy plants).
The most reliable and sensitive tool to do that is the usage of ^{14}C combined to Accelerator Mass Spectrometry (AMS) high precision measurements. The ASTM D7459 and UNI EN 13528 standards set the methods to quantify the CO2 emissions from waste-to-energy plants by using 14C analyses. One of the crucial points in these methods is the sampling techniques, that can be divided in two categories: "time integrated" sampling, using NaOH or KOH or soda lime (i.e. a mixture of CaO, NaOH and KOH) to trap CO_2 for 6-48 hours, and "instantaneous" sampling, using glass (flasks) or plastic (tedlar bags) canisters to trap flue gas for only a few tens of seconds. The methods accept both sampling techniques without discussing the potential differences that may arise when comparing sampling techniques of different durations.
To address this concern, we have measured the ^{14}C-CO_2 emitted by a waste-to-energy plant (Acerra, southern Italy). Sampling campaigns has been performed monthly for c.a. 6 years (from 2019 to 2025), from 3 gas emission lines using plastic Tedlar bags and glass flasks, or NaOH and soda lime, respectively, for continuous or instantaneous sampling. The ^{14}C content has been measured by AMS.

Preliminary results showed that the percentage of biogenic C ranged from 43 to 53 % (49 % on average), with an uncertainty associated with the sample preparation procedure (CO_2 extraction and analysis) of 0.3 %. No significant differences were found among the 3 emission lines in terms of ^{14}C inferred biogenic fraction suggesting homogeneity in the flue gas production by the plant. An increase in the biogenic fraction in gaseous samples taken during 2023 was observed when sampling with soda lime. Work is in progress to investigate the influence of the sampling technique on the measured fraction of biogenic vs fossil Carbon.

Radiocarbon (^{14}C); Accelerator Mass Spectrometry (AMS); Carbon cycle; Biogenic carbon; Fossil carbon; Waste-to-energy plants; CO_2 emissions; Sampling techniques; Time-integrated sampling; Instantaneous sampling; Soda lime; Tedlar bags; Biogenic fraction; ASTM D7459; UNI EN 13528; Flue gas analysis

I. Introduction

The anthropogenic influence on climate has long been recognized, drawing political attention to the management of the rising atmospheric concentration of climate-active gases. Among these, carbon dioxide (CO_2) is not only the most well-known but also the one that can be attributed the greatest radiative power, that is, the most important in terms of increasing the greenhouse effect and, therefore, climate change and its consequences (IPCC 2021).

Although CO_2 is subject to a biogeochemical cycle (the carbon cycle) controlled almost entirely by natural processes, the anthropogenic contribution—mainly due to the extensive use of combustion for energy supply—can significantly disrupt the planet's energy balance. This happens because the excess CO_2 in the atmosphere, resulting from ever-increasing human activities, is not counterbalanced quickly enough by the processes that remove tropospheric CO_2 (mainly ocean absorption and photosynthesis) on timescales relevant to the current development of society. This produces an increase in the concentration of this greenhouse gas in the troposphere. Along with the increase of other greenhouse gases, this phenomenon causes the rise in temperature that has been experimentally observed since the Industrial Revolution, with all its consequences.

Within this context lies the scientific debate on possible methods for to distinguish fossil fuel derived CO_2 emissions arising from fossil fuels and identifying procedures for controlling and monitoring their reduction. In the past, CO_2 emissions were quantified by emission inventories based on theoretical ratios (CO_2 emitted/amount and quality of fuel burned). Currently, it is necessary to verify the emission inventories with experimental methods and on-site measurements. To be practically useful and to influence CO_2 emission management policies, these measurements must be able to quantify the fraction of carbon in emitted CO_2 that comes from fossil fuels and the fraction that comes from renewable or "biogenic" carbon (i.e., from non-fossil plant material). In fact, biogenic carbon enters a "fast" carbon cycle governed by photosynthetic processes and does not originate, unlike fossil carbon, from underground deposits formed millions of years ago. Consequently, lawmakers seeking to intervene in CO_2 emissions must focus particularly on reducing the use of fossil carbon.

To identify the origin of emitted CO_2, radiocarbon (the radioactive isotope of carbon-14 or ^{14}C) represents one of the most powerful methods for quantifying the fossil contribution of emitted CO_2, since ^{14}C is absent in carbon of fossil origin. This is due to its natural radioactivity, which, in a closed system, leads to its completely decay into ^{14}N within c.a. 57ka of years (the half-life of ^{14}C is only 5730 years). As a result, the carbon trapped in fossil fuels such as coal, gas and oil, which can be considered closed systems because they have been isolated underground for millions of years, has completely decayed. Therefore, the emission of CO_2 into the atmosphere from the combustion of fossil fuels leads to a measurable depletion in the relative amount of $^{14}CO_2$ with respect to $^{12}CO_2$. The fraction of CO_2 derived from fossil material combustion can thus be determined by quantifying the dilution effect of the ^{14}C concentration in the CO_2 emitted by any sources.

In order to quantify the fossil emission we have applied this method to the flue gas released by a waste-to-energy plant.

II. Materials and Methods

Since there are no known variations in the commercial characteristics of the incoming material at regular frequencies, it was decided to carry out sampling at regular intervals. For logistical and organizational convenience, sampling was performed during monitoring operations periodically performed by third-party control companies at the waste-to-energy plant, or during periodic inspections carried out by ARPA Campania.

The CO_2 emitted from the Acerra waste-to-energy plant was collected using four different sampling methods:

1. **Glass flasks.** Before sampling, the flasks can be stored in an atmosphere with ambient CO_2 concentration. In this case, they require several "washings" with the sampled gas (i.e., the flue gases emitted from the plant's chimney) to ensure that the air from the incinerator completely replaces the air previously contained in the flasks. Alternatively, the flasks can be kept under vacuum before sampling, in which case there is no need to "wash" them with the sampled gas.
2. **Plastic containers (tedlar bags).** These are plastic bags that can be filled with gas at a pressure slightly higher than ambient. They have the advantage of being much cheaper than flasks, but the disadvantage of poorer long-term sealing, which exposes the sample to contamination risks during storage.
3. **Soda lime (NaOH + CaO).** This is also an integrated, non-instantaneous sampling method. Unlike NaOH solutions, which are liquid, soda lime is present in the form of solid granules. This sampling method is officially accepted for ^{14}C measurements using liquid scintillation counting (LSC) according to the UNI/TS 11461 standard protocol.

Each sample was stored, prior to pretreatment and ^{14}C measurement, at the laboratories of the Department of Mathematics and Physics (University of Campania "Luigi Vanvitelli"). The determination of 14C abundance in atmospheric samples emitted by a waste-to-energy plant requires a sequence of chemical-

physical steps that transform collected CO_2 into graphite, enable its measurement with high-sensitivity instrumentation, and finally allow calculation of the fossil and biogenic carbon fractions present in the flue gases.

III. Sample preparation

The first step involves transforming carbon, initially present as carbon dioxide, into solid graphite. This operation is essential to make the samples suitable for subsequent analyses.

CO_2 is first extracted under vacuum through a cryogenic line, which isolates and purifies it. The gas is trapped in a calibrated volume using liquid nitrogen, enabling precise quantification of the collected amount.

The purified CO_2 is then cryogenically transferred into a Pyrex® glass reaction vessel. Inside the vessel are reducing agents (zinc and titanium hydride powders) and a small container with iron. After sealing, the system is heated in a muffle furnace for eight hours at temperatures between 550 and 560 °C. Under these conditions, CO_2 is reduced and elemental carbon deposits as graphite on the iron.

The resulting graphite is pressed into small pellets and mounted in standard aluminum holders, forming the solid targets to be used during measurement. (Marzaioli et al. 2008)

IV. Radiocarbon measurement

The atmospheric concentration of 14C is extremely low: only about one in a trillion CO_2 molecules contains radiocarbon. For this reason, a highly sensitive technique is required.

The measuring system relies on a high-voltage electrostatic accelerator (AMS). The facility consists of several modules: a sputter ion source holding up to forty samples, sequential injection magnets, electrostatic analyzers to suppress isobaric interferences, and a multi-anode ionization chamber for detection.

The sample wheel is loaded with both reference standards and unknown samples. Standards include certified materials from IAEA and NIST (cellulose, wood, sucrose, oxalic acid) along with commercial graphite. Blank samples, free of ^{14}C but processed with the same chemical steps as samples and standards, quantify any contamination introduced during preparation. Untreated graphite controls the machine background, i.e., contamination inherent to the measurement system itself.

To ensure data quality, standards are used both for normalization and for accuracy and precision checks. In particular, comparison between known standard values and measured values verifies the reliability of combustion and graphitization processes.

V. Data Processing

The final stage of the process is the analysis of the obtained data, which, starting from the concentration of ^{14}C, allows the determination of the percentage of modern carbon (pMC) and, ultimately, the percentage of fossil and biogenic carbon (XB) within the total CO_2 (XTC) emitted from the Acerra waste-to-energy plant.

The first step in data analysis is measuring the isotopic ratios $^{14}C/^{13}C$ and $^{14}C/^{12}C$, which represent the comparison between the amount of the rare (and radioactive) isotope ^{14}C and that of the more abundant (and stable) isotopes ^{12}C and ^{13}C in a sample. This ratio is compared with a known standard, namely oxalic acid (OxI or OxII).

The next step is determining the percentage of modern carbon (pMC), which is the relative ^{14}C content of a sample compared to a modern standard, calculated by normalizing the isotopic ratio of the sample (corrected for isotopic fractionation).

Finally, the fractions of fossil and biogenic CO_2 are quantified through an isotopic mass balance, in which the ^{14}C content in the sample is considered equal to the weighted average of the ^{14}C contents of its components, with weights corresponding to each component's fractional contribution to the total:

$$pMC_{sample} = pMC_{bio} \bullet f_{bio} + pMC_{fos} \bullet f_{fos} + pMC_{atm} \bullet f_{atm} \quad (1)$$

where bio = biogenic/renewable, fos = fossil, and atm = atmospheric. (Palstra et al. 2010)

Assuming the atmospheric contribution is negligible ($f_{atm} = 0$), and setting $f_{bio} = X_B/X_{TC}$ and $pMC_{bio} = REF$, the biogenic/renewable CO_2 fraction is expressed as:

$$x_b / x_{tc} = pMC_{sample\,/\,REF} \quad (2)$$

where X_B is the biogenic/renewable CO_2 content, X_{TC} is the total CO_2 content, and REF is the ^{14}C content in the reference sample.Regarding the Reference (REF) value, UNI/TS 11461 specifies the following:
"it recommends using the value proposed by ASTM D6866 in cases where the material composition of the SRF is not precisely known. (https://www.rug.nl/research/centre-for-isotope-research/customers/tools/reference-radiocarbon-values-palstra-and-meijer?lang=en)".

VI. Results

Figure 1 shows that the percentage of biogenic C ranged from 43 to 53 % (49 % on average), with an uncertainty associated with the sample measurement is around 0.3 %. No significant differences were found among the 3 emission lines in terms of ^{14}C inferred biogenic fraction suggesting homogeneity in the flue gas production by the plant.

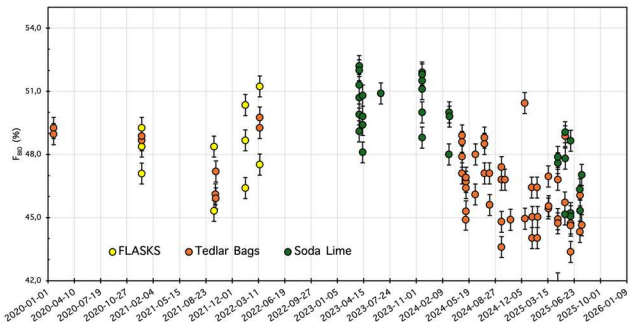


Figure 1: Biogenic fraction of the emission obtained by three different sampling methods

The reproducibility of sample preparation of Tedlar Bags was assessed by performing four repeated extractions from the same bag, an approach that was applied to four different bags (Figure 2). The results indicate that the variability among repeated measurements is comparable to the measurement uncertainty of the method. The error bars in figure 2 shows the value of the uncertainty associated with the sample measurement.

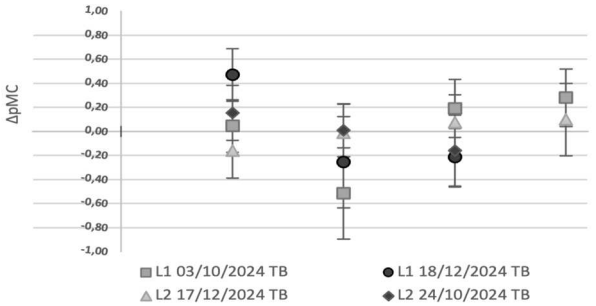


Figure 2: Riproducibility of the sample preparation of the Tedlar Bags

An increase in the biogenic fraction in gaseous samples taken during 2023 was observed when sampling with soda lime (Figure 1). This suggested that measurements carried out with Soda Lime might be overestimated. To test this hypothesis, from April 2025 to July 2025, both samples collected with Soda Lime and samples collected with Tedlar Bags from the same line on the same days, were measured in order to compare the results. The outcome was that in 80% of the cases, the biogenic fraction obtained from samples collected with Soda Lime was higher (by several percentage points in some instances) than Tedlar Bags (Figure 3).

According to current regulations, both sampling methods are considered equally reliable. However, the exposure time of Soda Lime to flue gas emissions is approximately 24 hours, whereas Tedlar Bags collect emissions over a period of about 30 seconds. So, the method are not directly comparable.

Furthermore, "blank" Soda Lime samples, i.e., samples analyzed without prior exposure to plant emissions, were also measured in order to assess potential background contributions.

Conclusion

A comparison between different CO_2 sampling techniques reveals systematic variations in the estimated biogenic fraction, especially between integrated (SL) and instantaneous (TB) sampling methods.

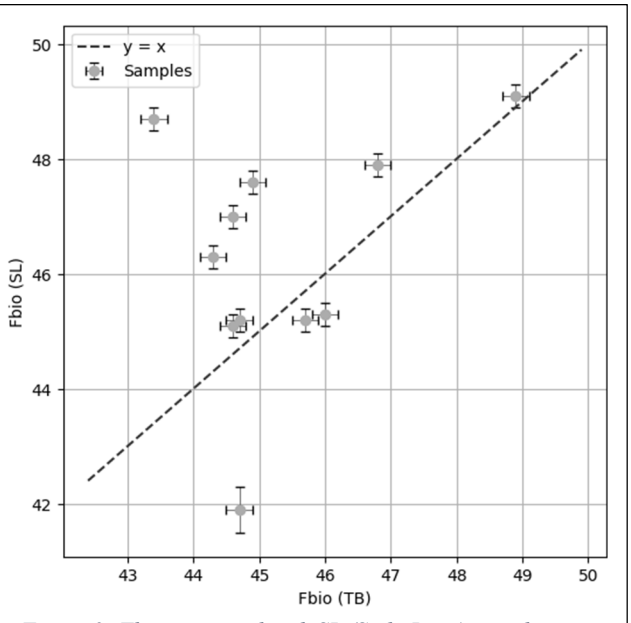


Figure 3: Fbio measured with SL (Soda Lime) sampling vs Fbio measured with TB (Tedlar Bags) sampling

Future work will aim to quantify the uncertainty associated with each sampling approach, in order to assess whether the observed temporal increase in the biogenic component is statistically significant. The potential impact of these variations on the overall carbon balance of waste-to-energy plants will also be evaluated.

This analysis will contribute to a better understanding of the implications for emission reporting and management strategies.

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Sustainability Decommissioning of Radioactive Wastewater from Nuclear Power Plants by Means of Zeolite Materials

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***Abstract*— Sustainability entails the conscious and careful management of available resources, without affecting the future generations. Minimizing the impact of radioactive waste from nuclear power plants falls within this framework, with the aim of reusing as much as possible. In this study, zeolite materials have been characterized regarding their capacity to adsorb and remove artificial radionuclides from aqueous solutions simulating wastewater from nuclear power plants. Three zeolites, in powder state, have been tested. The high efficacy of synthetic zeolites rather than natural one has been demonstrated, providing almost 100% of removal of artificial radionuclides in half an hour. These results are the basis for the use of the zeolite in adsorbing radioactive elements in contaminated water solutions from nuclear facility.**

Keywords—wastewater, nuclear power plant, synthetic zeolite, artificial radionuclide, adsorption.

I. Introduction

The idea of sustainability — understood as the mindful and responsible use of existing resources — has become a critical imperative to guarantee that future generations can satisfy their needs just as the current population does. This principle has acquired growing importance in many areas of human activity, particularly in healthcare, where achieving a balance between sustainability and effective measurement poses complex challenges. In the context of today's energy crisis and escalating climate change, nuclear energy has gained renewed attention as a low-carbon alternative to fossil fuel-based thermal power generation [1].

However, one of the main challenges of nuclear energy remains the management of radioactive waste, including contaminated wastewater, which constitutes a significant portion of this output. Such wastewater typically originates from routine operations like cooling and storing irradiated fuel, as well as from maintenance activities and fission reactions occurring within nuclear installations. To discharge this water safely into the environment, it must undergo rigorous decontamination processes aimed at removing radioactive contaminants [2].

Among the various treatment technologies proposed, one of the most promising and innovative approaches is the use of zeolites — highly porous mineral materials known for their resistance to radiation and effective cation-exchange capabilities. This study focuses on identifying specific zeolites capable of removing artificial radionuclides found in wastewater generated by decommissioned nuclear power plants in Italy. To confirm the presence of these radionuclides, gamma spectrometry was applied to analyze the wastewater samples.

An experimental system was then developed to test selected zeolites in purifying the contaminated water. Batch experiments were conducted using stable (non-radioactive) nitrate salts of the same radionuclides detected in the wastewater, given that the ion-exchange behavior remains consistent regardless of the isotope's radioactivity.

The concentration of ions absorbed by the zeolites over time was measured using inductively coupled plasma spectrometry, allowing for a kinetic analysis of the exchange process.

This research contributes to the broader goal of dismantling and safely decommissioning nuclear facilities by proposing an alternative and efficient method for treating radioactive wastewater. The primary outcome is the selection of a zeolite type with the highest capacity for adsorbing specific radionuclides typical of wastewater from Italian nuclear plants. The ultimate aim is to design an in-situ decontamination unit capable of purifying such water directly at the facility site. A notable advantage of this method is the reduced volume of secondary waste: the zeolite, once saturated with radionuclides, is treated to form stable, solid matrices — either cement-based or vitrified — which are then destined for storage at the National Repository. This significantly limits the environmental footprint compared to handling large volumes of contaminated liquid waste.

II. Materials and Methods

A. Wastewater

Following the 1987 national referendum that repealed the use of nuclear energy for power generation, Italy permanently shut down its four nuclear power plants. Since 1999, these facilities have been under the administration of SOGIN (Società Gestione Impianti Nucleari), a state-owned enterprise supervised by the Ministry of Economy and Finance, which is responsible for the decommissioning operations and the management of radioactive waste [3].

Radioactive liquid waste, primarily generated during the cooling and interim storage of spent nuclear fuel, accumulates in spent fuel pools (~1.5×10^6 L) and is subsequently designated for transfer to the future National Repository. The decontamination of such wastewater using zeolitic materials aims to reduce the volume of radioactive waste requiring long-term storage, thereby maximizing the quantity of material that can be safely recovered and potentially recycled.

Quantification of the artificial radionuclide content in the liquid waste is performed through high-resolution gamma-ray spectrometry.

For this purpose, a coaxial high-purity germanium detector (HPGe, model GMX-45P4ST by Ortec company) is employed. The detector exhibits a relative photopeak efficiency of 48%, an energy resolution of 2.16 keV at 1.33 MeV, and utilizes a beryllium window to enhance detection efficiency at photon energies below 100 keV. To minimize background interference, the detector is enclosed in a cylindrical lead shield of 7.5 cm thickness and is operated using a 30-liter liquid nitrogen cryogenic cooling system. The minimum detectable activity (MDA) of the system is estimated with a 95% confidence level. In order to achieve statistically significant spectral data, each measurement is conducted over a 48-hour acquisition time. The gamma spectrometry details, with calibration (efficiency, geometry etc.) are not included in this work for brevity; for more information please refer to the document [4].

The radiological profile of the wastewater is dominated by gamma-emitting fission and activation products, notably cesium-137 (Cs-137) and cobalt-60 (Co-60) [3]. Cs-137 is a long-lived radionuclide ($T_{1/2} \approx 30.17$ years) produced via the thermal fission of uranium-235. It decays by beta emission to barium-137m (Ba-137m), a metastable isomer that emits characteristic gamma radiation. Co-60, a synthetic radionuclide with a half-life of 5.2714 years, is generated through neutron activation of the stable isotope cobalt-59, commonly found in the structural materials of nuclear reactors. Co-60 undergoes beta-minus decay to the excited state of nickel-60 (Ni-60), which subsequently relaxes to its ground state through gamma emission.

B. Zeolite

Zeolites are a class of microporous, crystalline aluminosilicate materials with a well-defined three-dimensional framework composed of tetrahedrally coordinated silicon (Si^{4+}) and aluminum (Al^{3+}) atoms linked by shared oxygen atoms. The substitution of Al^{3+} for Si^{4+} introduces a negative framework charge, which is balanced by the presence of exchangeable extraframework cations (e.g., Na^+, K^+, Ca^{2+}).

The general chemical composition of zeolites can be represented as $M_x/n[Al_xSi_{1-x}O_2]\cdot yH_2O$, where M denotes the charge-compensating cation of valence n. This intrinsic property renders zeolites highly effective as ion-exchange materials [5]. Zeolitic frameworks are constructed from TO_4 (T = Si, Al) tetrahedra that form well-ordered channels and cavities of molecular dimensions (Figure 1).

These geometries define the pore sizes and shapes, typically characterized by the number of tetrahedrally coordinated atoms in the ring structures: small-pore zeolites possess 8-membered rings, medium-pore ones 10-membered, and large-pore types contain 12-membered rings or more. The International Zeolite Association assigns a unique three-letter framework code to each structure for classification and identification.

Due to their thermal and radiological stability, high ion-exchange capacity, specific adsorption properties, and chemical resistance, zeolites have been widely implemented across various fields, including catalysis, gas separation, water purification, and environmental remediation. In the context of nuclear energy production and radioactive waste management, zeolites offer a practical solution for the sequestration of radionuclides and heavy metals from aqueous streams [6]. Their structural resilience to ionizing radiation and affordability make them particularly suitable for large-scale decontamination efforts in nuclear facilities. Once saturated with contaminants, zeolites can be conditioned for safe disposal through vitrification, sintering, or encapsulation in cementitious matrices.

In this study, three zeolitic materials were investigated for their ion exchange performance: two synthetic zeolites, 4A and 13X, and one naturally occurring type, phillipsite (Figure 1). Zeolite 4A, a Linde Type A (LTA) structure, was supplied by Sigma-Aldrich and has the empirical formula $Na_{12}Al_{12}Si_{12}O_{48}\cdot 27H_2O$. It features uniform micropores formed by 8-membered rings with an aperture of ~4.1 Å. Zeolite 13X, sourced from Carlo Erba Reagents, is a Faujasite (FAU) type with the composition $Na_{43}Al_{43}Si_{53}O_{192}\cdot 132H_2O$ and 12-membered ring channels of ~7.4 Å diameter. The natural zeolite, phillipsite $(Na_2K_2Ca)Al_2Si_4O_{12}\cdot 6H_2O$, was derived from volcanic tuff deposits, including Neapolitan Yellow Tuff (NYT).

These materials are commonly found in hydrothermally altered volcanic rocks and exhibit ion exchange capacities generally lower than their synthetic counterparts.

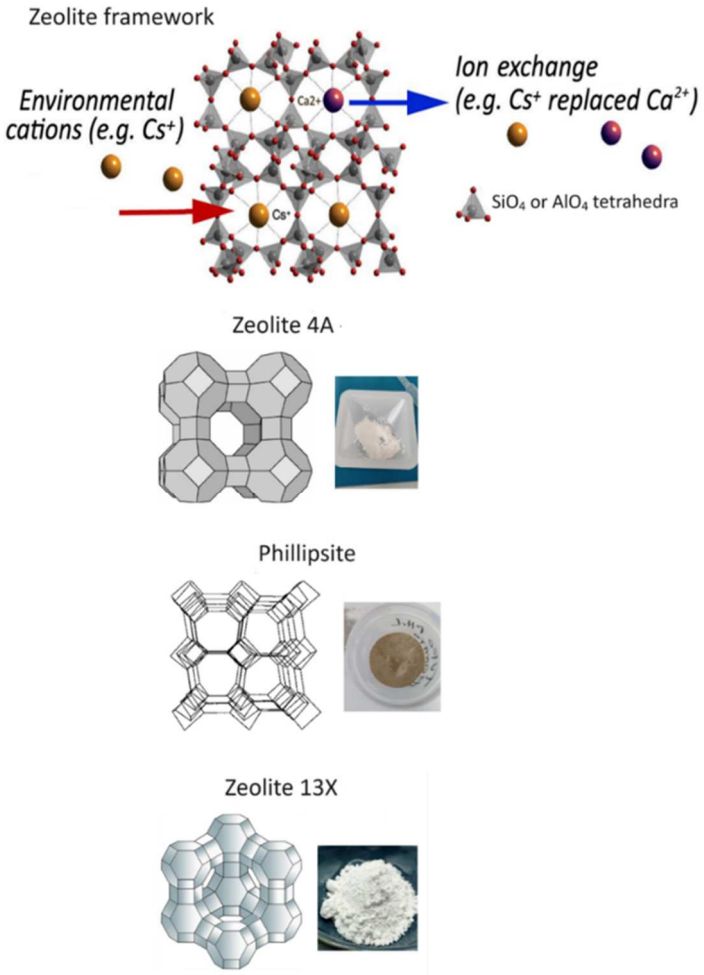


Fig. 1. Example of zeolite framework (top) and the three zeolites used in this work (bottom). Figure modified from [7].

To simulate ion exchange behavior under nuclear waste conditions without radiological hazards, a series of batch experiments were conducted using surrogate (non-radioactive) isotopes.

Cesium and cobalt were selected as representative fission and activation products, respectively, using cesium nitrate

($CsNO_3$) and cobalt nitrate hexahydrate [$Co(NO_3)_2 \cdot 6H_2O$] to prepare aqueous solutions at a fixed normality of 0.01 N. This concentration was chosen based on a survey of relevant literature to reflect typical levels found in contaminated wastewater.

Experiments were carried out by contacting varying masses of zeolite powders with 100 mL of solution in beakers placed on magnetic stirrers. For the synthetic zeolites, 0.5 g, 1 g, and 2 g of 13X or 4A were used. For phillipsite, higher dosages (1 g, 2 g, and 4 g) were employed to compensate for their comparatively lower cation exchange capacities.

The experimental matrix was replicated for both Cs^+ and Co^{2+} solutions, followed by mixed solutions containing both cations to evaluate competitive adsorption behavior. The most effective zeolite identified from single-cation trials was subsequently used for both ion removal tests. Solution aliquots were collected at predetermined time intervals (1, 2, 5, 10, 20, 30, 60, and 90 minutes), filtered through glass funnels with qualitative filter paper, and analyzed via inductively coupled plasma–optical emission spectroscopy (ICP-OES; PerkinElmer Optima 2100 DV) [6]. This instrument, operated with an argon plasma (15 L/min flow rate, 10,000 K temperature), offers a detection limit of 5 ppb and a sample uptake rate of 1.5 L/min. Dual-wavelength measurements were conducted for each analyte to enhance analytical accuracy, and results were reported in mg/L.

All details on the experimental setup are reported in the article [7], on which the present work is based.

The ion exchange process in zeolites is governed by well-defined stoichiometric mechanisms. If the exchange reaction is thermodynamically favorable, selective removal of target ions from the liquid phase occurs regardless of competing species or initial concentrations. These findings, derived from non-radioactive analogs, serve as a critical step toward the development of a pre-pilot system for on-site treatment of radioactive effluents at the nuclear facilities.

III. Results and Discussion

Analysing wastewater samples from Italian nuclear plants, the radionuclides contents of artificial origin is mainly represented by Co-60 and Cs-137 generated during the operation of the nuclear facility.

The average activity concentrations of both radionuclieds in Bq/L determined by gamma spectrometry using the HPGe detector are: 130±2 for Co-60 and 3000±10 for Cs-137. The full energy gamma peak at 661.7 keV was employed to determine the activity concentration of Cs-137, while for Co-60 the two gamma peaks at 1173.2 keV and 1332.5 keV. The activity concentrations uncertainties were calculated by considering the errors associated to counting, gamma emission probability, energy and efficiency calibration, and sample volume.

The average concentration in parts per million (ppm or equivalent to mg/L) for both radionuclides in the wastewater has also been estimated by considering molar mass and decay constant of each specific element, and the Avogadro's constant: $(3 \pm 0.4) \cdot 10^{-9}$ for Co-60 and $(8 \pm 0.2) \cdot 10^{-7}$ for Cs-137.

In accordance with the Italian legislative framework governing radiological protection—specifically Legislative Decree 101/2020, which transposes the provisions of European Directive 2013/59/EURATOM—the maximum allowable concentration of gamma-emitting radionuclides in wastewater for exemption or clearance is established at 100 Bq/L for each individual nuclide. When dealing with mixtures of radionuclides, as is the case in the present effluent samples, regulatory compliance requires that the sum of the ratios between the measured activity concentration of each radionuclide and its corresponding exemption threshold does not exceed unity.

In order to fulfill these regulatory conditions, it is necessary to implement measures aimed at reducing the activity levels of specific gamma emitters, notably Co-60 and Cs-137. Within this framework, the application of zeolitic materials as cation-exchange media for the selective removal of radionuclides emerges as a viable remediation approach. This strategy holds potential for the formulation of a standardized treatment protocol for radioactive wastewater, which could be uniformly adopted across nuclear industries throughout Italy.

The temporal evolution of cesium ion (Cs^+) removal from an aqueous solution (0.5 L, 0.01 N $CsNO_3$) was investigated using varying masses (0.5, 1.0, and 2.0 g) of three different zeolite materials: 4A, 13X and phillipsite The percentage of Cs^+ uptake was calculated using the equation: Upt.Am. % $=(C0-Ct)/C0 \times 100$, where $C0$ is the initial Cs^+ concentration and Ct is the concentration at time t.

Results indicate that zeolites 4A and 13X demonstrate superior and more consistent ion-exchange performance compared to phillipsite (Table I). When using the lowest adsorbent mass (0.5 g), all zeolites exhibit pronounced fluctuations in Cs^+ uptake efficiency. However, increasing the sorbent mass improves uptake performance, with maximal percentages observed as follows: ~55% for 13X, ~50% for 4A, ~44% for phillipsite. Equilibrium is rapidly achieved in all systems, typically within 5 to 10 minutes, confirming the fast kinetics of Cs^+ removal via zeolite-based exchange processes. Among the tested materials, zeolite 13X consistently showed the highest efficiency and stability.

Similarly, the uptake kinetics of cobalt ions (Co^{2+}) were examined using 0.5 L of 0.01 N $Co(NO_3)_2 \cdot 6H_2O$ solution and varying quantities (0.5, 1.0, and 2.0 g) of 4A and 13X zeolites (Table I). Data for phillipsite have negligible uptake levels, frequently below instrumental detection thresholds. Both 4A and 13X zeolites effectively removed Co^{2+} from solution, with zeolite 13X showing significantly higher performance at lower dosages. At 0.5 g and 1.0 g, 13X demonstrated nearly double the uptake efficiency compared to 4A. At 2.0 g, both zeolites reached near-complete removal (~100%). Notably, 13X achieved equilibrium within ~5 minutes, whereas 4A required up to 60 minutes, underscoring the more rapid exchange kinetics of 13X.

Given the outstanding performance of zeolite 13X in single-ion systems, further experiments were conducted with mixed solutions containing both Cs^+ and Co^{2+} (each at 0.01 N). The uptake behavior was assessed using 1.0 and 2.0 g of 13X over time. As illustrated in Figure 2, rapid Cs^+ uptake (~90%) was observed within the first minute using 2.0 g of zeolite, while Co^{2+} uptake reached 62% after 2 minutes. After 5 minutes, Co^{2+} uptake reached 100%, and Cs^+ uptake increased to 95%.

By 30 minutes, both ions were completely removed from solution. These findings reveal a marked shift in selectivity when transitioning from single to mixed systems. While in isolated solutions 13X showed a distinct preference for Co^{2+} over Cs^+ (99% vs. 55% uptake, respectively), this difference is significantly reduced in the mixed-ion scenario, with both cations being efficiently exchanged [8]. This behavior highlights the high ion-exchange capacity and adaptability of

13X zeolite, suggesting a balanced affinity for both monovalent and divalent cations under competitive conditions.

TABLE I. Cs^+, Co^{2+} UPTAKEN AMOUNT PERCENTAGES BY ZEOLITES

	Time (min.)	Zeolite 4A		
		Upt. Am % (0.5 g)	*Upt. Am % (1 g)*	*Upt. Am % (2 g)*
Cs^+	1	22.04	31.54	46.18
	2	25.43	31.72	48.79
	5	25.61	33.87	50.18
	10	25.00	32.47	49.97
	20	17.64	33.14	51.51
	30	17.60	33.64	49.76
	60	17.53	34.44	49.96
	90	27.78	36.01	50.98
	120	18.29	31.54	50.65

	Time (min.)	Zeolite 13X		
		Upt. Am % (0.5 g)	*Upt. Am % (1 g)*	*Upt. Am % (2 g)*
Cs^+	1	11.72	15.51	36.97
	2	11.65	21.00	41.28
	5	16.31	27.40	48.69
	10	14.25	30.94	53.52
	20	14.03	33.25	53.60
	30	14.97	31.90	53.79
	60	16.16	32.83	54.52
	90	16.81	33.22	55.04
	120	17.21	33.51	54.65

	Time (min.)	Phillispite		
		Upt. Am % (1 g)	*Upt. Am % (2 g)*	*Upt. Am % (4 g)*
Cs^+	1	13.93	15.48	25.09
	2	13.65	15.48	27.11
	5	17.35	16.05	30.27
	10	16.34	21.96	35.15
	20	17.31	24.97	36.75
	30	22.81	25.28	43.30
	60	19.11	27.66	39.73
	90	18.42	28.27	43.63
	120	7.88	29.70	43.74

	Time (min.)	Zeolite 4A		
		Upt. Am % (0.5 g)	*Upt. Am % (1 g)*	*Upt. Am % (2 g)*
Co^{2+}	1	5.55	23.15	35.65
	2	6.86	23.24	41.70
	5	12.77	31.28	43.81
	10	15.34	38.80	51.68
	20	18.08	40.95	81.16
	30	17.35	46.08	82.75
	60	29.39	54.80	97.61
	90	36.03	63.66	99.47
	120	37.23	67.89	99.42

	Time (min.)	Zeolite 13X		
		Upt. Am % (0.5 g)	*Upt. Am % (1 g)*	*Upt. Am % (2 g)*
Co^{2+}	1	51.44	70.42	84.46
	2	53.31	73.10	88.63
	5	58.82	77.30	92.94
	10	57.59	78.18	95.44
	20	62.25	78.32	97.46
	30	62.56	79.14	98.51
	60	64.67	80.70	99.13
	90	63.52	81.97	100.00
	120	62.93	81.47	100.00

	Time (min.)	Phillispite		
		Upt. Am % (1 g)	*Upt. Am % (2 g)*	*Upt. Am % (4 g)*
Co^{2+}	1	2.78	13.83	1.84
	2	5.22	11.86	2.12
	5	4.15	9.87	1.34
	10	9.90	8.33	2.77
	20	9.63	29.96	1.44
	30	4.62	19.47	5.21
	60	7.02	12.29	5.55
	90	1.30	9.08	8.82
	120	2.54	10.29	10.37

In conclusion, zeolite 13X emerges as the most effective and rapid exchanger among the tested materials for both Cs^+ and Co^{2+} ions, in both single and mixed systems. Its superior kinetics and high selectivity are likely due to the structural characteristics and accessible pore size distribution of the material, rendering it a promising candidate for practical applications in radioactive or heavy metal decontamination [7].

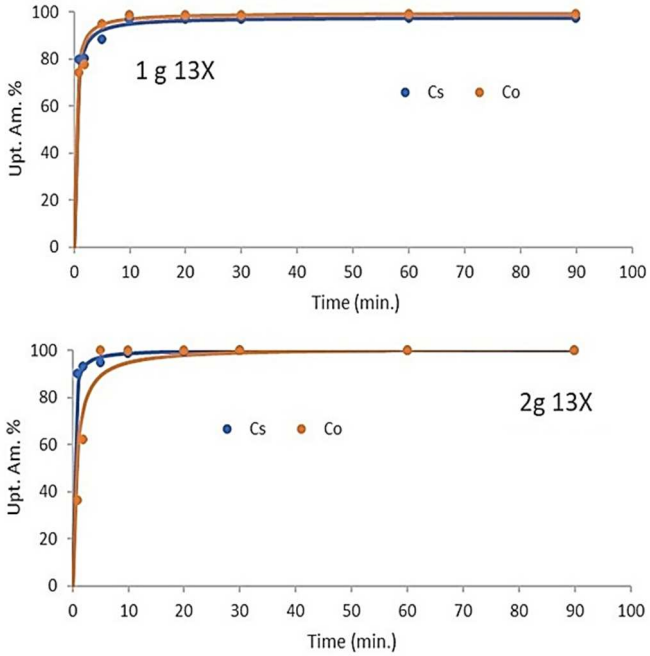


Fig. 2. Graphs of Cs^+ and Co^{2+} uptaken amount percentages from 0.5 L of a 0.01 N cesium and cobalt nitrate mixed solution as a function of time using 13X zeolite at 1 g (top) and 2 g (bottom). Figure modified from [7].

IV. CONCLUSIONS

This study investigates the ion-exchange performance of selected zeolitic materials—namely 4A, 13X and phillipsite—in the removal of cesium (Cs^+) and cobalt (Co^{2+}) ions from aqueous solutions, simulating conditions relevant to the treatment of radioactive effluents originating from decommissioned nuclear facilities. The work specifically addresses the mitigation of contamination by radionuclides Cs-137 and Co-60, which are commonly found in nuclear wastewater. The preliminary phase of the research involved the radiometric characterization of representative wastewater samples using γ-spectrometry, enabling quantification of both activity concentrations (Bq/L) and mass concentrations (mg/L) of Cs-137 and Co-60. Measured values were found to

exceed regulatory thresholds established by Legislative Decree 101/2020 and subsequent updates, highlighting the necessity for effective remediation strategies such as cation exchange. Given the chemical equivalence between radioactive and stable isotopes of Cs^+ and Co^{2+}, a series of controlled kinetic experiments were conducted using synthetic solutions containing either single cations (Cs^+ or Co^{2+}) or a mixture. Various solid-to-liquid (S/L) ratios were employed to assess the exchange performance of each zeolite. The experimental data were successfully interpreted, indicating adsorption as the dominant uptake mechanism. Key findings from the study include: (i) an increase in the S/L ratio leads to a higher equilibrium uptake of target cations in absolute terms; however, the specific uptake capacity (per gram of exchanger) decreases accordingly for all zeolites tested; (ii) among the materials studied, zeolite 13X exhibited the highest efficiency and fastest kinetics in single-cation systems, achieving up to 55% Cs^+ removal within 10 minutes and up to 99% Co^{2+} removal in approximately 5 minutes; (iii) in mixed systems containing both Cs^+ and Co^{2+}, complete removal of both cations was observed within 30 minutes when using 13X at an S/L ratio of 4 g/L. These results underscore the potential application of zeolitic exchangers—particularly 13X—as a viable and efficient solution for the remediation of low-level radioactive wastewater. Given the typical volume of spent fuel storage pools (~1.5×10^6 L) and the ultra-trace concentrations of Cs-137 and Co-60 (on the order of 10^{-7} to 10^{-9} mg/L, respectively), the application of 13X zeolite could enable a significant reduction in waste volume. Specifically, this method could potentially condense thousands of cubic meters of contaminated water into roughly one cubic meter of solid zeolitic waste, offering a compact and manageable form for subsequent disposal.

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Activity concentration measurements of radon gas in indoor environment of Benevento city, Campania region - South Italy

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***Abstract*— The Italian National Action Plan for radon 2023-2032 (PNAR) published in GU Serie Generale n.43 of 21-02-2024, together with the Italian Legislative Decree (D.Lgs) 101/2020, requires the Italian regions to monitor radon indoor activity concentrations in order to identify radon priority areas. A preliminary map of Campania region radon priority areas, in Italy, has been recently realized, based on indoor radon concentration measurements, by means of solid state nuclear track detectors (CR-39), in workplaces, residential and public buildings. In this work, a focus on the radon measurements performed in the city of Benevento is reported.**

Keywords—radon, map, CR-39, Campania, Benevento.

I. INTRODUCTION

Radon is a colorless, odorless and ubiquitous noble gas. It is both radiogenic, resulting from radioactive decay, and radioactive, further decaying by emitting ionizing radiation. Although three different radioactive radon isotopes are present in nature, namely ^{219}Rn, ^{220}Rn and ^{222}Rn, only the latter is considered significant from a radiation protection point of view and is referred to as "radon" itself [1].

^{222}Rn comes from the decay chain of ^{238}U and has a sufficiently long half-life (3.82 days) to escape from the soil and rocks where it is generated, then possibly migrate to indoor spaces. An important property of radon is its density of 9.73 g/L at 0°C, which is eight times that of air. As a result, radon tends to settle in the lower part of a confined space, meaning that a significant concentration of radon can be found at the average human height, which can consequently be inhaled [2].

When inhaled, radon is considered highly dangerous to health because of its daughter nuclides, ^{218}Po and ^{214}Po. These are non-gaseous alpha-emitting radioactive elements that can penetrate deep into the respiratory system when attached to airborne particles and cause damage to the DNA by emitting alpha particles [3]

Radon has been classified as a Group 1 carcinogenic agent by the International Agency for Research on Cancer - World Health Organization (IARC-WHO) [4]. In the United States it is considered the primary risk factor for lung cancer in non-smokers and the second leading cause, after tobacco, for smokers [1]. In Italy, the Istituto Superiore di Sanità (ISS), the leading technical-scientific body of the Italian National Health Service, estimates that the number of lung cancer cases attributable to radon exposure ranges between 1500 and 5500 each year [5]

In 2020, with the enactment in Italy of the Legislative Decree 101/2020 [6], which implement the European Directive Euratom 59/2013 about the basic safety standards for protection against the dangers arising from exposure to ionizing radiation [7], a new set of regulations on radiation protection were introduced: a radon reference level of 300 Bq/m^3 at underground, semi-underground or ground floor workplaces already existing at the time of the Decree, and a radon reference level of 200 Bq/m^3 for buildings built after December 31, 2024.

Aligning with the Directive's and Decree's provisions, the Italian National Action Plan for radon (PNAR) [8] was issued in February 2024. The PNAR outlines the need for a specific plan to measure and monitor indoor radon levels, with the aim of identifying radon-prone areas for further investigation and control in workplaces, public buildings and dwellings at lower floors. Healthcare facilities are among the public access buildings that the PNAR aims to investigate, together with schools and public administration buildings, where the high attendance rates make it important to closely monitor radon concentrations.

In this framework, at present a map of radon priority areas in Campania has been recently published [9]. The aim of this study is to report an analytical focus on the results of radon activity concentration measurements carried out in workplaces, residential and public buildings located in the city of Benevento in Campania region – South Italy.

II. Materials and Methods

A. Lithological characterization of Campania region

Radon activity concentration depends on the geological features and soil type, with its permeability controlling radon transport towards the surface [10].

Campania region has a complex geological and structural setting, shown in Fig.1. It is composed of Apennine mountains and four important volcanic centers – Roccamonfina, Vesuvius, Phlegrean Fields and Ischia island – which can contribute to radon indoor activity concentration.

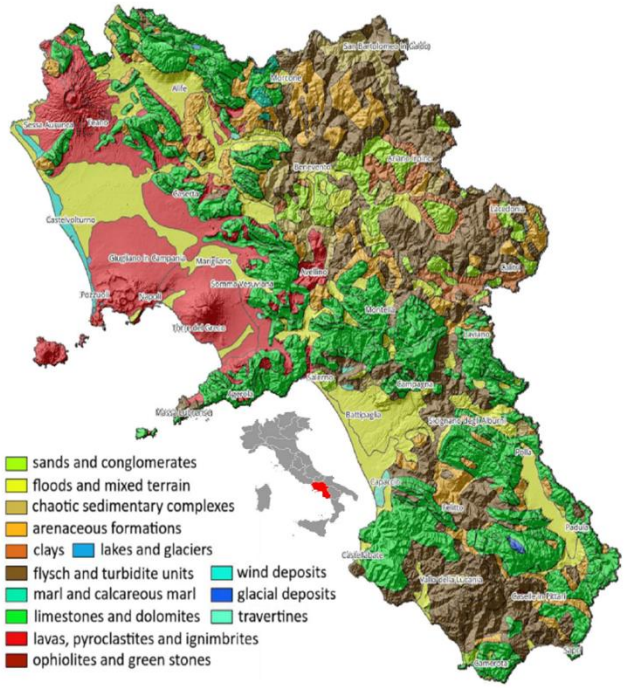


Fig.1 – Geolithological map of Campania [9].

The region's lithology was analyzed to classify areas into low, medium, and high potential natural radioactivity zones, i.e. high probability areas exceeding 300 Bq/m^3 [9]: it results that 15% of Campania's territory has high potential radiogenic emissivity, concentrated in volcanic areas, 17% in medium emissivity and 67% in low level.

Combining this lithological map with population density and distribution data for each municipality, it is possible to identify the areas with integrated potential radiogenic emission (ERPI) [9], shown in Fig.2.

Following the Italian National Action Plan for radon (PNAR) criteria and the European Basic Safety Standards Council directives, 191 municipalities have been identified as radon priority areas, primarily concentrated around volcanic centers (Fig.2) [9].

From the map it is evident that Benevento city is in the area with medium potential natural radiogenic emissivity.

In particular, the geology of Benevento is characterized by the presence of a Pleistocene intermountain basin, nestled within the Southern Apennines, known for its high seismicity due to its proximity to the Apennine earthquakes. The territory is composed of Meso-Cenozoic rock successions, with predominantly carbonate and sedimentary successions shaping the landscape, as is the case with the Mount Taburno massif [11]. In Fig. 3 the geological map of Benevento area is shown.

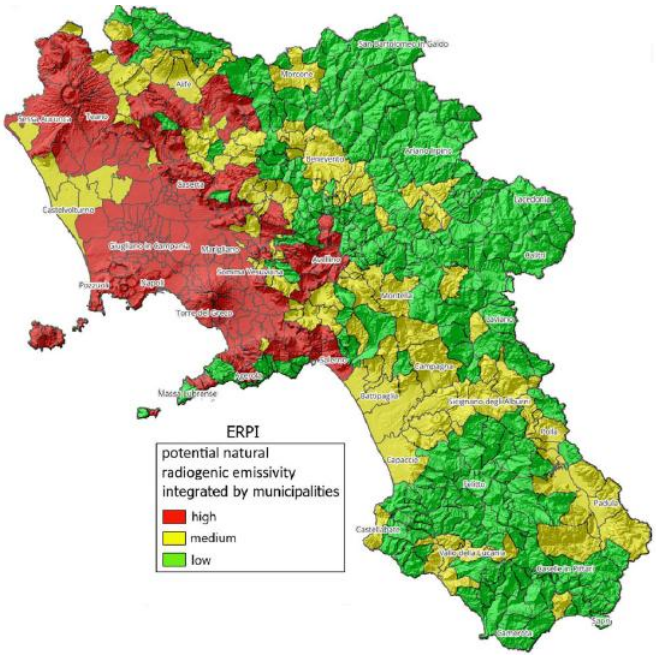


Fig.2 – Map of potential natural radioactivity emission in Campania integrated by municipalities [9].

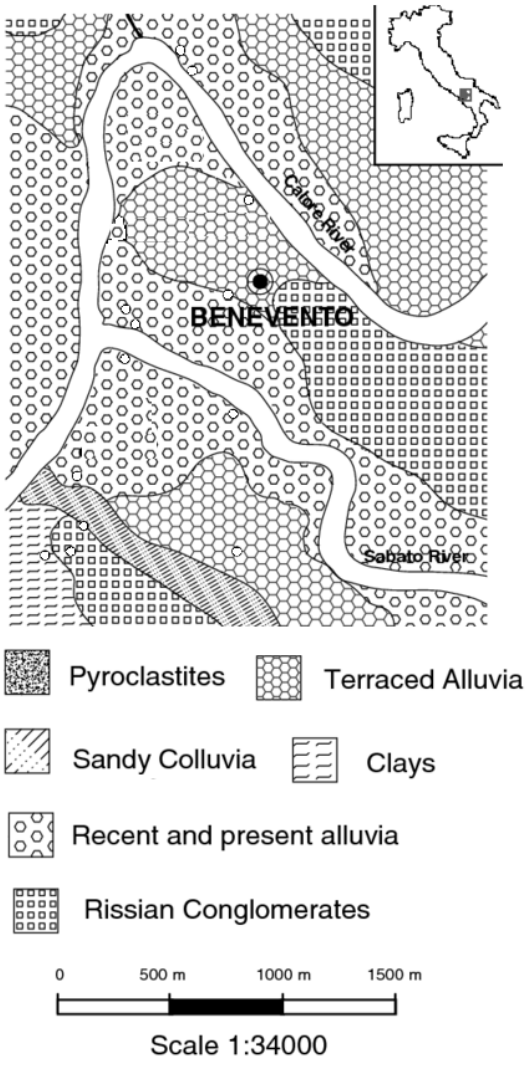


Fig.3 – Geological map of Benevento area, modified from [12].

B. *Radon measurements*

Radon activity concentration measurements have been conducted using CR-39 passive detectors and spanned over a year, divided into two semesters (fall-winter, spring-summer).

CR-39 detectors are Solid-State Nuclear Track Detectors (SSNTDs) made out of poly-allyl-diglycol-carbonate. The detection system consists of a sealed chamber Radout®, essential to selectively detect only ^{222}Rn, effectively excluding other radioisotopes or dust. In this case Radout®, a CR-39 holder produced by Mi.am srl, was used [13].

When α particles are emitted by radon and its decay products, they alter the polymer's structure, leaving latent tracks. These tracks become visible under an optical microscope after a chemical etching process, which involves immersing the detector in a 25% sodium hydroxide (NaOH) solution by weight/volume at 98 °C with a density of 1.181 g/cm³ for 1 hour, followed by a 30-minute soak in a 2% acetic acid (CH_3COOH) solution by weight/volume. Afterward, the detector is rinsed in distilled water for 1 hour to halt any further etching. Track images were acquired by using an optical microscope. The observed tracks were then converted into radon activity concentrations using a specific calibration factor [14].

The measurements performed in Benevento city were carried out for a whole year, divided into two semesters - generally the hot and the cold. The average annual indoor radon activity concentration was calculated as the average of the two semester measures.

Radon activity concentration measurements were carried out in workplaces, residential and public building, according to the indication of Italian Decree 101/2020. All the measurements were carried out on ground floor, placing detectors at least 1 m from the floor and away from doors or windows, in one or more rooms in the building.

According to the Italian PNAR, the measurement protocol, above described, for residential and public buildings is unique, as well as the exposure time and the positioning per room of the detectors.

III. Results and Discussion

Fig. 4 shows the nine buildings chosen for the indoor radon monitoring in the Benevento city, Campania region – South Italy.



Fig. 4 – Location of the buildings for the indoor radon monitoring in the Benevento city.

The buildings were chosen so as to be equally distributed throughout the city of Benevento. For privacy reasons, the buildings and their addresses are shown in capital letters on the map in Fig.4. The buildings are made of different construction materials, i.e. tuff and concrete/bricks, which can affect the value of the indoor radon activity concentration. In particular, the buildings B, E and F are all tuff building.

The rooms of A, C, D, G, H, I are made of concrete and/or bricks (Fig. 4). For each building several measurements were carried out in different rooms, precisely 89 (3 for A, 6 for B, 3 for C, 8 for D, 12 for E, 15 for F, 18 for G, 18 for H, 6 for I), all located at the ground floor.

TABLE I. INDOOR RADON ACTIVITY CONCENTRATION RESULTS IN THE BUILDINGS OF BENEVENTO CITY.

	Radon activity concentration (Bq/m3)			**Radon activity concentration (Bq/m3)**			**Radon activity concentration (Bq/m3)**	
	Value	**Err.**		**Value**	**Err.**		**Value**	**Err.**
A	55	11	E	241	22	G	90	13
A	62	12	E	391	27	G	96	20
A	88	14	F	107	17	G	104	13
B	162	18	F	132	16	G	105	16
B	220	21	F	141	16	G	101	24
B	250	22	F	151	87	H	31	3
B	394	28	F	154	21	H	35	6
B	414	28	F	163	25	H	41	7
B	201	56	F	178	22	H	48	9
C	28	8	F	179	26	H	52	7
C	52	11	F	190	32	H	55	9
C	32	8	F	195	24	H	56	8
D	160	18	F	245	33	H	57	5
D	118	16	F	262	40	H	65	8
D	142	17	F	271	35	H	66	11
D	141	18	F	325	39	H	73	8
D	150	17	F	335	48	H	74	10
D	131	17	G	34	3	H	77	9
D	106	15	G	40	8	H	85	7
D	66	12	G	41	6	H	88	12
E	86	14	G	41	6	H	131	11
E	106	15	G	42	6	H	177	69
E	97	15	G	43	6	H	101	103
E	80	13	G	45	8	I	116	33
E	171	19	G	53	6	I	41	13
E	87	14	G	54	7	I	69	20
E	184	20	G	54	6	I	27	19
E	142	17	G	55	8	I	37	30
E	242	22	G	57	7	I	171	51
E	248	22	G	57	7			

Two CR-39 detectors have been deployed per location, one for the cold semester and one for the warm semester; finally an annual average has been derived.

CR-39 detector calibration for radon involves exposing the detectors to a known radon concentration in a controlled chamber and then counting the etched alpha-particle tracks to obtain a calibration factor. This factor represents the relationship between the track density and the radon concentration. In this work, the calibration of CR-39 has been made and validated during international intercomparison surveys [13].

The results of radon activity concentration of all measurements are reported in Table I and simple statistics on the data are in Table II: the average value, the minimum and maximum value of indoor radon activity concentration (Bq/m^3) in the buildings. All results, reported in the Tables, are accompanied by absolute uncertainty.

TABLE II. STATISTICS ON INDOOR RADON ACTIVITY CONCENTRATION RESULTS IN THE BUILDINGS OF BENEVENTO CITY.

Building	Radon activity concentration (Bq/m^3)		
	Average value	Minimum	Maximum
A	68 ± 10	55 ± 11	88 ± 14
B	274 ± 3	162 ±18	414 ± 28
C	37 ± 7	28 ± 8	52 ± 11
D	127 ± 11	66 ± 12	160 ± 18
E	173 ± 27	80 ± 13	391 ± 27
F	202 ± 18	107 ± 17	335 ± 48
G	62 ± 6	34 ± 3	105 ± 16
H	73 ± 8	31 ± 3	177 ± 69
I	76 ± 23	27 ± 19	171 ± 51

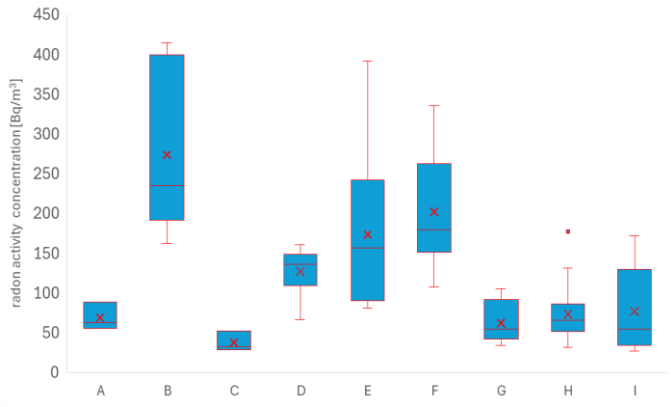


Fig.5 – Box plot of the results of radon activity concentration (Bq/m^3) in buildings of Benevento city. In red are marked: minimum, first quartile, median, third quartile, maximum.

Moreover, the distribution of the results is graphically shown in the box plot in Fig. 5.

From Table II, it emerges that the indoor radon activity concentrations in buildings B, E and F are on average higher than those obtained in other buildings. These higher values can be linked to the building material, which is the tuff. Tuff is known to contribute significantly to radon activity concentration, being a porous naturally occurring radioactive building material [15,16]. The average values of radon activity concentration in the other investigated buildings A, C, D, G, H and I are lower that B, E and F since they are built with concrete and/or bricks [17].

The variability of the data for each building depends on the their intrinsic intended use, hence some rooms are more ventilated than others and this favors a change of air and a decrease of indoor activity concentration.

IV. CONCLUSIONS

Starting from the first preliminary map of Campania region radon priority areas, the results obtained for the city of Benevento are reported in this work. Indoor radon activity concentration measurements were carried out in 9 buildings and 89 rooms. Results show higher activity concentrations in tuff buildings, compared to concrete/bricks ones. The overall results of radon monitoring in Benevento city highlight how the city falls within the area of medium potential natural radiogenic emissivity, always having values on average that do not exceed the reference value of 300 Bq/m^3.

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Reusing Phosphate Fertilizer By-products in Construction: Balancing Circular Economy Benefits with Radiological Safety

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***Abstract*—Naturally Occurring Radioactive Material (NORM) are of increasing interest for radiation protection due to the recent economic guidelines, aimed at a complete reuse of each component of a production cycle for a sustainable use of the natural resources. Of particular interest is the industrial sector of phosphate fertilizers, which produces phosphogypsum and metasilica phosphate as primary and secondary by-products. Due to the favorable mechanical properties, these materials have been studied as additive for mortar and cements. This study focuses on the city of Crotone (Italy), where in the past 50 years many reconstruction works have been incorporating residues of the local fertilizer industries, bringing to an enhanced activity concentration of radionuclides such as ^{238}U, ^{226}Ra and ^{40}K. International reference tools like the Radium Equivalent Activity and the Activity Concentration Index were calculated for samples collected from different hot spots around the city and a dose assessment for construction workers was performed using the IAEA's NORMALYSA software. Results indicated that despite the indexes being above the indicated safety values, doses to workers were below the reference levels. Overall, this study supports the idea of a complete radiological assessment when introducing NORM residues into new exposure situation for a fully sustainable strategy of industrial waste reuse. This complies with the principles of Green Economy while at the same time ensures the complete radiation protection of all individuals involved.**

Keywords—Naturally Occurring Radioactive Material (NORM), radiological risk assessment, NORMALYSA, circular economy.

I. Introduction

Natural radioactivity is linked to life on Earth as it is ubiquitous in the environment, from cosmic rays passing through the atmosphere to mineral ores and rocks in the Earth's crust that contain natural radionuclides. International Atomic Energy Agency (IAEA) classifies the latter as Naturally Occurring Radioactive Material (NORM) [1]. Specifically, NORM include the radionuclides from the decay chains of ^{238}U, ^{232}Th and ^{40}K, exposure to which is not generally of concern in terms of radiological protection. However, since they are used in some peculiar industrial activities, from ores mining to oil and gas extraction to phospate or potassium fertilizers processing, a regulatory oversight is needed because their activity concentration is enhanced [2].

For each industrial sector involving the use of NORM, it is also fundamental to point out that not only the raw materials but also by-products and residues undergo the same regulations, especially when reused as primary materials in new production cycles. Among these, phosphogypsum, a by-product of the phosphate fertilizer production industry, represents one of the most relevant cases.

Because of its mechanical durability and cost-effectiveness, following the push from the European Union to pursue a Circular Economy model [3], it has been studied in civil engineering as a component for cement, mortar or concrete.

Phosphogypsum itself is composed of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) but it is often enriched with impurities, among which NORM can be found. Within the same industrial sector, metasilica phosphate ($SiO_2 \cdot H_3PO_4$), a secondary material originating from the processing of phosphogypsum which is also used as an additive for cement or glass, also requires radiological evaluation [4].

At European level, NORM reuse is regulated by directive 2013/59 EURATOM, whose provisions have been transposed into the Italian Legislative Decree 101/2020 ([5], [6]). The regulations provide the Exemption Levels and Clearance Levels in terms of both activity concentration and effective dose as tools for risk assessments for workers and representative person - e.g. population individuals.

This study focuses on the city of Crotone (Italy), where these by-products from the local phosphate fertilizer industries were reused in construction projects, from schoolyards to square pavements and roads [7]. This perspective emphasizes how the safe management of NORM residues is of crucial importance not only for radiation protection, but also in the light of a sustainable use of natural resources, aligning with the European goals for a sustainable economy.

II. MATERIALS AND METHODS

A. Sampling and experimental measurements

Natural radioactivity measurements were performed by the *Agenzia Regionale per la Protezione Ambientale Calabria* (ARPACal) and provided to the authors for analysis.

In 62 locations (out of which 55 were selected in the city of Crotone and 7 outside the city but in the Crotone province) ambient dose equivalent rate H*(10)/t was measured by using dose rate meter at the height of 1 m above ground. The 6150AD is a portable, battery-operated dose rate meter for measuring photon radiation (both gamma and X-radiation) using a built-in Geiger-Müller counting tube as a detector [8]. For all the location coordinates were taken with a GPS device made by Garmin, maintaining the Integrity of Specifications.

For 16 samples collected from a core drilling of the road and for 28 samples collected on a seaside area where the top covering collapsed and exposed the NORM layer, in situ gamma measurements were performed. For these measurements InSpector 1000 Digital Hand-Held MCA equipped with an IPROS-2 stabilized 2″ × 2″ NaI probe with integrated preamplifier and programmable HVPS (Canberra) was used [9]. The instrument includes a multichannel analyzer with 4096 channels, covering an energy range from 25 keV to 3 MeV, and an efficiency of 36%. It can store more than 256 spectra. The device has several physical characteristics that make it particularly advantageous for fieldwork: compact dimensions (190 × 165 × 64 mm), a mass of 2.4 kg, an operating temperature range from −10 °C to +55 °C, and a battery life of approximately 12 hours under full charge. The InSpector 1000 can operate in four modes: dose measurement, source localization, spectroscopy, and nuclide identification (NID).

The collected samples were prepared according to the standard procedure for gamma spectrometry, which includes drying and homogenization and the waiting of a month in a sealed container to allow for secular equilibrium to be reached. Table 1 shows the results for the 16 road pavement samples along with their uncertainties.

The ambient dose equivalent rate was estimated using the highest radionuclide activity concentrations measured among the sixteen road pavement samples. Equation (1) was applied to represent a worst-case scenario.

$$\dot{H}^*(10) = 0.0512 \cdot A\left(^{40}K\right) + 0.564 \cdot A\left(^{238}U\right) + \\ + 0.749 \cdot A\left(^{232}Th\right) \qquad (1)$$

The calculated ambient dose equivalent was 894 nSv/h.

The 28 samples from the collapsed site were divided into five different aliquots of 1 kg after the homogenization protocol was applied. Results for the gamma spectrometry on the five aliquots are reported in Table 2.

TABLE I. ACTIVITY CONCENTRATION WITH ASSOCIATED UNCERTAINTY EXPRESSED AS STANDARD ERROR FOR EACH RADIONUCLIDE FROM THE ROAD SAMPLES.

Radionuclide	Activity concentration (Bq/kg)	Uncertainties (Bq/kg)
^{238}U	1235	280
^{230}Th	280	80
^{226}Ra	1212	215
^{210}Po	105	65
^{210}Pb	105	35
^{40}K	317	35
^{232}Th	47	15
^{228}Ra	50	15
^{228}Th	52	16

TABLE II. ACTIVITY CONCENTRATION FOR EACH RADIONUCLIDE FROM THE 5 ALIQUOTS.

	Activity concentration (Bq/kg)			
RN	***#1***	***#2***	***#3***	***#4***
40K	51±5	34±4	43±6	140±4
232Th	48±5	45±3	48±4	46±6
226Ra	1212±54	888±65	768±59	1116±71
214Bi	1010±20	1030±21	1090±23	854±25
214Pb	716±12	1070±15	1080±17	1150±15

B. Computational modelling – NORMALYSA software

The NORMALYSA (NORM And LegacY Site Assessment) software, developed by IAEA within the MODARIA project, is a tool aimed at the modelling of real-life exposure scenarios. It simulates radionuclides transport mechanism in the different environmental media (soil, air, water) and calculates effective doses from all exposure pathways chosen by the user ([10],[11]). NORMALYSA is organized in a framework of five libraries: Source, Cover Layer, Transport, Receptor, Dose. The libraries all include their specific parameters, detailed in [10], and allow for the calculation of doses for three receptors of different age: adult, child and infant.

Here, the software was used to estimate radiation doses through multiple exposure pathways, including external irradiation, inhalation, and ingestion. As input data, the average activity concentrations of each radionuclide from the Tables 1-2 were combined with site-specific parameters such as soil composition, atmospheric dispersion factors, and occupancy factors. The scenario was modelled using the "Contaminated Land" module as a source term. This module simulates a contaminated area where individuals perform different activities and where exposure is due to inhalation, accidental ingestion and external irradiation. The "Dose from occupancy outdoor" and the "Total Dose" were selected among the dose modules to calculate the dose rate from each pathway and the total annual dose rate. The receptor

considered was the adult worker, with an amount of time spent on the contaminated land equal to 200 h per year [12].

C. Radium Equivalent Activity

In order to make a radiological assessment and to quantify the combined activity of three naturally occurring radionuclides - ^{226}Ra, ^{232}Th, and ^{40}K - the Radium Equivalent Activity (Ra_{eq}) was determined as indicated in (2), where *C* is the activity concentration [13].

$$Ra_{eq} = C_{Ra} + 1.43 \cdot C_{Th} + 0.077 \cdot C_K \quad (2)$$

This index accounts for the different radiation hazards posed by these radionuclides based on their gamma-ray emission and biological impact. It also expresses the total radioactivity in a material in terms of an equivalent amount of radium-226, since radium is a major contributor to external gamma radiation exposure.

International guidelines typically set the safe limit for Ra_{eq} in building materials at 370 Bq/kg, which ensures that external gamma radiation exposure remains approximately below 1 mSv per year for the general public [5].

D. Activity Concentration Index

The Activity Concentration Index (I) is a second parameter that was determined. It is a regulatory parameter used to assess the suitability of construction materials, including phosphogypsum waste, based on their gamma radiation emissions according to (3) [6].

$$I = \frac{C_{Ra}}{300} + \frac{C_{Th}}{200} + \frac{C_K}{3000} \quad (3)$$

This index determines if the radiation levels from building materials are within acceptable safety limits for human exposure (is it below 1 mSv or 0.3 mSv for workers or representative person, respectively). The activity concentration index for building materials should not exceed the specified limits, depending on the dose criterion and the type of material used. The material is considered safe for unrestricted use in buildings if the index $I \leqslant 1$. And if the index $I \geqslant 1$ material may exceed recommended radiation limits, requiring further evaluation or restrictions of its use as follows:

- For bulk materials (e.g., concrete):
  - $I \leqslant 0.5$ for a dose criterion of 0.3 mSv/year
  - $I \leqslant 1$ for a dose criterion of 1 mSv/year
- For superficial and restricted-use materials (e.g., tiles, dry walls, ceilings boards):
  - $I \leqslant 2$ for a dose criterion of 0.3 mSv/year
  - $I \leqslant 6$ for a dose criterion of 1 mSv/year

III. RESULTS AND DISCUSSION

A. Ambient dose measurements

To enhance the visualization of the spatial distribution of NORM across the surface of the study area based on ambient dose rate measurements, geostatistical map was built and is presented in Figure 1. This map was obtained by using the Inverse Distance Weighted (IDW) interpolation method within the ArcGIS software. By employing this geostatistical approach, it is possible to delineate regions exhibiting elevated dose rates, which correspond to areas with higher radionuclide deposition and activity, commonly referred to as "hot spots". This visualization facilitates a more precise assessment of NORM distribution patterns and potential radiological hazards within the surveyed area.

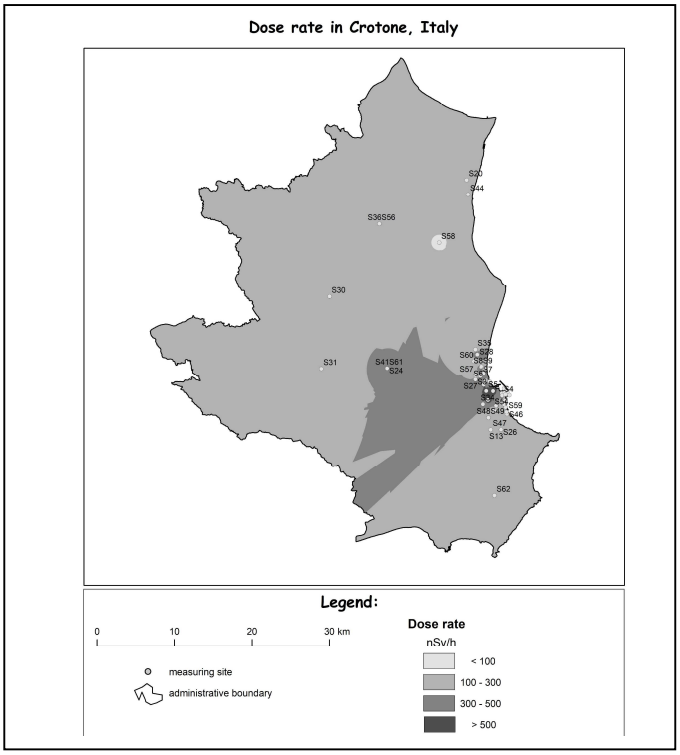


Fig. 1. Geostatistical interpolation of the ambient dose rate measurements in the study area by using the Inverse Distance Weighted (IDW) method in ArcGIS.

B. Radium Equivalent Activity

Ra_{eq} activities derived from the measured radionuclide concentrations are shown in Table 3. The calculated values for the analyzed samples ranged between 839.9 and 1303.6 Bq kg^{-1}, clearly exceeding the recommended safety threshold of 370 Bq kg^{-1}. The highest value recorded (road sample) was approximately 3.5 times higher than the safe limit. Even the lowest sample (#3) exceeded the reference value by more than a factor of 2.3, indicating elevated gamma-emitting radionuclide content across the investigated materials.

These findings suggest that such materials would require restricted or controlled use if intended for further future construction applications.

TABLE III. THE CALCULATED Ra_{EQ} FOR THE SAMPLES GATHERED IN CROTONE.

Sample	Ra_{eq} (Bq/kg)	Ra_{eq}/Ra_{eq_limit}
Road (highest values)	1303.6	3.5
#1	1284.5	3.5
#2	954.9	2.6
#3	839.9	2.3
#4	1192.5	3.2
#5	1195.3	3.2

C. Activity Concentration Index

The activity concentration index (*I*) values calculated for the samples varied from 2.8 to 4.4, exceeding the I = 1 criterion for unrestricted use of bulk construction materials, implying that the materials could contribute to annual effective doses above 1 mSv/y if reused in buildings. Nevertheless, the proportion of material that could safely be incorporated without exceeding regulatory dose limits is estimated at 23–38 % for the 1 mSv/y criterion and 7–11 % for the 0.3 mSv/y criterion. This indicates that partial reuse or blending with low-activity materials could be considered to meet radiological safety requirements. Results for the calculated *I* are reported in Table 4.

TABLE IV. TOTAL DOSE RATE FROM THE DIFFERENT EXPOSURE PATHWAYS.

Sample	*I*	% of material in use (1 mSv/year)	% of material in use (0.3 mSv/year)
Road (highest values)	4.4	23%	7%
#1	4.3	24%	7%
#2	3.2	31%	9.5%
#3	2.8	38%	11%
#4	4.0	25%	7.5%
#5	4.0	25%	7.5%

D. NORMALYSA dose assessment

The radiological risk assessments for humans were performed in the NORMALYSA software by entering the values of the measured radionuclides activities from the composite asphalt samples. NORMALYSA was utilized to simulate radiation exposure scenario for the radiation protection experts who check the condition of the metasilica phosphate deposit sites. According to the obtained information, at this site experts spent around 200 h each year ([10],[12]). The assessment run on NORMALYSA modelled a 100-years scenario and dose evaluations were obtained for 11 time points. From results in Table 5, it can be seen how the greatest contribution to total dose comes from the external exposure pathway at first and then, from 10 years on, it is due to soil ingestion. In any case the dose rate is well below the 1 mSv/y limit for workers thus leading to no significant exposure for the target receptors, identified with workers in charge of performing environmental controls on the deposit sites.

TABLE V. TOTAL DOSE RATE FROM THE DIFFERENT EXPOSURE PATHS

Time (y)	Total dose rate from all exposure pathways (Sv/y)	Dose rate from external exposure (Sv/y)	Dose rate from soil ingestion (Sv/y)
0.0	1.59E-5	1.14E-5	4.55E-6
10.0	4.80E-6	2.69E-7	4.54E-6
20.0	4.79E-6	2.67E-7	4.52E-6
30.0	4.78E-6	2.66E-7	4.51E-6
40.0	4.75E-6	2.64E-7	4.49E-6
50.0	4.73E-6	2.62E-7	4.47E-6
60.0	4.71E-6	2.60E-7	4.45E-6
70.0	4.69E-6	2.58E-7	4.43E-6
80.0	4.67E-6	2.57E-7	4.41E-6
90.0	4.64E-6	2.55E-7	4.39E-6
100.0	4.62E-6	2.53E-7	4.37E-6

IV. CONCLUSIONS

This study was aimed at evaluating a radiation risk assessment for the city of Crotone, where residues of the phosphogypsum industry were reused for civil works. A map of the ambient dose rate was built, that highlighted the areas where the higher activity concentration of natural radionuclides would be found. Laboratory gamma measurements of road and seaside sites samples, together with computational modelling using the NORMALYSA software indicated that, while the calculated radium equivalent activity (Ra_{eq}) and activity concentration index (I) consistently exceeded international radiological safety guidelines, in some cases by factors of 2.6–3.5, suggesting that unrestricted use of these materials in construction may not be radiologically safe., However, the estimated radiation doses to occupationally exposed workers remain below the applicable regulatory limits.

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Radon exposure monitoring and dose assessment for workers in drinking water distribution and sewerage plants in Naples, South Italy

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***Abstract*—The exposure to radon and its progeny represents the largest dose contribution received by the public and workers indoors. Some workplaces, due to their position in relation to the earth's crust, can be characterized by very high average annual radon activity concentration in the air. In this study, the risk of exposure to radon indoor at the workplaces of "Acqua Bene Comune (ABC)" Company in Naples is evaluated, and the annual effective dose received by the workers of this company is evaluated.**

Keywords—radon, effective dose, drinking water, sewerage.

I. Introduction

Radon (^{222}Rn) is a radioactive noble gas, with half-life of 3,8 days, that belongs to decay chain of ^{238}U. The radon is the decay product of ^{226}Ra and is present in the earth's crust, groundwater and air.

Indoor radon, and its decay products such as ^{214}Po and ^{218}Po, are considered the primary sources of population's exposure background ionizing radiation.

Radon itself is, after inhalation, completely exhaled, and therefore contributes little to the annual effective dose (about 10%). On the contrary, its progeny, mainly ^{214}Po and ^{218}Po, being electrically charged, can bind to dust particles present in the air, and they are the leading responsible for the radon dose.

Decay products can reach the tissues of the bronchi through breathing, and by emitting alpha particles, they can damage lung epithelial tissue and potentially cause cancer. It is estimated that radon can cause between 3% and 14% of lung cancer in a country depending on the average radon level in the air in that given country [1,2]. In the ^{238}U decay chain there are radionuclides which, in addition to emitting alpha particles, also emit beta particles and gamma photons.

The presence of radon in a certain area, is connected with the percentage of uranium present in the rocks that characterize that specific territory [3,4]. Because the radon is chemically inert, it tends to spread easily through rocks, into available space, and when it reaches the surface of the earth's crust it can spread inside any buildings, such as dwellings and workplaces, located on the surface. Radon can infiltrate indoor environments through fractures and openings, for example pipes for the passage of services, and thus accumulate in poorly ventilated environments.

World Health Organization has established that most radon-induced lung cancers are caused by low and moderate radon concentrations rather than high radon concentrations. In 2009, the WHO report established an action level of 100 Bq/m^3 for residential radon with the recommendation not to exceed 300 Bq/m^3. In Italy, with decree 101/2020, in according to 59/2013/EURATOM Directive of the European Commission, the reference level for dwellings and workplaces was set at 300 Bq/m^3 [5], and at 200 Bq/m^3 for dwellings built after 2024.

At present, Italian legislation has required employers to carry out measures of annual average radon activity concentration in air, in the following places:

- underground workplaces,
- workplaces in basement rooms or located on the ground floor, located in the radon prone-areas,
- specific types of workplaces identified in the National Radon Action Plan,
- thermal baths.

The "Acqua Bene Comune (ABC)" Company in Naples, manages the drinking water distribution plants and sewerage plants of the city of Naples. The workplaces of this company consist of long tunnels, caverns and underground rooms with different sizes. In these types of workplaces, also considering the presence of tuffaceous rocks with different concentrations of uranium in the territory of the city of Naples, high concentrations of radon are expected. As a consequence, effective doses from radon exposure for workers could be high. Furthermore, it is very interesting to evaluate the exposure in these types of workplaces considering that these places represent an almost unique condition, in terms of the

conformation of the workplaces. In such workplaces, as in the tunnels and caverns, of course, the contribution of radon is due to the exhalation of gas not only from the floor, but also from the walls and ceiling.

In this study, annual average radon activity concentration in air measurements were carried out in the workplace of "Acqua Bene Comune (ABC)" Company in Naples and the annual effective dose was calculated for each worker using data from the company's activity register.

II. Materials and Methods

A. Measurement sites

The ABC Company manages the drinking water resources collection and supply systems and the sewerage lifting systems of the city of Naples. The average annual concentration of radon activity in air for 53 sites located in drinking water resources collection and supply plants and in 27 sites located in sewerage lifting plants was measured.

The workers of this company spend part of their working time in the inspection and maintenance activities of the aforementioned plants.

The workplaces for this company consist of:

- for the drinking water resources collection and supply plants: long tunnels, with lengths from a few hundred meters to a few km, often located below the tuffaceous hills that orographically characterize the city of Naples;
- for the sewerage lifting plants: rooms with variable width from 50 to 150 square meters in the basement, underground floor or second underground floor.

TABLE I. Description of 53 workplaces for drinking water plants and numeber of measurement points

Workplaces code	***Name of workplace***	***Number of Measurement points***	***Floor level***
1	Cave Reichlin	14	Under tuffaceous hill
2	Garittone	1	-1
3	Cappella Cangiani	4	0, -1
4	Scudillo	7	Under tuffaceous hill
5	Centrale Pagliare	3	0, -1
6	S. Giacomo dei Capri	6	Under tuffaceous hill
7	Chiaiano	3	0, -1, -2
8	Zanfagna	2	Under tuffaceous hill
9	Via Pacuvio	3	Under tuffaceous hill
10	Vallone Miano	3	0, Under tuffaceous hill
11	San Prisco	1	Under tuffaceous hill
12	Lufrano	1	-1
13	Caserta al bravo	1	-1
14	San Sebastiano	2	-2
15	Ventaglieri	1	0
16	Galleria cane	1	Under tuffaceous hill

For the drinking water resources collection and supply plants, 22 main work sites have been identified, with collaboration of the Prevention and Protection Services of the ABC company, each with a variable number from 1 to 14 measurement points, for a total of 53 measurement sites (Table I).

For the sewerage lifting plants, 12 main work sites have been identified, with collaboration of the Prevention and Protection Services of the ABC company, each with a variable number from 1 to 3 measurement points, for a total of 27 measurement sites (Table II).

Average annual Radon activity concentration in the air measurements were carried out at 80 sites in total, at the ABC company.

For some years now, this company has adopted a system of daily control of workers' entries and exits from the sites. Thanks to this access register, it is possible to know the residence time of each worker and for each site, in a specific time interval.

In order not to underestimate the risk of exposure to radon for workers, in collaboration with the Prevention and Protection Services of the ABC company, the different work scenarios that could arise during the year were examined. In this way it was possible to identify all the work sites where workers spend the most time during the year.

Furthermore, all workers in the ABC company were informed and trained about the risks deriving from ionizing radiation and in particular in relation to the presence of radon in the workplace. The company periodically delivers to all workers a semi-facial mask with high filtration efficiency for fine dust and toxic vapours.

For the drinking water resources collection and supply plants, there are a total of 45 workers investigated for exposure to radon, 34 hydraulic systems maintenance technician and 11 electromechanical technician. For the sewerage lifting plants, there are a total of 30 maintenance technicians investigated for the exposure to radon.

B. Radon measurement

Measurements of radon activity concentration in the air were carried out using solid-state nuclear track detectors CR-39. CR-39 is a polymer, in the form of poly allyl diglycol carbonate (PADC) and produced in sheet 1-2 mm thick, which has high sensitivity to charged particles, as alpha-particles and heavier nuclei. This type of detector are not sensitive to gamma

TABLE II. Description of 27 workplaces for sewerage plants and numeber of measurement points

Workplaces code	***Name of workplace***	***Number of Measur. points***	***Floor level***
1	*Via Coroglio*	*4*	*0, -1*
2	*Via Acton*	*2*	*-2*
3	*Villa comunale*	*2*	*-1*
4	*Mergellina*	*2*	*-1, -2*
5	*Vigliena*	*1*	*-1*
6	*Rondinelle*	*3*	*-2, -3*
7	*Rione Villa*	*1*	*-1*
8	*Galleria Vittoria*	*4*	*0, -1*
9	*Taverna del ferro*	*2*	*-1*
10	*Campo d'isola*	*2*	*-1*
11	*Arco Mirelli*	*3*	*-1, -2, -3*
12	*La pietra*	*1*	*-1*

and beta radiation, which is a great advantage when measuring radon.

The detectors were supplied by the radioactivity laboratory of CeSMA - University of Naples Federico II, which has accreditation according to the European Standard EN ISO/IEC17025 for the "Integrated measurement method for determining average activity concentration of the radon 222 in the environment air using passive sampling and delayed analysis" (UNI ISO 11665-4: 2021) [6].

CR-39 detectors are a passive detectors and provide an average measurement of the concentration of radon activity in the air over the exposure time interval.

The detectors were prepared by inserting the polymer CR-39 inside a plastic diffusion chamber, as in Fig. 1, which controls the entry of radon excluding dust and progeny. Each detector has been identified with a unique code by the manufacturer.

The detectors were positioned in the identified workplaces at a height varying between 1 and 2 meters from the ground, and where possible, away from the walls to exclude the contribution of the thoron. However, the minimum distance from the wall was 5 cm. Each detector is accompanied by a signal to avoid damage or tampering to the detector itself.

For each monitoring workplaces, the detector were exposed for two consecutive semesters to obtain the mean radon activity concentration over a year. After exposure the detectors were taken and delivered to the laboratory for reading.

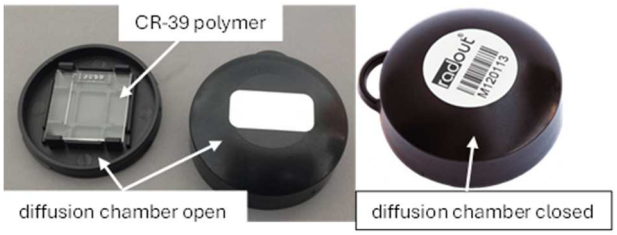


Fig. 1.CR-39 detector

C. *Exposure situations*

The radon dose depends on several factors such as ventilation of rooms, the presence and the size of dust in the air and respiration rate. High ventilation reduces the probability of progeny formation, thereby reducing the equilibrium factor and the dose received, the presence of dust in the air reduces the unattached fraction of radon progeny, and therefore reduces the radon dose, a high breathing rate, associated with more intense activities, naturally increases the inhaled activity of radon and its progeny. In order to calculate the dose coefficients, ICRP publication 137 adopts four exposure situations, "indoor work activity", "indoor sedentary work activity", "Mine work activity", "Tourist cave work activity" , characterized by certain values of the fraction and dimensions of the unattached fraction, the breathing rate and the equilibrium factor F.

The workplaces of the ABC company, are characterized largely by very long tunnels of some kilometers with heights varying from 3 to 10 meters. Although remedial actions, such as the installation of forced ventilation systems have been taken into account, considering the considerable volume of working environments, the modest length of time workers remain during the year and the principle of optimizing radiation protection which must also take into account economic and societal factors, the aforementioned remedial actions have not been adopted.

Therefore a large part of the working environments are poorly ventilated and characterised by the presence of non-negligible dust

in any case, since precise data on the environmental conditions that influence the radon dose were not available, it was considered more appropriate to associate these work environments with the "indoor work activity" condition considered, characterized, according to the approach used by the ICRP, by a breathing rate equal to 1.2 m^3/h, an unattached fraction equal to 8% and an equilibrium factor equal to 0.4.

Therefore, for the dose calculation it was carried out considering the aforementioned value for the equilibrium factor.

D. *Effective dose calculation*

The annual effective dose E due to exposure to radon and progeny was calculated, according with Italian decree 101/2020 and ICRP 137 [7], and according to the following formula:

$$E = \textit{radon level} \times \textit{time} \times \textit{dose coefficient} \qquad (1)$$

where:

- E = annual effective dose (mSv/year),
- *radon level* = average radon activity concentration in air (Bq/m^3)
- *time* = exposure time per year (h/year),
- *dose coefficient* = 6,7 x 10^{-9} Sv Bq^{-1} h^{-1} m^3

Thanks to the updated activity register for each worker, it was possible to calculate the annual effective dose for the individual worker.

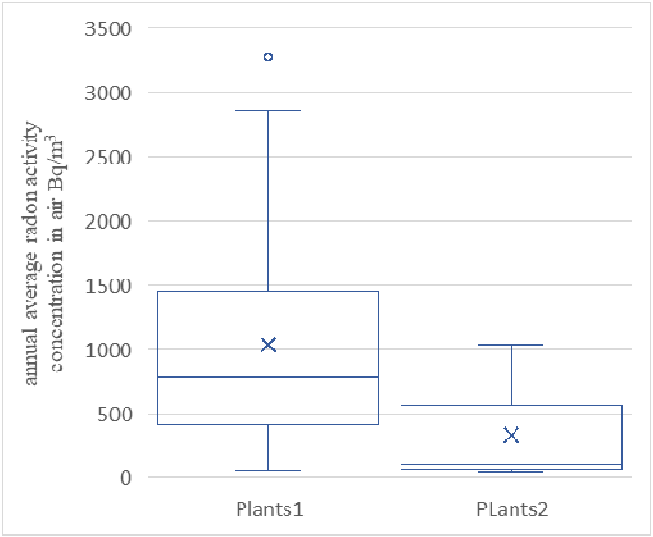


Fig. 2. Annual average radon activity concentration in air, for drinking water resources collection and supply plants (Plants 1), and for sewerage lifting plants (Plants 2). The lower and upper whiskers represent the minimum and maximum value of the data respectively. The segment inside the box represents the median. The symbol "x" represents the mean.

In fact, the register, updated by the person responsible for maintenance and inspection activities, contains the times each

worker stays on a specific site, where the radon activity concentration measure were carried out.

The dose received by a specific worker at a specific site, is that obtained from formula (1) where the "radon level" is equal to the annual average radon activity concentration measured at that site, and the "time" is the residence time of that particular worker at that specific site. The time (residence time) noted in the register also take into account the travel times to the site, due to entry and exit from a specific long tunnel to reach the specific work site.

The effective dose for the individual worker was calculated by summing the dose contributions received by the individual worker at the workplaces attended in a year.

III. Results and Discussion

For the campaign of measurements of average annual concentration of radon activity in air, 160 detectors were deposited in the workplaces of the "Acqua Bene Comune (ABC)" Company in Naples, 80 for the first half of the year and 80 for the second half of the year. All detectors were recovered, thus indicating the effectiveness of the training for workers regarding the importance of risk assessment and the signals placed in the places where the detectors were deposited.

The results of the measurements return annual radon concentration values that vary over a significantly wide range, from a minimum of 48 ± 8 Bq/m^3 to a maximum of 3,3 ± 0,3 kBq/m^3 for drinking water resources collection and supply plants, and from a minimum of 37 ± 7 Bq/m^3 to a maximum of 1,0 ± 0,1 kBq/m^3 for the sewerage lifting plants. The minimum values correspond to rooms with a connection with free air and are quite ventilated, while the maximum values correspond to tunnels under the hill or rooms with no direct connection with free air and very little frequented.

The annual arithmetic mean indoor radon concentration, for the drinking water resources collection and supply plants, is 1,034 ± 0,1 kBq/m^3 while for the sewerage lifting plants, is 0,33 ± 0,04 kBq/m^3.

All results of radon activity concentration are reported in the boxplot in Fig. 2.

The uncertainty include the uncertainty associated with the detector readings, the exposure time and the statistical uncertainty of the average of the detector readings.

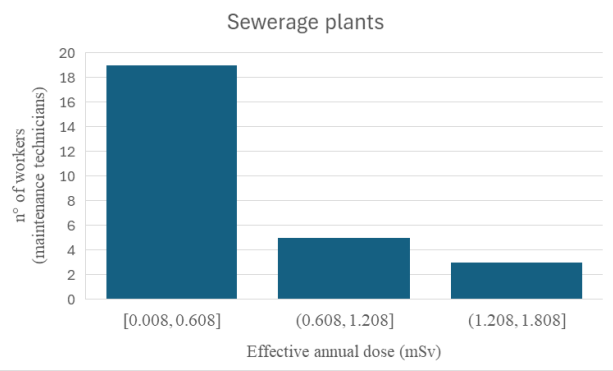


Fig. 3. Effective annual dose for workers of sewerage lifting plants.

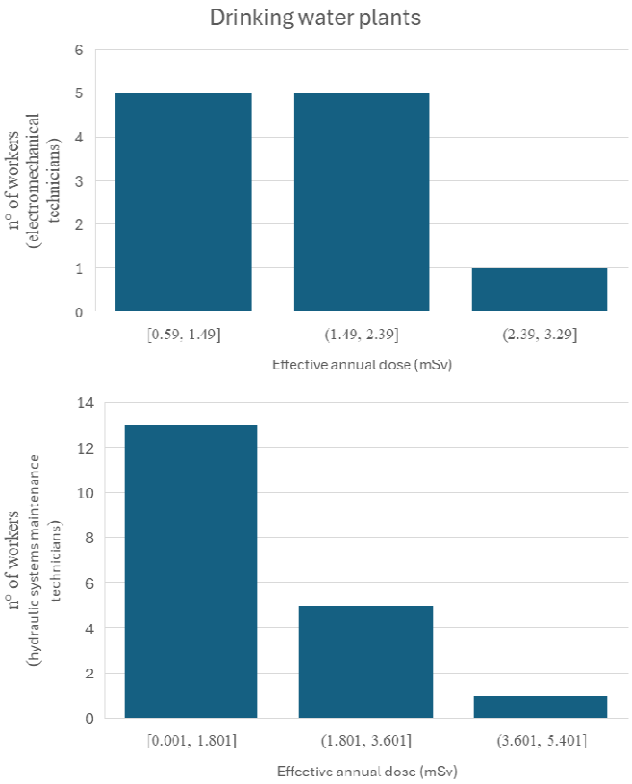


Fig. 4. Effective annual dose for workers of drinking water resources collection and supply plants.

The uncertainties obtained ranged from 11% for high radon concentration values above 200 Bq/m3 to 16% for low values below 200 Bq/m3.

For the water collection and supply plants 45 out of 53 sites have a concentration value greater than the reference level of 300 Bq/m^3 (80%), and for the sewerage plants 12 out of 27 sites have a concentration value greater than the reference level of 300 Bq/m^3 (44,4%).

In relation to the results of the calculated annual effective dose, it is noted that the values are all quite smaller than the reference level identified by Italian legislation, 6 mSv/y.

In fact, as it appears from the activity records, workers spend a limited time during the year in the work environments covered by this paper (average value 10 hours/year maximum value 130 h/year).

If the ABC company had not used the activity records, the dose assessment would have been carried out on the basis of the standard working time parameter of 2000 h/year with a consequent significant overestimation of the dose to workers.

For the sewerage lifting plants, the effective dose for maintenance technicians is in the range 0,192-1,218 mSv/y (Fig. 3).

For the water supply plants, we have two different types of workers, hydraulic systems maintenance technicians and electromechanical technicians. Some workers, belonging to both categories, did not carry out any risk activities during the year and therefore will not be considered in the following analysis.

For the former, the effective dose varies between 0,001 mSv/y to 3.712 mSv/y, with an arithmetic mean of 1,238 mSv/y. For the latter the effective dose is in the range 0,59-2,427 mSv/y, with an arithmetic mean of 1,488 mSv/y (Fig. 4).

IV. Conclusion

In the workplaces of the ABC company, the average annual radon activity concentration was measured with CR-39 passive detectors, in the most significant places from the point of view of exposure to radon. Considering the types of workplaces, in particular for drinking water supply systems, this result was expected. Most measurements showed radon concentrations much higher than the reference level of 300 Bq/m^3.

Under such working conditions, the evaluation of the effective dose received by workers is a critical problem for the employer. In this case the employer has implemented a system for recording access to workplaces and their residence times, in this way it was possible to calculate the personalized dose for each worker based on their activity conducted during the year.

The recording of effective doses small compared to high radon concentrations was probably also possible thanks to the presence of workers with equal skills who were able to rotate during the interventions that became necessary during the year.

Acknowledgment

The authors would like to thank the staff members of Prevention and Protection Services of the "Acqua Bene Comune" ABC company.

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Quality assurance of radon activity concentrations measurement in wells and water supply systems of Osijek-Baranja County, Croatia

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***Abstract*— This paper presents the results of radon (^{222}Rn) activity concentration measurements in groundwater and public water supply systems in Osijek-Baranja County, eastern Croatia. Measurements of the collected water samples were carried out using two analytical techniques: the emanometric method (by using the AlphaGUARD with the AquaKIT module) and/or the liquid scintillation counting method (by using the TriCarb 2900 LSC system). Water samples were collected from public water supply systems in urban areas, as well as from private wells and natural springs typically found in rural areas. The aim of the study was to determine radon activity concentrations in the water samples, to estimate ingestion dose due to intake of radon through drinking water and to assess quality assurance and quality control (QA/QC) of the measurement process. The obtained radon activity concentrations were all significantly below the EU reference level of 100 Bq/L for drinking water. The annual effective dose from water ingestion was very low (order of μSv), indicating no radiological risk to the population. The applied QA/QC procedures confirmed the reliability and reproducibility of the measurement results.**

Keywords—radon, water samples, emanometry, liquid scintillation counting, quality assurance

I. INTRODUCTION

Radon-222 is a naturally occurring radioactive noble gas formed in the primordial decay chain of uranium–238. Due to its gaseous nature and chemical inertness, radon migrates from mineral grains into pore spaces in both soil and rock. Radon typically enters aquifers by dissolving into groundwater that is surrounded by different geological formations. To a much lesser extent, radon may also dissolve into water from the air. Typically, the highest radon concentrations are found in wells and groundwater i.e., untreated water, while the lowest levels are usually measured in surface waters and processed water (both chemically and mechanically) [1].

The Euratom Drinking Water Directive establishes a parametric value of 100 Bq/L for radon in drinking water. Concentrations above this level require an assessment of potential health risks and consideration of remedial actions. For optimization purposes, Member States may define national reference levels higher than 100 Bq/L but not exceeding 1,000 Bq/L. Concentrations greater than 1,000 Bq/L necessitate immediate corrective measures without further evaluation [2].

According to the World Health Organization [3] the annual effective dose from long-term ingestion of radionuclides in drinking water should not exceed 0.1 mSv. Assuming an average daily water consumption of 2 L, guidance levels for most natural and artificial radionuclides can be derived using appropriate dose conversion factors. However, for radon-222 (^{222}Rn), no specific guidance level is provided. Instead, the WHO recommends repeated monitoring when radon activity concentrations in public water supplies exceed 100 Bq/L [4]. Although there is currently no national program for systematic monitoring of radon in water in the Republic of Croatia, measurements are carried out when reliable data indicate that activity concentrations may range between 100 and 1,000 Bq/L [5]. Nevertheless, the Laboratory for Low-Level Radioactivity, at the Department of Physics, University of Osijek decided to include measurements of radon activity concentration in water [6] as a part of the broader studies of radon in indoor air and soil, aiming to gain a more detailed insight into radon concentrations across the ecosystem [7,8]. In addition, we also measured radon in thermal waters (spas) across the Republic of Croatia to obtain a further understanding of radon migration through the ecosystem [9]. While the previous nationwide survey [6] provided an overview of radon activity concentrations in drinking water across Croatia, regional variations related to local geology and hydrogeology could not be fully resolved due to the spatial averaging of data. Therefore, Osijek–Baranja County was selected for a detailed investigation as a representative area within the Pannonian Basin characterized by well-defined sedimentary formations, extensive groundwater use, and contrasting water supply sources (deep artesian aquifers vs. shallow private wells). Focusing on our local region allowed the implementation of quality assurance and quality control (QA/QC) procedures, as well as more refined evaluation of radon behaviour in groundwater systems. This targeted approach complements and validates the earlier national assessment by providing locally specific data. The structure of this paper is as follows: section II describes the geological characteristics of Osijek–Baranja County that influence radon occurrence in groundwater. Section III details the sampling strategy, analytical methods, calibration procedures, and the applied quality assurance and quality control (QA/QC) measures. Section IV presents and

interprets the results, including statistical analysis, assessment of potential sampling and transport effects, and the estimated dose. Section V concludes the paper by summarising the key findings and discussing their implications for future radon monitoring in water.

II. GEOLOGICAL CHARACTERISTICS OF OSIJEK-BARANJA COUNTY

Osijek–Baranja County, situated in the eastern part of Croatia within the Pannonian Basin, is characterized by predominantly young Neogene to Quaternary sedimentary formations composed of riverine and lacustrine deposits, extensive alluvia, and widespread loess layers that dominate the elevated zones. The Pannonian Basin in this region accumulated sediments during the Pliocene–Pleistocene epochs, comprising fine-grained materials such as silt, clay, and sand typical of fluvial and alluvial environments [10]. Along the major rivers, particularly the Drava and Danube, extensive alluvial deposits of sand, silt, and gravel create highly permeable strata that strongly influence local hydrology, groundwater dynamics, and soil productivity. In contrast, the elevated terraces and upland areas—most notably in Baranja—are covered by loess deposits, giving rise to fine-textured, nutrient-rich, and easily cultivated soils. The interplay of these geological and geomorphological features with the regional climate, fluvial processes, and a long history of agricultural use make Osijek–Baranja one of Croatia's most fertile and intensively cultivated regions.

Radon production in soils and aquifers primarily depends on the concentration of its parent radionuclides, uranium (^{238}U) and radium (^{226}Ra). In the Pannonian Basin, these elements are found within fine-grained detrital sediments—such as mica, feldspar, and volcanic ash fragments dispersed throughout alluvial and lacustrine deposits. Consequently, soils and sediments derived from uranium and radium-enriched layers within certain formations may exhibit locally enhanced radon generation and exhalation potential.

The previously described soil types—loess, sandy alluvium, and clay or alluvial clay—exhibit distinct hydrogeological properties that influence radon transport. Highly permeable formations, such as coarse sands and gravels, promote enhanced radon diffusion and advective migration through the soil profile. In contrast, fine-grained, clay-rich soils with low permeability act as effective barriers, significantly limiting radon mobility [11].

Water supply in Osijek-Baranja County relies largely on groundwater resources. Urban centres such as Osijek are connected on the centralized water treatment and distribution systems. This water supply system is based on deep groundwater wells drilled into artesian aquifers. In this system water comes from deep, protected groundwater layers, often 100–200 meters below ground, which helps ensure good quality and protection from surface contamination. EU and national investment in recent years has targeted upgrading water and wastewater infrastructure around Osijek and nearby settlements. In rural, areas many households still use private drilled wells connected to individual plumbing. These wells are typically fed by shallow to moderately deep groundwater.

For this reason, the study evaluated the radiological risk associated with radon in drinking water by collecting samples from both the public water supply system and private wells, as both sources continue to be used by residents in the study area. Expecting low radon activity concentrations, particularly in samples collected from public water supply systems—since the water is technically treated before distribution—special measures were implemented to ensure comprehensive quality assurance and control of all variables and procedures, from sampling to measurement, that could influence the analytical results.

III. MATERIALS AND METHODS

Radon-222 concentrations in water were quantified using two independent analytical approaches to ensure robustness of the results. The first approach relied on liquid scintillation counting with a Tri-Carb 2900 TR system (PerkinElmer). The instrument response was established following the guidance of ISO 13164-4:2015 [12]. Calibration solutions were prepared by diluting a certified Radium-226 standard (Czech Metrology Institute) into radon-free water, after which the mixtures were stored for roughly one month to allow secular equilibrium between Radium-226 and Radon-222. Measurement spectra were processed with SpectraView software, which was used to subtract instrumental background and determine the calibration factor (CF = 275 ± 2 cpm/Bq; $R^2 = 0.999$).

Radon concentrations c_{Rn} (Bq/L) and their associated 2σ uncertainties were obtained from the expressions:

$$c_{Rn} = \frac{G-B}{CF \cdot D \cdot V} \qquad (1)$$

$$2\sigma = \frac{2\sqrt{\frac{G}{T_G}+\frac{B}{T_B}}}{CF \cdot D \cdot V} \qquad (2)$$

where G and B (cpm) are the gross and background count rates, $D=e^{-\lambda t}$ corrects for radioactive decay between sampling and counting time, V is the sample volume (L), and T_G and T_B (min) denote the count durations for the sample and background vials.

The minimum detectable activity (MDA) (Bq/L) was derived from Currie's approach [13]:

$$MDA = \frac{2.71+4.65\sqrt{B \cdot T_B}}{CF \cdot V \cdot T_G}. \qquad (3)$$

yielding 1.2 Bq/L for a 60-min measurement of both sample and blank. In all equations, the radon activity concentration c_{Rn} is expressed in becquerels per litre (Bq/L), which represents the number of radioactive decays occurring per second in one litre of water.

The second analytical technique used in this study was an emanometric method based on an AlphaGUARD PQ2000 PRO coupled with an AquaKIT module, operated according to ISO 13164-3:2013 [14]. In this configuration, a 100 mL aliquot of water was circulated through a sealed loop where radon was degassed into a 0.56 L ionization chamber. The radon activity concentration in water was calculated from the monitored air concentration and system parameters using:

$$c_w = \frac{c_a\left(\frac{V_{system}-V_{sample}}{V_{sample}}+k\right)-c_0}{1000} \qquad (4)$$

In this equation, c_a (Bq/m³) represents the radon activity concentration in the air within the closed system, c_0 (Bq/m³) is the radon activity concentration in the ambient room air, V_{system} (mL) is the air volume of the enclosed system, V_{sample} (mL) is the volume of the water sample, and k is the temperature-dependent Bunsen coefficient. The MDA limit for this

configuration was 0.1 Bq/L, considerably lower than that achieved with liquid scintillation counting.

The accuracy of both measurement techniques (liquid scintillation counting and emanometric method) was verified through participation in the international intercomparison exercise "Measurement of ^{222}Rn activity in water samples" organized by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN, Report IRSN/2020-00754; English version of IRSN/2020-00384). The results obtained by our laboratory were within ±5% relative error of the reference value, demonstrating excellent analytical performance and measurement traceability. In addition, instruments were periodically cross-checked with reference and blank samples to ensure measurement reliability. Repeated measurements confirmed consistency within the defined uncertainty limits, supporting the complementary use of both techniques for accurate assessment of radon activity in drinking water.

Water samples for radon analysis were collected in accordance with ISO 13164-1:2013. Prior to sampling, the outlet was flushed for several minutes to remove stagnant water and ensure representative conditions. Each sample was collected directly into airtight glass or scintillation vials without the inclusion of air bubbles, immediately sealed to prevent radon loss, and labelled with the sampling time, date, and location. In addition to standard procedures, this study investigated the influence of sampling and handling conditions on the measured radon activity concentration. Specifically, the effects of temperature variation between sampling and measurement, different sampling techniques (direct filling from the tap, collection via hose, and sub-surface sampling from a container), as well as mechanical agitation and shaking during sample transport, were systematically evaluated. These factors were assessed to quantify their potential contribution to radon loss or variability in measurement results and to improve the reliability of future sampling protocols in field conditions.

IV. RESULTS AND DISCUSSION

A. Results and statistical analysis

In total, 194 samples were collected and all samples were divided in four different categories according to the type of the sampled water source: public water systems (PW), springs of public water systems (PW-S), private groundwater wells (Wells) and surface water (Surface). The obtained results and corresponding descriptive statistics of radon activity concentrations in the analyzed water systems are presented in Table 1 as well as corresponding box-and-whisker plots in Figure 1.

TABLE I. DESCRIPTIVE STATISTICS (N, AM, SD, MED, MIN, MAX, GM, GSD) OF EXPERIMENTALLY OBTAINED VALUES OF RADON CONCENTRATIONS IN DIFFERENT WATER SYSTEMS (PW – PUBLIC WATER SYSTEMS, PW-S – SPRINGS OF PUBLIC WATER SYSTEMS, WELLS – PRIVATE GROUNDWATER WELLS, SURFACE - SURFACE WATER) USED IN OSIJEK-BARANJA COUNTY, CROATIA.

Water systems	N	AM [Bq/L]	SD [Bq/L]	MED [Bq/L]	MIN – MAX [Bq/L]	GM [Bq/L]	GSD
PW	110	4.5	3.4	2.5	0.8 – 15.9	3.4	2.1
PW-S	17	5.6	3.8	4.1	1.6 – 12.6	4.5	2.0
Wells	40	6.9	4.0	5.9	1.8 – 17.4	5.9	1.8
Surface	27	1.0	0.3	0.9	0.6 – 1.6	0.9	1.3

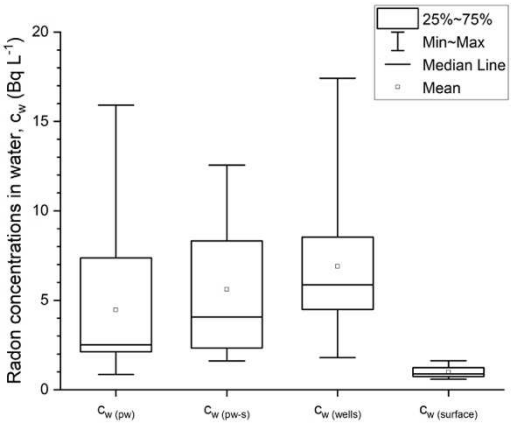


Fig. 1. Box-and-whisker plots of measured values of radon activity concentrations in water for different water systems (PW – public water systems, PW-S – springs of public water systems, Wells – private groundwater wells, Surface - surface water) used in Osijek-Baranja County, Croatia. Boxes represent the interquartile range (25^{th}–75^{th} percentile), whiskers show minimum and maximum values, the horizontal line indicates the median, and open squares denote the mean.

In the different scenarios of groundwater sources such as public water systems (PW), springs of public water systems (PW-S), and private groundwater wells (Wells) showed higher arithmetic mean (AM) values of 4.5, 5.6, and 6.9 Bq/L, respectively. In contrast, surface water displayed a much lower mean concentration of 1.0 Bq/L. Median values followed a similar trend, ranging from 2.5 to 5.9 Bq/L in groundwater and only 0.9 Bq/L in surface water. The observed variability (standard deviations of 3.4–4.0 Bq/L for groundwater) reflects the heterogeneous geological settings influencing radon release into the aquifers. Maximum values reached up to 17.4 Bq/L in well water, whereas surface water remained consistently low (0.6–1.6 Bq/L). This pattern aligns with the known behaviour of radon in the environment: radon is continuously generated from radium-bearing minerals in aquifer sediments and dissolves into groundwater during its residence time. Surface waters, in contrast, are more aerated and experience rapid radon degassing to the atmosphere, resulting in much lower activity concentrations. Similar findings have been reported in other European studies [1].

The relatively low concentrations measured in all water types reflect the geological and hydrogeological characteristics of the Pannonian Basin, where the aquifers consist mainly of young, fine-grained Neogene–Quaternary sediments with low uranium and radium content [15, 16]. In addition, the water from public supply systems originates from deep, confined aquifers (100–200 m) so called artesian well, further isolated from near-surface sources of radon emanation.

To evaluate whether the observed variations in radon activity concentrations among different water source types were statistically significant, a series of inferential statistical tests were performed. Prior to hypothesis testing, the normality of data distributions (radon activity concentration) in four different water system categories (PW, PW-S, Wells, and Surface) was examined by using the Shapiro–Wilk and Kolmogorov–Smirnov tests.

TABLE II. RESULTS OF THE APPLIED NORMALITY TESTS.

Water System	Shapiro–Wilk p-value	Decision (α = 0.05)	Kolmogorov–Smirnov p-value	Decision (α = 0.05)
PW	7.6×10^{-10}	Reject normality	6.7×10^{-7}	Reject normality
PW-S	0.0158	Reject normality	0.563	Cannot reject
Wells	7.6×10^{-4}	Reject normality	0.460	Cannot reject
Surface	0.0244	Reject normality	0.291	Cannot reject

Both tests indicate that none of the datasets follow a normal distribution at the 0.05 significance level, although the Kolmogorov–Smirnov test was less sensitive for smaller groups (PW-S, Wells, Surface). Given the consistent rejection by the Shapiro–Wilk test (more powerful for small–medium samples), non-parametric statistical methods are justified for further analyses. Consequently, Mann–Whitney tests and Spearman correlation were applied in subsequent analyses. Since data are non-normally distributed, the Mann–Whitney U test was applied to compare median radon concentrations between different water source categories.

TABLE III. MANN–WHITNEY U TESTS APPLIED BETWEEN DIFFERENT WATER SOURCE CATEGORIES.

Comparison	U	p-value	Z	Decision (α = 0.05)
PW vs. PW-S	0.186	-1.33	Not significant	No difference
PW vs. Wells	1.5×10^{-4}	-3.79	Significant	Wells > PW
PW vs. Surface	3.2×10^{-14}	7.59	Significant	PW > Surface
PW-S vs. Wells	0.155	-1.42	Not significant	No difference
PW-S vs. Surface	3.9×10^{-8}	5.50	Significant	PW-S > Surface
Wells vs. Surface	5.3×10^{-12}	6.90	Significant	Wells > Surface

Median radon concentrations in groundwater sources (PW, PW-S, Wells) were significantly higher than in surface waters ($p < 0.001$). However, differences within the groundwater group (PW vs. PW-S vs. Wells) were not statistically significant, indicating similar radon levels among these sources.

Spearman's rank correlation coefficients, r_s were used to examine relationships between radon concentrations across different water source categories.

TABLE IV. SPEARMAN'S RANK CORRELATION RESULTS AMONG DIFFERENT WATER SOURCES.

Comparison	Spearman r_s	p-value	Correlation
PW vs. PW-S	-0.515	0.0345	Significant, moderate negative correlation
PW vs. Wells	-0.472	0.0021	Significant, moderate negative correlation
PW vs. Surface	0.449	0.0189	Significant, moderate positive correlation
PW-S vs. Wells	0.267	0.300	Not significant
PW-S vs. Surface	-0.145	0.580	Not significant
Wells vs. Surface	-0.198	0.321	Not significant

The significant negative correlations observed between radon concentrations in public water systems (PW) and both their source springs (PW-S) and private wells (Wells) suggest that these water types are influenced by distinct hydrogeological and hydrogeochemical conditions. Elevated radon levels in PW-S and Wells likely show direct interaction with radium-bearing geological formations and limited aeration in confined aquifers, whereas lower concentrations in PW may result from dilution, aeration, or mixing of water from multiple sources during treatment and distribution. In contrast, the moderate positive correlation between PW and surface water ($\rho = 0.45$) may indicate partial mixing between shallow groundwater and surface systems. These findings imply that both geological heterogeneity and water supply management practices contribute to the observed spatial variability of radon concentrations. From a practical perspective, the results highlight the effectiveness of public water treatment and distribution processes in reducing radon exposure, while emphasizing the need for continued monitoring to ensure the protection of drinking-water quality across different supply sources.

B. Field environment and quality assurance

Field measurements and sampling were carried out under diverse environmental conditions including variable terrain, bumpy access roads, as well as a range of hydrogeological settings such as public water supply wells, private wells, springs, and surface water sources. Seasonal variations were pronounced, with air temperatures exceeding 35 °C during summer and dropping below −10 °C in winter, potentially influencing sample handling and radon retention. In addition to routine QA/QC procedures, we aimed to investigate the potential influence of sample temperature variations, the maintenance of temperature stability, shaking of samples during transport, and different sampling techniques on the measured radon activity concentrations. These factors are known to affect radon degassing and may introduce additional uncertainty during sampling and transport, especially under the variable field conditions. For these reasons, we analysed the influence of these three variables:

a) temperature

Two sample sets are divided according to temperature stability and statistical analysis was performed to evaluate the potential influence of temperature changes during transport on the measured radon activity concentration in water samples. The Shapiro–Wilk normality test indicated that data obtained under constant temperature conditions (samples transported in the thermally insulated transport box) did not follow a normal distribution, while data obtained under variable temperature conditions (samples transported in the transport bag, not thermally insulated) were normally distributed. Therefore, both parametric (two-sample t-test) and non-parametric (Mann–Whitney U) tests were applied to compare the two datasets. In both cases, the results (t-test: $p = 0.384$; Mann–Whitney U test: $p = 0.50$) showed no statistically significant difference between the two sampling conditions. These findings suggest that moderate temperature fluctuations during sample transport did not significantly affect the measured radon concentrations, confirming the robustness of the applied sampling and storage procedures.

b) agitation and shaking

Again, two sample sets are divided according to sample agitation during transport in order to investigate it's influence

on the measured radon activity concentration in water and statistical analysis was performed. One sample set was shaken vigorously during transport, while other sample set was vertically fixed in a transport box. The Shapiro–Wilk normality test indicated that both data sets are normally distributed. Therefore, parametric (two-sample t-test) was applied to compare the two datasets. Obtained results (t-test: $p = 0.119 > \alpha_0 = 0.05$) confirmed that the difference between two sample averages is not big enough to be statistically different. These findings suggest that physical agitation during sample transport did not significantly affect the measured radon concentrations.

c) sampling procedure

Two sample sets are divided as well according to the sampling method. One data set was sampled directly in the glass airtight bottle, while other set was sampled by using a different approach (indirect sampling from the bucket filled with the hose connected to the tap). The Shapiro–Wilk normality test indicated that both data sets are normally distributed. Therefore, a parametric (two-sample t-test) was applied to compare the two datasets. Obtained results (t-test: $p = 0.441 > \alpha_0 = 0.05$) confirmed that the difference between the two averages of the data sets is not big enough to be statistically different. These findings suggest that the sampling method did not significantly affect the measured radon concentrations.

C. Dose estimation and radiological risk

If the arithmetic mean value of the measured radon activity concentration in public water supply systems as representative for the vast majority of the population, the annual effective dose resulting from radon ingestion can be estimated. This estimation assumes annual water consumption rates of 100 L for infants, 75 L for children, and 50 L for adults. Given that these population groups represent 5%, 30%, and 65% of the total population, respectively, the weighted average annual water consumption is calculated to be 60 L per person. The annual effective dose due to radon ingestion can therefore be estimated using the following relationship:

$$E_{ing} = K \cdot c_w \cdot KM \cdot t \qquad (5)$$

In this expression, E_{ing} is the effective dose due to radon ingestion (Sv), K is the conversion factor between radon activity and dose ($3.5 \cdot 10^{-9}$ Sv/Bq), c_w is the determined radon activity concentration in the water sample (Bq/L), KM is the water consumption (60 L/year) [15]. If equation (5) is applied, with a very conservative estimation of drinking 60 L of water per year from a specific water source (which is less than one cup of water per day), the annual effective dose due to radon ingestion of water from the public water supply is 0.94 μSv. Using the same equation and assumption, for the highest measured radon concentration in private wells of 17.4 Bq/L, a ingestion dose of 3.7 μSv is obtained. When estimating the annual effective dose from ingestion, a population-weighted annual water consumption of 60 L/year per person was applied. This value was derived from the relative proportions of infants (5%), children (30%), and adults (65%) in the county and does not represent physiological intake of each age group, but rather provides a single representative parameter for assessing the collective exposure of the population. The ingestion dose coefficient for ^{222}Rn is not strongly age-dependent because radon is a noble gas with extremely short residence time in the gastrointestinal tract, leading to negligible retention. For this reason, both WHO and UNSCEAR recommend the use of a single dose coefficient (3.5×10^{-9} Sv/Bq) for all age groups. Nevertheless, to address potential differences, separate dose estimates for children and adults were additionally evaluated. Even when applying age-specific consumption rates (100 L/year for infants, 75 L/year for children, and 50 L/year for adults), all resulting annual ingestion doses remained in the range of only a few μSv/year—well below the WHO recommended limit of 0.1 mSv/y [3, 4]. These findings confirm that the radiological impact of radon ingestion from drinking water is negligible for all age categories. In addition, the obtained ingestion dose values are consistent with those reported in neighbouring countries that share the same geological setting of the Pannonian Basin [16, 17, 18].

Effective dose from the inhalation of radon and its progeny (E_{inh}) originating from radon in water can be calculated from the following equation:

$$E_{inh} = c_w \cdot R \cdot D \cdot F \cdot T \qquad (6)$$

where c_w is the mean radon (^{222}Rn) activity concentration in water (Bq/L), R is the concentration ratio of radon in the air to radon in water (10^{-4}), D is the dose conversion factor for radon ($9\ \mathrm{nSvh^{-1}}\ (\mathrm{Bq/m^3})^{-1}$), F is the indoor equilibrium factor between radon and its progeny (0.4), and T is the estimated time spent indoors (7000 h per year) [19]. For both forementioned cases, these annual doses are very low: 11.3 nSv and 43.9 nSv, respectively. When compared to inhalation doses of the residential indoor radon (of origin other than water) in the same county, these doses were hundreds of times higher [20] than the joint doses from inhalation and ingestion of radon originating from the water used for household purposes.

V. CONCLUSION

The results of this study confirm that radon activity concentrations in all analysed water samples from Osijek–Baranja County are significantly below the EU reference level of 100 Bq/L, indicating negligible radiological risk to the population. The estimated annual effective doses from both ingestion and inhalation pathways were on the order of only a few μSv/y, far below the WHO guideline value of 0.1 mSv/y. These findings demonstrate that radon in drinking water does not represent a relevant exposure pathway in the investigated region but rather serves as a useful indicator of geological and hydrogeological processes.

The implemented quality assurance and quality control (QA/QC) procedures—covering calibration, intercomparison testing, and evaluation of sampling and transport conditions—confirmed the robustness and reliability of the applied measurement techniques. Statistical analyses showed that moderate variations in temperature, agitation during transport, and different sampling approaches did not significantly affect the measured radon activity concentrations. However, the most evident factor affecting measurement reliability was the presence of air bubbles in sample bottles, which can facilitate radon degassing and lead to underestimation of the true activity concentration. This aspect is currently under further investigation to quantify the exact decrease of measured radon concentration caused by air inclusions. Therefore, ensuring airtight sample collection remains the most critical step in ensuring the reliability and quality of the measurement process.

In line with the open-science requirements of the project No. 581 – UNIOS – 103 "FIZIONAR", all validated radon-in-water measurement data obtained in this study will be made publicly available through the institutional data repository. Uploading of the complete dataset is mandatory under the project framework and will be completed after the project preparation process. Until the repository publication is finalized, the dataset is available from the authors upon request.

ACKNOWLEDGMENT

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CloudChain: Decentralized Marketplace for AI Compute Resources

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***Abstract*—The artificial intelligence (AI) infrastructures have been centralized leading to limited accessibility, monopoly of computational resources, and an uneven distribution of services. CloudChain is a decentralized AI compute market that is made out of blockchain and can solve these challenges with a transparent, trustless, and fair system. It brings together decentralized storage, smart contracts, as well as token incentives to allow fairness, privacy, and auditing. Privacy is ensured through encryption and zero-knowledge proofs, task allocation, distribution of rewards and enforcement of SLA is automated through smart contracts. The performance metrics measured in a 30-day simulation of the major cloud providers (AWS, Google Cloud, Azure, Hetzner, Lambda Labs) and the community nodes included the performance measures of latency, throughput, and SLA compliance, as well as token allocation and resource utilization. Findings indicate that CloudChain does provide the necessary balance in the workloads, high quality in the service delivery, and equitable rewards among heterogeneous members. The suggested framework envisioned will create a democratized, secure, and sustainable platform of decentralized AI, enabling innovation, openness, and diversity of global AI ecosystems.**

***Index Terms*—Decentralized AI, Blockchain, Smart Contracts, Token Economy, Privacy Preservation, AI Marketplace, Distributed Storage**

I. Introduction

Artificial Intelligence (AI) is also changing the industries of healthcare and transportation, finance, and the metaverse, by streamlining operations, making decisions data-driven, and creating new business opportunities [6] [11]. The present AI ecosystem, though with its revolutionary capabilities, is still extremely centralized with a small number of large corporations, having overwhelming amounts of processing power, distinctive algorithms, and infrastructures, which require large amounts of capital to recreate and maintain [4] [5]. This monopoly limits entry to independent developers and other smaller organizations and suppresses innovation and prioritizes AI creation to corporate goals and not the needs of society [4].

The current AI distribution platforms such as GitHub and commercial marketplaces do not have monetization, transparency, and efficient auditability, and monopoly of information remains accessible to single points of failure and centralized providers [5] [7]. With these constraints, there is the necessity to have decentralized systems that are fair, transparent, and equally accessible throughout the ecosystem of AI [9].

The blockchain has become an important facilitator of decentralization in terms of distributed registries, consensus, and smart contracts, which form environments of trustless collaboration [12]. It assists in numerous provable transactions, giving rewards to participants through token economies, and data and model protection [7] [9]. More recent models like Decentralized Physical Infrastructure Networks (DePINs) and Learning Markets (LM) present the scalability and universality of decentralized AI markets, on the way to a more cooperative development of a more fair AI ecosystem [2] [10] [9] [4].

Nonetheless, there continue to be limitations in the form of performance stalling in distributed storage, agreement delays, information alignment, and hazards on data privacy. The peer-to-peer networks such as IPFS have much better read/write throughput than a consensus-based system, such as Tendermint and Hyperledger but demand stronger coordination [1]. Also, such sophisticated economic frameworks as Stackelberg games are required to balance providers, requesters, and verifiers interests against each other [3].

To overcome such problems, the current paper offers a blockchain-based decentralized AI compute resources platform called CloudChain. CloudChain will be the platform that will allow open interactions between AI providers and consumers through smart contracts, decentralised meta-management, and token incentive systems. CloudChain is a scalable incentive and privacy-preserving trustless federated learning-based, peer-to-peer storage system providing a trusted infrastructure to democratize AI ecosystems [1] [9] [11].

II. Literature Review

The current literature on the cross-section of artificial intelligence, cloud infrastructure, and blockchain technologies has shown both great opportunities and remarkable challenges [1] [12]. Analysis of the inventory of decentralized storage platforms IPFS, Tendermint, and Hyperledger shows that even though peer-to-peer networks are more resilient and guarantee data integrity, the mechanisms of consensus have been linked to scalability and efficiency limitations that slow the creation of sustainable AI markets [1] [13].

The threats of centralization continue to exist at the ecosystem level, where large corporations have the hegemonic control of computational resources, data sets and access to models [4] [5] [14]. Meanwhile, the current repositories and marketplaces

such as GitHub-based and commercial such as repositories do not monetize, provide provenance, or do so equitably as it is audited, and independent developers are handicapped [5] [15]. Most of the solutions suggested though may provide scalable infrastructures, and trustless infrastructures but very few provide solutions to these structural limitations [4] [5] [11] [16].

Federated environments (based on blockchain) have tried to address these concerns through the provision of trust, transparency and auditability [3] [17]. Potholes like oracle-supported decentralized federations and Hyperledger Fabric also allow the verifiability of AI training and model integrity but are limited by the ineffective throughput of transactions, the intensive use of energy, and the inadequate overlap of incentives [7] [8] [18] [12] [19].

It is also being realised through new models like Decentralized Physical Infrastructure Networks which show how blockchain and IoT, and token-based incentives can be used to share resources within distributed environments [2] [10] [20]. Nevertheless, they are not yet adapted to AI workloads due to the inefficiency of incentive alignment and unequal resources allocation. Other projects such as SingularityNET and blockchain-based Learning Markets envision decentralized and fair future AI ecosystems but have problems related to scalability and interoperability as well as uptake [4] [9] [13] [14].

Based on the literature that has been reviewed there are three key observations that can be made:

1) Unified AI systems limit creativity, inclusiveness, and equality [4] [5] [13].
2) Blockchain offers trust and provenance tracking and alignment of incentive but scalability continues to be one of the biggest issues [1] [3] [7] [12] [14].
3) No single model incorporating decentralized storage, compute, privacy and economic sustainability remains unified [2] [9] [10] [15].

It is these research gaps, which are the basis of the proposed CloudChain framework a decentralized system of AI compute market-focused on ensuring efficiency, fairness, and long-term sustainability [4] [5] [9] [10] [11].

III. Methodology

CloudChain will be built as a decentralized AI compute resource marketplace, where blockchain, decentralized storage, smart contracts, and incentive mechanisms will be used to guarantee accuracy, equity, and efficiency. This segment describes the infrastructure design, business process, decentralized hyper store policies, incentive and price schemes, privacy-compliant technologies, and performance measurement system.

A. System Architecture

CloudChain is established on a stacked design comprising blockchain management, Compute coordination, and decentralized storage. The machine is mainly composed of three kinds of players; resource providers, requesters and oracles.

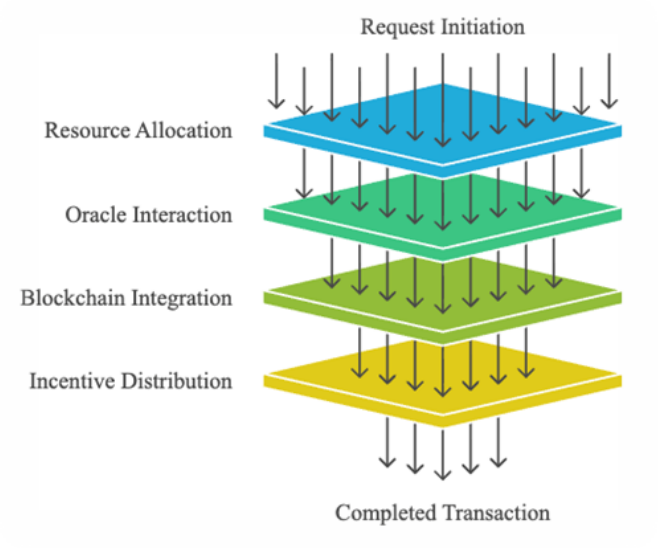


Fig. 1. Operational Workflow of CloudChain

Resource providers invoke idle computation resources, including GPUs and TPUs, and requesters invoke AI workloads, including training a model, using it, or preprocessing data. Oracles are intelligent agents that independently receive notifications of resource performance and SLA compliance and post the outcomes, which are reported to the blockchain smart contracts.

The architecture consists of four layers: the application layer provides task submission, tracking, and payments through interaction with the user; the blockchain layer provides the ability to perform tasks on trustless systems by using platforms such as Ethereum or Hyperledger Fabric [7] [12]; the decentralized storage layer stores model and metadata with the help of IPFS or Swarm to offer high speed to the user; and the compute orchestration layer load balances, allocates resources dynamically and schedules tasks across multiple providers. The design guarantees scalability and transparency in CloudChain with decentralization.

Fig. 1 illustrates the stack architecture of a blockchain transaction framework with the process starting with request initiation followed by a series of stages or steps until a completed transaction is attained. In the initial level, resources are assigned such that they guarantee provision of computational and network capacity needed in processing. This is then succeeded by oracle interaction external datas are looked up to prove dependable regarding decision making and validation of transactions. After verification, the information becomes part of the blockchain, which is indisputable, trustful, and transparent. Lastly occurs the incentive distribution which appreciates those involved into the system due to their contribution towards maintenance and Agility of the systems. The integrated movement of these layers creates a full circle of transaction and this proves the organized systematic nature of

Its data retrieval time T_r and write time T_w can be formalized as below:

$$T_r = S/B_r, \quad T_w = S/B_w + T_c \tag{1}$$

in which S denotes the size of the data, B_r and B_w denote read and write bandwidths, respectively, and T_c is the consensus overhead time that is added in the distributed systems. Utilizing this formula enables CloudChain to actively plan resource placement and access strategies in order to reduce latency.

the process.

B. Decentralized Retrieval Mechanism

Effective decentralized AI market forces require the storage of models, metadata, and transaction logs. CloudChain considers three types of storage, simple peer-to-peer replication, permissionless consensus replication, and replication under private consent replication [1]. P2P networks such as IPFS provide the highest performances in terms of read and write speed especially in those data that are read and written most often and Tendermint Cosmos and Hyperledger Fabric introduce overheads in their consensus process that can create slowness in the system. CloudChain IPFS stores frequently used AI models and metadata to optimize latency, and transactional metadata, as well as SLA records, are stored using consensus-driven platforms to guarantee integrity.

C. Incentive and Pricing Model

CloudChain introduces maximum participation and fairness by adopting a token-based incentive system with dynamic pricing. The units of resources contributed and authenticated using oracle resources are rewarded, based on the units of compute. The requesters are billed based on the quality of service and actual use of resources. Following the concept of Stackelberg differentiation games [3], the provider is considered to be a leader; the requesters and oracles are followers. The maximization of profits of providers is:

IV. Privacy-Preserving Gradient

Mathematically, the privacy-preserving gradient $\Delta\theta'$ is calculated as:

$$\Delta\theta' = \Delta\theta + \mathcal{N}(0, \sigma^2) \tag{2}$$

where $\mathcal{N}(0, \sigma^2)$ denotes the Gaussian noise with variance σ^2.

A. Implementation Details

The system is produced with Solidity smart contracts in the Ethereum testnet to perform blockchain business, IPFS to decentralize file storage, and Python to coordinate tasks and track them. Oracles will be simulated to offer SLA verification, and SLA will be coded into smart contracts to ensure automation and transparency. Scalability, efficiency, and robustness can be analyzed under real conditions by experimenting with different network structures, such as the number of peers, provider capacity, request patterns, etc., and using a set of experimental simulation tools to measure reliability and scalability of these structures and the network process itself [1] [3] [7].

B. Experimental Setup and Evaluation Metrics

CloudChain performance and evaluation were carried out in a controlled simulation setup based on real life decentralized compute conditions. A Python-written discrete event simulator contained a testnet of the Ethereum smart contract execution service and an IPFS cluster of decentralized storage. Models of providers (enterprise-grade providers) and community nodes with adjustable compute capacities were used as simulated entities. The simulation was done over a period of 30 days, and during this period the workloads were given dynamically in allotsion depending on the availability, SLA conditions, and verifications occurring in oracle.

Network delay was stochastically characterized as 10-120 ms, bandwidth was 50- 200 Mbps of constituent community nodes and greater than 1Gbps enterprise nodes and task arrivals were characterized as a Poisson process to represent asynchronous workloads. The experiments were carried out ten times at different loads and the average results were stated to decrease the randomness. Variability sources were the latency, bandwidth variations, oracle delays and variability in the node performance.

On-chain logs and oracle outputs provided the performance metrics. The metrics were Latency (mean time to complete a task), throughput (completed operations/s second), token allocation developed using blockchain ledgers, and fairness was calculated using the Index to Jain distribution across requester allocations. Such an arrangement makes sure results making up CloudChain reported values such as latency, throughput, fairness, and token allocation are empirically-based, reproducible, and representative of real-world decentralized AI systems.

Algorithm 1 Privacy-Preserving Gradient Mechanism

procedure PrivacyPreservingGradient($\Delta\theta$, σ)
Input: Raw gradient $\Delta\theta$, noise variance σ^2
Output: Privacy-preserving gradient $\Delta\theta'$

Step 1: Generate Gaussian Noise
$\epsilon \sim \mathcal{N}(0, \sigma^2)$ ▷ Sample noise from Gaussian distribution

Step 2: Apply Noise to Gradient
$\Delta\theta' \leftarrow \Delta\theta + \epsilon$ ▷ Equation: $\Delta\theta' = \Delta\theta + \mathcal{N}(0, \sigma^2)$

Step 3: Validate Privacy Guarantees
CheckDifferentialPrivacy(σ) ▷ Ensure (ϵ, δ)-DP guarantees

return $\Delta\theta'$
end procedure

V. Results

The functionality of CloudChain was tested in several aspects such as storage latency, compute throughput, allocation of incentives and equity. Entailed experiments were performed when simulated providers and requesters had the chance to

Algorithm 2 Differential Privacy Verification

procedure CHECKDIFFERENTIALPRIVACY(σ, ϵ, δ)
Input: Noise scale σ, privacy parameters ϵ, δ
Output: Privacy compliance status

Step 1: Calculate Privacy Bound
$\epsilon_{actual} \leftarrow$ ComputePrivacyBound(σ, δ)

Step 2: Verify Compliance
if $\epsilon_{actual} \leq \epsilon$ **then**
return True ▷ Meets differential privacy requirements
else
return False ▷ Privacy parameters need adjustment
end if
end procedure

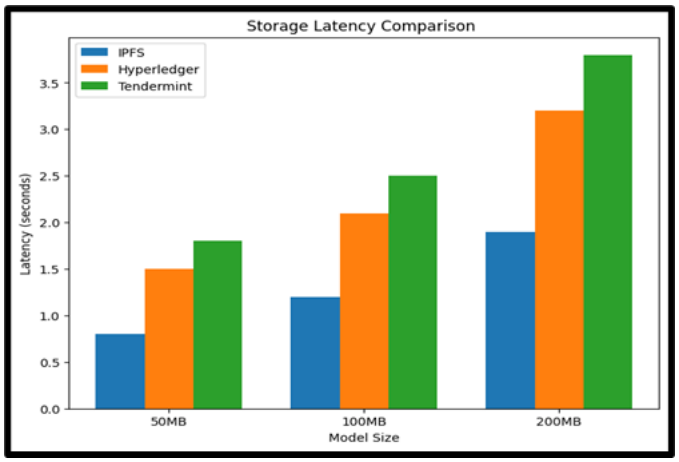


Fig. 2. Storage Latency Comparison Across Decentralized Systems

interact in a blockchain testnet with decentralized storage integration with IPFS. All evaluation metrics are represented through relevant graphs that will help to reveal the efficiency, scalability, and appropriateness of the suggested marketplace

A. Storage Performance Evaluation

To evaluate the efficiency of the hybrid storage model introduced by CloudChain, we have contrasted the read/write latency of IPFS, Hyper sucular, and Tendermint with dealing with AI model of varied size (50 MB, 100MB, and 200MB).

In the given Fig. 2 shows how various storage platforms fate with a read/write latency. Just as it was anticipated, IPFS had always the lowest latency especially with smaller files since it was a peer-to-peer based design. Hyperledger and Tendermint had further delays due to consensus overheads that were amplified by the scale of the model. This finding justifies the use of IPFS as the default storage model in CloudChain when the model cannot be easily accessed (through consensus-based systems), but for important metadata needing more integrity assurances, they are saved by consensus-based systems.

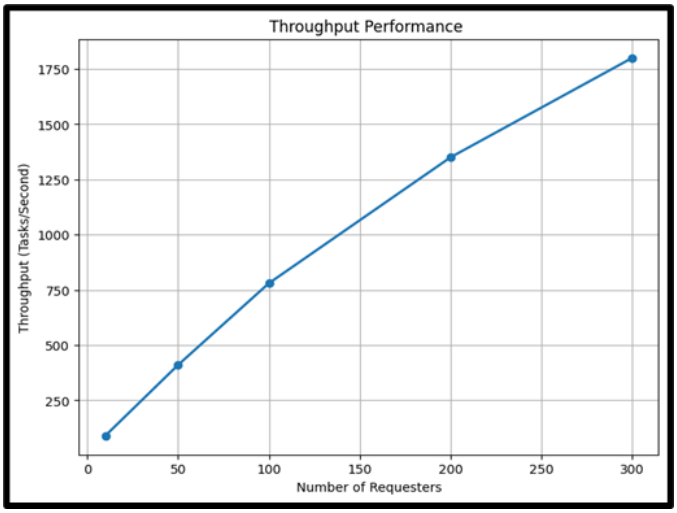


Fig. 3. Throughput Performance of CloudChain

B. Compute Throughput

The throughput of CloudChain was also defined as the count of AI operations that were successfully executed in one second with more and more parallel requester.

In the given Fig. 3 indicates that the throughput appreciation rate is almost linear when the requester count is increased between 10 and 300. This is made possible by the decentralized layer of compute orchestration that allocates tasks to multiple providers without any single point of failure. The findings verify that CloudChain can support large scale workloads without being adversely affected in terms of performance.

C. Incentive Distribution

The incentive system based on tokens was tested to determine the way officers award rewards based on the number of different degrees of compute resources provided by a provider.

In the given Fig. 4 shows a simulated experiment of CloudChain on the allocation of tokens to over 28 compute providers over a 30 day period. Unsurprisingly, large cloud vendors, including AWS, Google Cloud, and Azure, secured the most tokens because these vendors boast significant computing resources and high reliability in uptime. Nevertheless, the significantly smaller communities (in terms of membership size) like Community Node 1, 2, and Community Node 3 also received a substantial share of rewards, proving that the system could ensure the introduction of smaller contributors into the decentralized marketplace. CloudChain has achieved this equilibrium, which justifies its purpose of providing an ecosystem that allows enterprise-tiered providers to interact with single contributors on an equal footing.

D. Fairness Evaluation

The Fairness Index by Jain was used to gauge fairness in the distribution of resources based on the distribution of compute tasks among the requester.

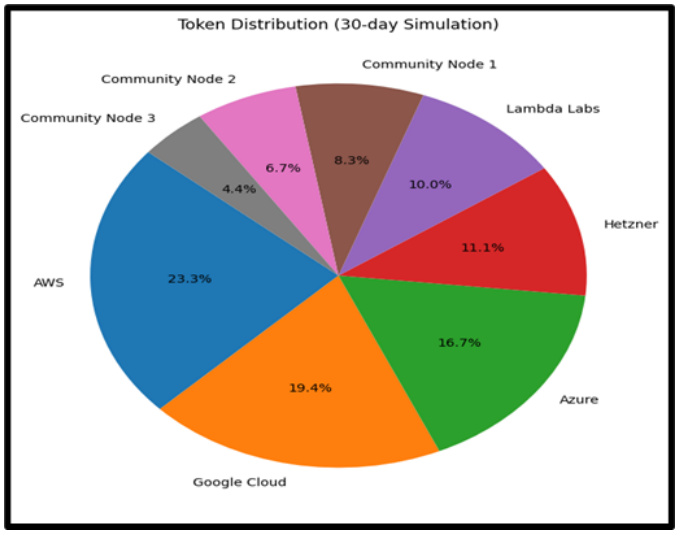


Fig. 4. Token Distribution among distributors

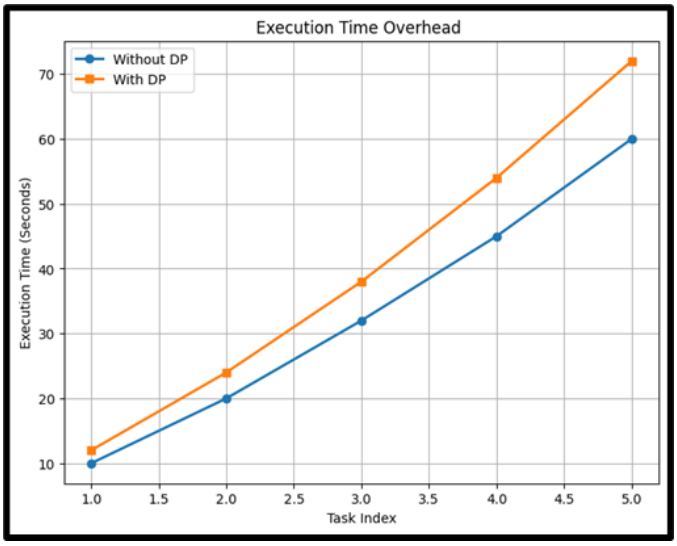


Fig. 6. Execution Time Overhead of Privacy-Preserving Computation

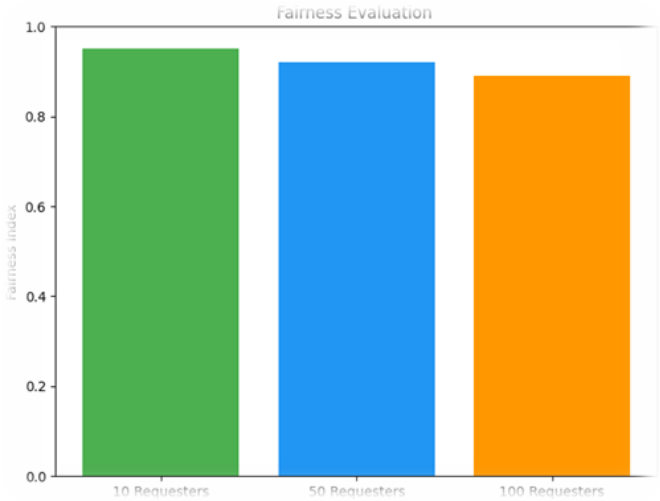


Fig. 5. Fairness Evaluation in Resource Allocation

In the given Fig. 5 shows the fairness index using various sizes of requester groups. Individual indexes are at least 0.89, indicating that CloudChain continues to achieve equal distribution of resources regardless of whether the number of participants increases or decreases. This affirms the fact that the system does not lead to resource monopolization and is not exclusive.

E. Privacy-Preserving Computation Overhead

In order to analyze the effects of loss of privacy on computation, we have compared task processing time in the presence of and without privacy preserving techniques.

In the given Fig. 6, whenever differential privacy is included, a significant overhead in terms of the execution times is observed since task completion time is affected by it by around 15 and 20. Nevertheless, this overhead can always be accepted taking into account all the strong improvements in data privacy and model confidentiality. The findings confirm the incorporation of privacy preserving mechanisms as a requisite compromise of CloudChain.

VI. Conclusion

Artificial intelligence (AI) infrastructures remain centralized and restrict access to improve innovation and transparency in the international AI ecosystem. The suggested CloudChain system solves these issues by creating a decentralized AI compute resource marketplace, which operates on top of blockchain technology, smart contracts, and token incentives. This model allows transparent communication, equitable distribution of resources and verifiable delivery of services between various players without the use of central mediators.

An enterprise level, and heterogeneous nodes, comprising of cloud providers and community based contributors, 30-day simulation confirmed the performance and equity of CloudChain. The framework registered substantially low latency, almost linear scale of throughput with requester increases, and indices of fairness of higher than 0.9 which indicated even distribution of computational tasks. Indicators of exclusivity in token allocation had also shown inclusiveness where small community nodes were granted proportional reward and the large cloud vendors received proportional rewards.

CloudChain showed significant sustainability increases as up to 22%-27% percent higher resource usage was obtained than centralized cloud pools. The non-centralized orchestration has a small amount of idle capacity and less redundant energy, which adds to greener compute ecosystems. Moreover, the combination of federated learning and the mechanism of differential privacy guarantees secure cooperation and integrity of the models, and oracles and smart contracts are associated with auditability and automatic SLA verification.

The next step in work will involve the implementation of CloudChain into a real-life environment whereby the testbeds will be geographically separate to test the operational scalability and carbon efficiency of the cloud chain when it is used under live network conditions. Integration of the decentralized autonomous organization (DAO)-based governance is also expected to augment community-based transparency and resources control.

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Unlocking the Potential of Cloud Computing for Sustainable Energy and Cost-Efficient Artificial Intelligence Workloads

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***Abstract*—The escalating energy consumption and static resource constraints of large-scale Artificial Intelligence (AI) workloads present a critical challenge to sustainable computing. This paper introduces a highly scalable serverless parallel processing architecture designed to overcome the limitations of scalability and resource inefficiency. The novel technique employs a distributed map state within a generalized workflow orchestration service to handle massive data concurrency, validated on datasets exceeding 50,000 files. Resource efficiency is optimized through a data-driven function power tuning methodology that automatically balances cost and performance, preventing resource over-provisioning. The system integrates robust environmental accountability via a customer carbon footprint tool to provide granular, verifiable Greenhouse Gas Protocol-compliant emissions data. Empirical results confirm the architectural superiority, achieving a consistent ∼6x speedup in execution time and ∼80 percent reductions in compute, cost, and CO_2 emissions. Furthermore, task-specific model fine-tuning significantly improves predictive accuracy, making this architecture platform-agnostic, cost-effective, and environmentally responsible pathway for deploying AI in diverse, compute-intensive domains.**

***Index Terms*—artificial intelligence (AI) workloads; serverless computing; parallel processing; resource optimization; sustainable AI; cloud carbon accounting; distributed map; model fine-tuning.**

I. Introduction

The escalating energy consumption and environmental impact of artificial intelligence (AI) workloads [1], particularly from large language models (LLMs) like BERT and GPT, present a significant challenge to sustainable computing. The sheer scale of modern AI presents profound resource challenges. By 2030, AI data center clusters are estimated to consume over 1000 terawatt-hours annually which is Japan's annual electricity consumption. These hyperscale data centers, often demanding upwards of 100 MW—energy consumption comparable to a small city—require water-intensive cooling systems, which further increase power needs. Consequently, these massive facilities contribute a substantial portion of global greenhouse gas emissions [2]. For instance, training a single large model like DistilBERT requires significant energy and computational resources. Beyond environmental damage, this immense computational demand directly translates to higher operational costs and longer processing times, issues that conventional, non-parallel processing techniques are fundamentally ill-equipped to manage efficiently [3]. While our previous work demonstrated substantial efficiency gains from a serverless parallel processing architecture on a major cloud platform [4], it exposed critical limitations that restricted its viability for large-scale production deployments. Specifically, the foundational architecture suffered from a crippling scalability bottleneck due to the limitations of its workflow orchestration service, relied on static and suboptimal function resource provisioning, and lacked granular, verifiable environmental reporting, thereby constraining overall predictive performance and real-world applicability.

This paper introduces a highly scalable serverless architecture that directly addresses these deficiencies through a comprehensive suite of cloud-native enhancements. While the architectural principles are transferable to other environments (e.g., Azure or GCP, which offer similar services), the solution presented here was implemented on the Amazon Web Services (AWS) platform, leveraging its accessibility and student resources. The core novelty lies in the integrated system of data-driven optimization and resource scaling combined with verifiable environmental accountability. To achieve massive scalability, we replace the limiting inline map functionality with the Distributed Map state [5], enabling the orchestration of large-scale parallel workloads by iterating over millions of items stored in object storage (Amazon S3). This architectural change is crucial for processing datasets containing over 50,000 files and scaling to high-volume, real-world streaming datasets.

To tackle resource inefficiency, we implemented a methodology for Lambda function power tuning [6]. This data-driven approach moves beyond static memory allocation, automatically analyzing execution logs across various memory configurations to identify the optimal balance between cost and performance for each serverless function. This methodology ensures compute resources are never over-provisioned, substantially reducing variable costs. Concurrently, we enhance the framework's academic rigor and transparency by integrating the cloud provider's Customer Carbon Footprint Tool (CCFT) [7] [8] [9]. This provides a precise and verifiable

analysis of the environmental impact, offering emissions data broken down by cloud region and service, adhering strictly to Greenhouse Gas (GHG) Protocol standards [10] [11] [12] [13].

Furthermore, we significantly enhance the framework's predictive power by incorporating task-specific model fine-tuning [14]. This process adjusts the parameters of pre-trained models, such as DistilBERT, on a smaller, domain-specific dataset, leading to a substantial boost in classification accuracy and improved inference diagnostics. The framework's resulting parallel and scalable nature makes it highly suitable for new compute-intensive domains beyond NLP. In image processing, the architecture can efficiently accelerate critical tasks like large-scale feature extraction and model inference for tasks such as in environmental and land use classification monitoring [15] [16]. For green storm water infrastructure, it is well-suited for processing sensor data from urban environments and running complex simulations necessary for optimizing the design, placement, and effectiveness of green infrastructure projects monitoring [17] [18].

This work demonstrates a highly scalable, cost-effective, and environmentally responsible pathway for deploying AI workloads. The remainder of this paper is structured as follows: Section II outlines the full methodology for scalability, optimization, platform independence and environmental reporting, Section III presents the performance results, Section IV provides a thorough discussion of the findings, Section V covers the limitations followed by section VI highlighting the future work and finally Section VII concludes the paper.

II. Methodology

This section outlines the structured approach taken using serverless framework, focusing on the refined architectural components and data-driven techniques employed for scalability, cost optimization, verifiable sustainability reporting, and improved model generalization.

A. Serverless Parallel Processing Architecture Framework

The core architecture remains a cloud-native, event-driven system built on the principles of serverless computing. The primary enhancement in this expanded work involves upgrading the parallel processing orchestration layer. To overcome the inherent payload limits of the previous inline map approach, we utilized the Distributed Map state capability within the cloud's workflow orchestration service (AWS Step Functions). This feature is essential for handling large-scale data ingestion, as it launches each iteration as a separate child workflow execution, supporting up to 10,000 parallel executions for high concurrency. This upgrade allows the framework to efficiently process datasets containing 50,000+ files by using the object storage list (Amazon S3) as the definitive data source.

B. Cost and Performance Optimization

To transition from static and inefficient resource allocation, we employed a data-driven approach using a dedicated tool for serverless function power tuning (AWS Lambda Power Tuning) [19]. The goal was to identify the optimal memory configuration for the compute functions. This tool runs a series of tests, invoking the target function with various memory settings (from 128 MB up to 10 GB), and then analyzes the resulting execution time and compute cost. This systematic process allows us to define a strategy that optimizes specifically for the lowest cost, fastest speed, or a balanced approach, ultimately enabling a data-driven decision on the ideal memory setting to maximize efficiency and substantially reduce variable operational costs.

C. Enhanced Sustainability Metrics

For robust and academically rigorous environmental impact reporting, we utilized the cloud provider's CCFT [20] [21] [22]. This tool provides a verified methodology for estimating and reporting GHG emissions resulting from cloud usage. The CCFT quantifies emissions as Metric Tons of Carbon Dioxide equivalent ($MTCO_2e$), covering both Scope 1 (direct) and Scope 2 (indirect) emissions. Crucially, it provides data broken down by cloud Region and service, ensuring adherence to the GHG Protocol and related ISO standards. This integration yields a much more granular and precise analysis of the environmental benefits compared to the simplified, formula-based estimations used in previous studies [23].

D. Model Fine-Tuning and Application

To improve the predictive performance and generalization of the framework, we performed task-specific model fine-tuning on our Natural Language Processing (NLP) models [24] [25] [26]. This involves taking a pre-trained transformer model (e.g., DistilBERT) and continuing its training on a smaller, domain-specific labeled dataset, such as the IMDb Reviews dataset [27]. This process is vital as it adjusts the model's parameters to better understand the semantic nuances of a specific task, leading to improved accuracy [28] [29]. The methodology for fine-tuning involves three core steps:

- Dataset Preparation: Gathering and preprocessing a labeled dataset relevant to the task, ensuring it is correctly split into training and validation sets.
- Hyperparameter Tuning: Adjusting critical parameters such as learning rate, batch size, and number of epochs to find the optimal configuration for fine-tuning.
- Evaluation: Assessing the model's performance on a held-out test set to provide an unbiased evaluation of its expected accuracy on unseen data.

E. Platform Independence and General Applicability

Although the current implementation utilizes the Amazon Web Services (AWS) platform, chosen primarily for cost efficiency through student resources and prior experience, the core architectural and methodological enhancements are not tied to a single commercial platform [30]. The foundational contributions are based on generalizable, cloud-agnostic principles: parallel workflow orchestration, data-driven resource optimization, and domain-specific model tuning.

These principles ensure direct transferability to other major cloud environments, such as Azure and Google Cloud Platform (GCP) [31] [32] [33], which offer analogous services for AI workload execution:

- Parallel Processing: The high-concurrency capability of the Step Functions Distributed Map can be mirrored by equivalent orchestration services on Azure (e.g., Logic Apps or Durable Functions) and GCP (e.g., Cloud Workflows) [34].
- Resource Optimization: The data-driven resource scaling methodology (like AWS Lambda Power Tuning) is a general optimization strategy applicable to all Function-as-a-Service (FaaS) platforms, including Azure Functions and Google Cloud Functions, to automatically find optimal resource settings for efficiency and cost [35].

To confirm general applicability, future work is proposed to include a comparative analysis of the serverless architecture across AWS, Azure, and GCP, demonstrating its portability and platform-agnostic performance consistency.

F. Validation of Environmental Reporting (CCFT)

The use of the AWS CCFT is justified by emphasizing its methodological rigor and adherence to international standards.

- Adherence to Global Standards: The CCFT is utilized as a verified methodology for estimating and reporting Greenhouse Gas (GHG) emissions. Crucially, this methodology strictly adheres to the international GHG Protocol and related ISO standards, lending academic rigor to the sustainability claims.
- Granular and Verifiable Data: The tool provides a granular and precise analysis by breaking down emissions data by cloud Region and service. This level of detail is superior to the simplified, formula-based estimations used previously, aiming to establish verifiable environmental accountability.
- Decoupling the Reduction Claim: The estimated ∼80% reduction in CO_2 emissions is independently validated by the measured ∼80% reduction in Total Compute (GBs). This parallel relationship confirms the environmental benefit, as less compute proportionally translates to less energy consumption, irrespective of the absolute $MTCO_2e$ values.
- Future Validation: Future research should integrate multi-cloud monitoring and reporting to provide a comparative validation of the CCFT against other platforms' tools or independent energy models, further strengthening the analysis credibility.

III. Results

The proposed framework's performance was evaluated under sequential and parallel execution modes. The results demonstrate significant efficiency gains across multiple key metrics, which are then extrapolated to larger datasets and validated across different models. The scalability of the new architecture is highlighted by its ability to process a dataset of 50,000 files.

TABLE I
EXECUTION TIME FOR A 50,000-REVIEW EXECUTION ACROSS VARIOUS SENTIMENT DISTRIBUTIONS.

Dataset Split	Execution Type	Execution Time (Sec)
20% Neg / 80% Pos	Parallel	4,840
	Sequential	29,772
40% Neg / 60% Pos	Parallel	4,124
	Sequential	24,960
50% Neg / 50% Pos	Parallel	4,204
	Sequential	25,752
100% Neg	Parallel	4,340
	Sequential	28,176
100% Pos	Parallel	4,385
	Sequential	28,424

TABLE II
COST COMPARISON FOR A 50,000-REVIEW EXECUTION ACROSS VARIOUS SENTIMENT DISTRIBUTIONS.

Dataset Split	Execution Type	Cost (USD)
20% Neg / 80% Pos	Parallel	0.166
	Sequential	0.820
40% Neg / 60% Pos	Parallel	0.142
	Sequential	0.690
50% Neg / 50% Pos	Parallel	0.145
	Sequential	0.712
100% Neg	Parallel	0.152
	Sequential	0.778
100% Pos	Parallel	0.157
	Sequential	0.785

A. General Performance and Scalability

The framework uses the AWS Step Functions Distributed Map, was successfully tested on a dataset of 50,000 reviews. This directly addresses the scalability limitations of the previous Inline Map approach.

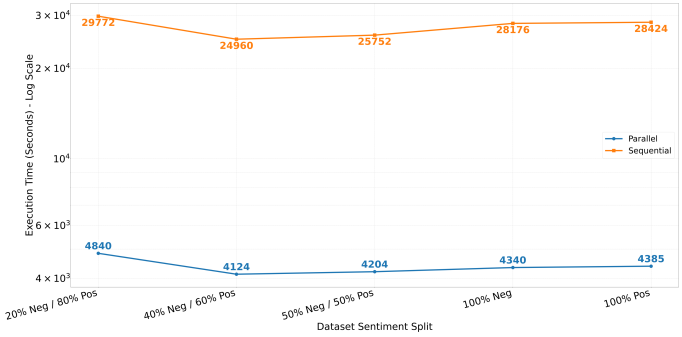


Fig. 1. Execution Time Comparison: Parallel (Blue Color) vs. Sequential (Orange Color) by Dataset Sentiment Split

Fig. 1 and Fig. 2 illustrate the execution time and cost comparisons across different sentiment splits, respectively.

The results in Table 1 and Table 2 show that the efficiency gains observed on smaller datasets are maintained at a significantly larger scale. The average reductions in compute, cost, and CO_2 emissions are summarized in Fig. 3.

The data confirms that the ∼6x speedup in execution time and the ∼80% reductions in compute, cost, and environmental impact hold true for a dataset five times larger than the



Fig. 2. Execution Cost Comparison: Parallel vs. Sequential by Dataset Sentiment Split

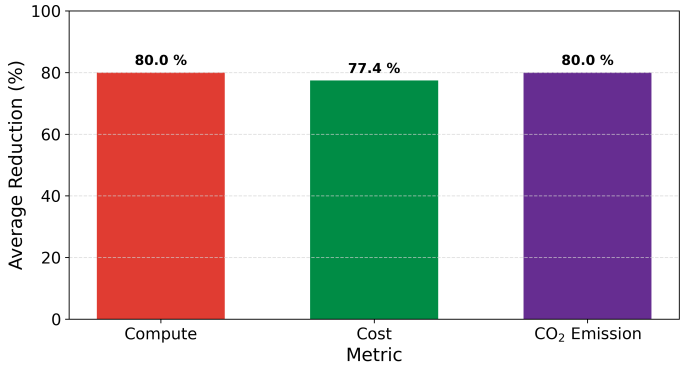


Fig. 3. Average Reductions in Compute, Cost, and CO_2 Emissions

previous maximum. This showcases the framework's ability to handle production-level workloads.

B. Performance by Dataset Sentiment

To provide a more granular view of the framework's performance, the results for the 50,000-review dataset are broken down by sentiment distribution. As shown in Table I and II, the efficiency gains from parallel execution are consistent across all dataset compositions, even though the raw values for execution time and compute may vary.

TABLE III
EXTRAPOLATED EXECUTION TIME FOR DATASETS UP TO 5 BILLION FILES.

Files	Execution Type	Time (Sec)
50,000	Parallel	4,382
	Sequential	26,568
5 Million	Parallel	438,200
	Sequential	2,656,800
50 Million	Parallel	4,382,000
	Sequential	26,568,000
5 Billion	Parallel	438,200,000
	Sequential	2,656,800,000

C. Long-Term Scalability

The efficiency gains from parallel processing persist and compound as the dataset size increases, providing a consistent ∼6x speedup in execution time and ∼80% reductions in compute, cost, and emissions.

TABLE IV
EXTRAPOLATED COST AND COMPUTE COMPARISON FOR DATASETS UP TO 5 BILLION FILES.

Files	Execution Type	Compute (GBs)	Cost (USD)
50,000	Parallel	8,355.85	0.15925
	Sequential	44,552.50	0.76255
5 Million	Parallel	835,585	15.925
	Sequential	4,455,250	76.255
50 Million	Parallel	8,355,850	159.25
	Sequential	44,552,500	762.55
5 Billion	Parallel	835,585,000	15,925
	Sequential	4,455,250,000	76,255

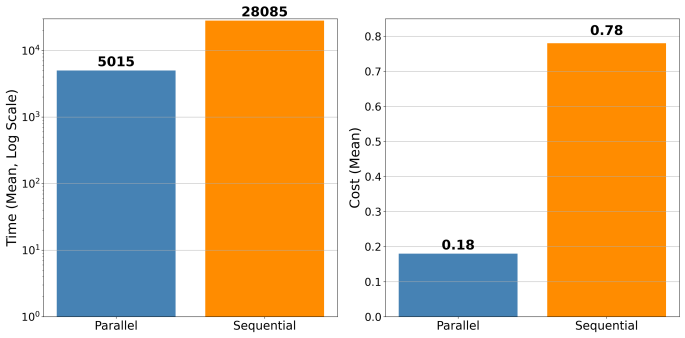


Fig. 4. Time and Cost benefits for Parallel vs. Sequential Execution

This analysis confirms that the serverless architecture is well-suited for very large-scale NLP workloads, a feat not possible with the previous architecture's limitations.

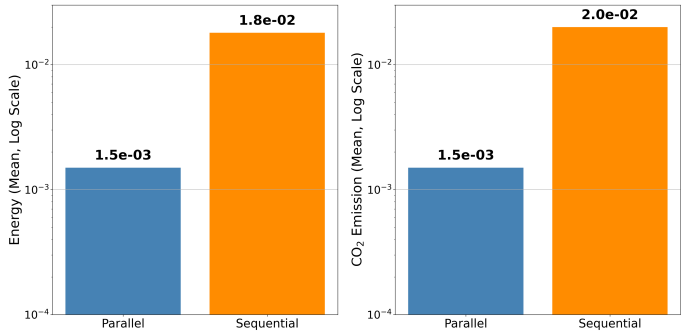


Fig. 5. Energy and CO_2 benefits for Parallel vs. Sequential Execution

Fig. 4 and Fig. 5 provides a visual comparison of the performance metrics. The data in Table III and Table IV provides a high-level view of the framework's performance at a global scale.

IV. DISCUSSION

This work significantly advances the previous framework by directly addressing its key limitations through several architectural and methodological enhancements, culminating in a robust and production-ready system. The integration of the Distributed Map state was the core enhancement for scalability, successfully overcoming the concurrent-iteration limits of the previous inline approach. This change enabled the efficient processing of large, real-world datasets exceeding

50,000 files, as evidenced by the consistent performance gains maintained across varying dataset sizes and sentiment distributions (Tables I & II). The parallel execution mode achieved a reliable 6x speedup in execution time and approximately 80 percent reductions in both compute time and variable cost. Resource management was drastically improved through the implementation of Power Tuning, which shifts allocation away from static, inefficient provisioning toward a data-driven approach. This automation identifies the precise optimal resource configurations required by the serverless functions, ensuring resources are not over-provisioned, thereby directly contributing to the measured cost and energy reductions (Fig. 3). Crucially, the sustainability metrics were enhanced by integrating a CCFT. This provides a more rigorous and verifiable environmental impact analysis compared to prior theoretical models, adhering strictly to GHG Protocol standards. The 80 percent reduction in compute usage provides an independent validation for the corresponding reduction in CO_2 emissions.

Beyond architectural efficiency, predictive performance was significantly improved via task-specific model fine-tuning (using DistilBERT). This enhancement addressed a known limitation of using un-optimized models and resulted in high classification accuracy. As shown in the Confusion Matrix (Fig. 6), the model achieved an impressive 92.00 percent accuracy. Specifically, out of 125,000 negative samples, 115,000 were correctly classified (True Negative, 92.0 percent), and similarly, 115,000 of the positive samples were correctly classified (True Positive, 92.0 percent). The low rate of False Positive and False Negative 8.0 percent each) demonstrates the high reliability of the fine-tuned model for sentiment analysis tasks. This high accuracy, combined with the demonstrated scalability and cost efficiency, makes the serverless framework a viable and responsible solution for deploying AI workloads not only in NLP but also in emerging compute-intensive domains like image processing and neuroscience.

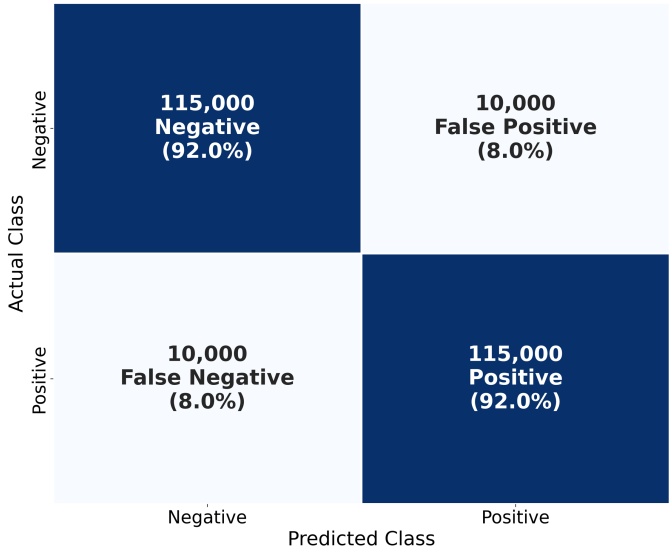


Fig. 6. Confusion Matrix (Accuracy: 92.00%)

V. Limitations

While the refined serverless architecture demonstrates significant advancements in scalability and cost-efficiency, the current work has several limitations that constrain its immediate general applicability and the definitive verification of its sustainability claims:

- Single-Platform Dependency for Metrics: Quantitative results are derived exclusively from an AWS implementation, limiting reproducibility and platform-agnostic evaluation.
- Reliance on Proprietary Carbon Tooling: Environmental analysis relies solely on the proprietary CCFT tool, limiting platform-agnostic verification of absolute CO_2 emission values.
- Focus on NLP and Specific Model: The study focuses narrowly on NLP/DistilBERT (for sentiment analysis), requiring further validation of efficiency and predictive benefits across diverse, compute-intensive domains.

VI. Future Work

To address the limitations of the current study and further validate the generalizability of the proposed framework, the following directions for future research are proposed:

- Multi-Cloud Comparative Analysis: The most critical next step is to execute the AI workload using the refined serverless architecture on equivalent services across two other major cloud providers, Azure asnd Google Cloud Platform (GCP). A direct comparative study will demonstrate the architecture's portability and validate the platform-agnostic nature of the efficiency gains (the $\sim$6x speedup and $\sim$80% reductions in compute and cost).
- Independent Carbon Validation: Future work should integrate multi-cloud monitoring and reporting to compare the CCFT data against other platforms' reporting tools and/or independent, third-party energy measurement models. This will enhance the transparency and definitively confirm the CO_2 emission reductions on an absolute, verifiable scale.
- Validation in New Domains: The architecture must be empirically validated in new compute-intensive fields such as image processing (e.g., large-scale feature extraction for environmental monitoring) and neuroscience (e.g., accelerating model inference for disease detection). This will prove its utility beyond the initial NLP application.

VII. Conclusion

This work successfully addresses the primary limitations of earlier serverless approaches to AI workloads, delivering a highly efficient, scalable, and environmentally accountable framework. By implementing architectural enhancements like the Distributed Map state, we addressed the initial scalability bottleneck, enabling the reliable processing of massive datasets (50,000+ files). The resulting quantified improvements are significant: achieved speeds are consistently 6x faster than

sequential execution, resulting in an an approximate 80 percent reduction in both time and variable cost, directly validating our approach against foundational prior work. Our methodology incorporated sophisticated, data-driven resource optimization via Power Tuning, mitigating issues like cold start latency and ensuring optimal compute allocation based on dynamic metrics rather than static provisioning. Furthermore, we enhanced environmental accountability by integrating the native CCFT, providing verified, GHG Protocol-compliant emissions data, confirming the proportional reduction in CO_2e emissions due to compute efficiency.

The predictive capability was markedly improved through task-specific fine-tuning of transformer models like DistilBERT, resulting in a verified 92.00 percent classification accuracy. This flexible, parallel framework demonstrates immense potential for scaling AI beyond NLP. While the immediate evaluation relies on a single cloud provider environment, future work must focus on empirical multi-cloud comparative analysis and independent validation of carbon reporting against third-party models to confirm platform independence and generalizability. Overall, this research provides a robust, evidence-based roadmap for transforming computationally intensive AI operations into genuinely sustainable and economically viable cloud-native solutions.

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Life Cycle Assessment of Private Blockchain-based Solar Photovoltaic Traceability System

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***Abstract* — A key challenge in sustainability assessment lies in the accurate, transparent, and reliable quantification of environmental impacts across complex and globally dispersed supply chains, where traditional life cycle assessment methods often struggle with data quality and traceability limitations. Emerging digital technologies, particularly blockchain, offer promising solutions by enhancing data integrity and traceability throughout product life cycles. To understand the environmental impacts of blockchain use itself, this study evaluates the life cycle environmental impacts of a private Hyperledger Fabric-based traceability system, supported by Internet of Things sensors and smart meters, applied to the solar photovoltaic industry. A cradle-to-grave life cycle assessment was conducted using SimaPro 9.6 and the ReCiPe 2016 midpoint and endpoint method to quantify the impacts of the proposed system operating for traceability of 76.15 GWp of photovoltaic panels over one year. Results revealed that the highest impacts were observed in the human health category, driven primarily by the extraction and processing of materials used in electronic components. The findings highlight the critical need to address the social and environmental burdens of electronic hardware in digital traceability systems and suggest directions for future research, including social life cycle assessment and integration with broader photovoltaic system assessments.**

Keywords—blockchain, LCA, solar, photovoltaics

I. INTRODUCTION

Considering growing environmental concerns and the need for sustainable development, currently life cycle assessment (LCA) methodologies have become essential tools for quantifying environmental impacts across various sectors, providing critical insights into sustainability performance, highlighting aspects for improvement and fostering data-driven decisions from raw material extraction, through production and end-of-life stages covering entire product's value chain [1], [2]. However, traditional LCA practices and methods face significant challenges, particularly regarding the collection and verification of precise, high-quality data throughout complex, globally dispersed supply chains [3], thus affecting the overall reliability of LCA outcomes and indicating the need for holistic and more advanced technologies in this field.

Blockchain-enabled data collection and management systems therefore could be used for automating the preparation and verification processes for these declarations [1]. Accurate environmental characterization, facilitated by blockchain, could not only support regulatory compliance but also promote consumer trust and informed purchasing decisions, enhancing overall market competitiveness. Also, increased traceability and transparency can significantly enhance social accountability, particularly regarding ethical sourcing and labor practices. As demonstrated in Circulor's application for tantalum traceability in Rwanda, Hyperledger Fabric-based systems can be used to prevent child labor and certify ethical sourcing in conflict regions [4]. So, by providing clear visibility into production processes, blockchain could support efforts to mitigate risks of unethical labor, thereby fostering also socially responsible supply chains [5].

Meanwhile, blockchain technology has emerged as an innovative solution to enhance transparency, reliability, and traceability across supply chains, significantly improving the level of detail and accuracy of LCA data collection [6], [7]. Blockchain is a distributed therefore decentralized digital ledger system that securely records transactions across its network. By enabling real-time, precise monitoring of physical parameters across the supply chain, blockchain could ensure the reliability and accuracy of data, thus overcoming critical limitations of traditional LCA methodologies [8].

Also, it must be mentioned that there is very small amount of research regarding energy consumption of especially private blockchains (including Hyperledger Fabric) [9]. Sedlmeir et al. has mentioned that Hyperledger Fabric's system is eight orders of magnitude less energy-intensive than public blockchains, nevertheless it can consume ten times more energy than traditional centralized networks [10]. Another study by Pinchiera et al. provides assessment that blockchain use (Ethereum based) in water management system only increased energy consumption by 6 % when compared to traditional management system's energy usage and blockchain used only 0.004 % of the total daily energy consumption [11]. Considering aforementioned possibilities to improve supply chain traceability and data quality using blockchain and with this clear research gap regarding studies that analyse environmental performance of such systems, further assessment for private blockchain's life cycle impacts is self-evident.

Solar photovoltaics (PVs) are selected for further analysis as an example for the application of blockchain-based traceability system. Within the PV industry, such system should aim to precisely characterize the life cycle impacts of specific PV panel models, rather than generic products, providing stakeholders with detailed, actionable insights [5], [12] on materials used, manufacturing and shipping conditions, time of use of panel, materials recovered, etc. With growing demand for renewable energy generation worldwide and with the prevailing assumption that renewable energy generation is fully sustainable, the authors of this study selected solar PVs as an example in order to expand the scope and detail of research related to the life cycle impacts of emerging digital technologies such as blockchain for sustainability tracing via measurements of renewable energy technologies that are currently in high demand. Overall, this

study is performed in order to improve the aspects of accurate LCA determination of blockchain technology that could further improve the precision and accuracy of solar PV sustainability reporting and associated measurements.

Therefore, using cradle-to-grave LCA, this study aims to assess the life cycle of a Hyperledger Fabric-based blockchain traceability system that is used to trace the solar PV panel throughout its life cycle (cradle-to-cradle). To the knowledge of the author's, currently there are no published studies assessing life cycle impacts for a private blockchain used for traceability and data collection throughout renewable energy technological equipment's life cycle. As follows, this study provides a first exploration in this topic, rising the awareness of impacts and opportunities of digital age technologies and determining further research directions in this promising topic.

II. Scope of The Study

A. System architechture

This study proposes a Hyperledger fabric based system architecture for traceability of solar PV panels throughout their life cycle. Solar PV panels in this study are offered to the market as a service – the manufacturer is responsible for their circularity – decommissioning, reuse, recycling and repurposing. In this study, Hyperledger fabric as a private blockchain was chosen due to its modularity, high transaction processing abilities [13] and proven capability of this platform in business applications [14], [15]. In this case it is assumed that the Hyperledger fabric system is using byzantine fault tolerance consensus protocol (as suggested for multi-party, decentralized applications [16]) and is cloud-based.

Fig. 1 shows the operational architecture of proposed Hyperledger fabric system. As can be seen, the manufacturer is the main system "holder", meaning that it communicates through all three established channels, has the access to whole supply chain data and is responsible for ordering service operation. This proposed system foresees that in order to eliminate data privacy risks only organizations in respective channel can see the data. In cases where it's needed, data privacy is ensured via use of channels. Smart contracts (named chaincodes) are used to execute transactions throughout the blockchain network. A transaction is initiated when client (from any supply chain participant) submits a transaction proposal to the endorsing peers (see number 1 in Fig. 1 representing the relationship between client and endorsing node). Endorsing policy for this proposed system is designed in a way that in order to execute the transaction, manufacturer's endorser node must be one of the endorsers (to maintain the data integrity and prevent malicious transactions) [17]. After the endorsement is gained from set amount of endorser nodes (which can depend on the size of the channel), the transaction proposal is returned to the client which submits the transaction to the ordering service node (see number 2 in Fig. 1 representing this step). Then when the consensus is reached, the transaction is written in a block and sent to all peers in the respective channel (see number 3 in Fig. 1 representing this action). After the peers have received the block, each peer validates the block using validation system chaincode (smart contract) to gain the approval that the endorsement policy was fulfilled (appropriate amount of endorsements was received) (see number 4 in Fig. 1 representing this step). If so, read-write conflict check is performed to compare transaction's readset with the ledger and if the transaction pass all the checks, it is written in the ledger.

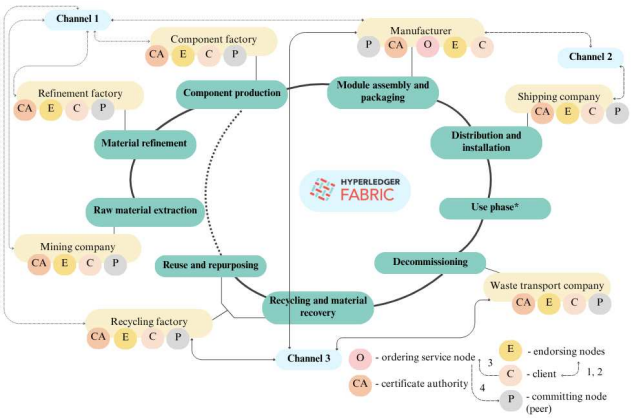


Fig. 1. Hyperledger fabric architecture for cradle-to-cradle system for solar PV (*excluding use-phase), made by the author using [1], [3], [13]

The system is designed to record Internet of Things (IoT) sensor data on gas emissions, temperature and humidity and smart meter data on electricity, heat, liquid flows throughout the solar PV life cycle from raw material acquisition to removal of equipment after its use phase and further recycling and repurposing. It must be mentioned that the use phase is not accounted for in this proposed blockchain traceability system due to the fact that the proposed system would serve as a tool for the manufacturer (to further improve its environmental performance) and the environmental impacts from solar PV usage can be viewed as negligible.

B. Goal and scope definition

ISO 14040 and ISO 14044 standards were used to perform this study. The main aim of this LCA is to evaluate the environmental impacts of a Hyperledger fabric-based blockchain traceability system for solar PV panel lifecycle tracking.

The functional unit in this study is the Hyperledger fabric-based and IoT supported traceability system operating for the production of 76.15 GWp solar PV over 1 year, from cradle-to-grave. 76.15 GWp were chosen to represent typical solar PV manufacturer's output in one year [18], [19]. It must be clarified that blockchain system is analysed from cradle-to-grave perspective, though it is used to ensure cradle-to-cradle solar PV traceability. Blockchain system is viewed as a supplementary information technology application that provides additional traceability data, therefore it can be assessed as a self-standing solution with its own lifecycle. It is assumed that the factory works 24 hours, 7 days a week, in one second making around four 590 W solar PV panels. For this amount it is estimated that there would be 2.8 million recordings from sensors, smart meters and laptops (manually entered data) each day, therefore the system will be able to validate approximately 33 transactions per second. Respective amounts of laptops (15 pcs), available on the market routers (15 pcs), IoT sensors (691 pcs), LoRAWAN gateways (463 pcs), smart meters (79 pcs), radio-frequency identification tags (33.56 t), cloud storage (1996 GB/year), and energy usage (13 626 kWh, incl. assumption that each GB of data consumes 3 kWh per year and each transaction's size is 2 kB [20]) is assumed for further study. Associated energy for cloud storage (not the storage hardware itself since it is assumed as a service) is proportionally added to each stage based on the needed recordings on the blockchain to account for additional

energy needed to run such traceability system. It is assumed that the whole PV production is located in China, but the use and further recycling happens in Europe.

C. Life cycle assessment method

SimaPro 9.6 software was used for the LCA calculation. Ecoinvent 3 database was used for determination of inputs. All assumptions are made on existing (in the market) devices that could potentially be used for the practical implementation of proposed system. The data was gathered from the respective environmental product declarations. In the case of laptops, device data from the Ecoinvent 3 database were used. In the view of the authors the chosen data represent a system that is as close to real-life as possible, thus improving the reliability of input data for LCA. ReCiPe 2016 method was applied to analyse midpoint and endpoint impacts. The ReCiPe 2016 was used as a standard method described in [21], which is already embedded in the software, and no additional assumptions were made regarding the modeling method used. The indicators from ReCiPe 2016 method are particulate matter (kg $PM_{2.5}$ eq), tropospheric ozone formation (hum) (kg NO_x eq), ionizing radiation (kBq Co-60 eq), stratospheric ozone depletion (kg CFC11 eq), human toxicity (cancer) (kg 1,4-DCB eq), human toxicity (non-cancer) (kg 1,4-DCB eq), global warming (kg CO_2 eq), water use (m^3), freshwater ecotoxicity (kg 1,4-DCB eq), freshwater eutrophication (kg P eq), tropospheric ozone formation (eco) (kg NO_x eq), terrestrial ecotoxicity (kg 1,4-DCB eq), terrestrial acidification (kg SO_2 eq), land use/transformation (m^2 yr crop eq), marine ecotoxicity (kg 1,4-DCB eq), marine eutrophication (kg N eq), mineral resources (kg Cu eq), fossil resources (kg oil eq) and, resulting from damage pathways, three endpoint areas of protection are distinguished – damage to human health, damage to ecosystems, damage to resource availability. This method was chosen due to its proven abilities to provide holistic impact assessment of the categories of damage proposed [22]. It must be mentioned that some underlying processes in Ecoinvent 3 database were tagged as obsolete – since there are no other data available for these specific processes, it was decided to continue the use of these values. Another uncertainty in this study is the energy mix used for the operation of the system – the provided respective values from Ecoinvent 3 were used, but actual energy mix might vary depending on different factors such as day/night time, season, specific location, etc.

III. Results

ReCiPe 2016 midpoint results for each system's stage are summarized in Table 1 and Table 2. The first column in both tables states the impact category, whereas third, fourth and fifth column shows specific results for each system's stage.

TABLE I. MIDPOINT RESULTS FOR TRACEABILITY SYSTEM'S STAGES – RAW MATERIAL EXTRACTION, MATERIAL REFINEMENT, COMPONENT PRODUCTION

Impact category	*Unit*	*RM*[a.]	*MR*[b.]	*CP*[c.]
Global warming	kg CO2 eq	2.08E+00	8.90E-01	1.27E+00
Stratospheric ozone depletion	kg CFC11 eq	1.11E-01	4.86E-02	6.91E-02
Ionizing radiation	kBq Co-60 eq	2.85E+00	1.23E+00	1.75E+00
Ozone formation, Human health	kg NO_x eq	2.40E+00	1.06E+00	1.52E+00
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.37E+00	5.99E-01	8.43E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.85E+00	1.26E+00	1.80E+00
Terrestrial acidification	kg SO_2 eq	1.79E+00	7.99E-01	1.12E+00
Freshwater eutrophication	kg P eq	3.05E+01	1.40E+01	1.99E+01
Marine eutrophication	kg N eq	3.65E-01	1.07E-01	1.45E-01
Terrestrial ecotoxicity	kg 1,4-DCB eq	1.15E+01	5.12E+00	7.11E+00
Freshwater ecotoxicity	kg 1,4-DCB eq	3.10E+02	1.48E+02	2.10E+02
Marine ecotoxicity	kg 1,4-DCB eq	2.39E+02	1.14E+02	1.61E+02
Human carcinogenic toxicity	kg 1,4-DCB eq	3.16E+02	1.24E+02	1.70E+02
Human non-carcinogenic toxicity	kg 1,4-DCB eq	3.99E+00	1.92E+00	2.72E+00
Land use	m^2 yr crop eq	1.31E-01	6.21E-02	8.86E-02
Mineral resource scarcity	kg Cu eq	3.51E-03	1.71E-03	2.41E-03
Fossil resource scarcity	kg oil eq	4.14E+00	1.81E+00	2.58E+00
Water consumption	m^3	4.90E-01	2.23E-01	3.11E-01

[a.] RM – Raw material extraction stage

[b.] MR – Material refinement stage

[c.] CP – Component production stage

TABLE II. MIDPOINT RESULTS FOR TRACEABILITY SYSTEM'S STAGES – MODULE ASSEMBLY AND PACKAGING, DISTRIBUTION AND INSTALLATION, RECYCLING, MATERIAL RECOVERY, REUSE, REPURPOSING

Impact category	*Unit*	*MA*[d.]	*DI*[e.]	*R*[f.]
Global warming	kg CO2 eq	4.35E-01	1.03E+01	3.93E-01
Stratospheric ozone depletion	kg CFC11 eq	1.67E-02	6.00E-01	1.41E-02
Ionizing radiation	kBq Co-60 eq	4.18E-01	1.51E+01	3.47E-01
Ozone formation, Human health	kg NO_x eq	4.67E-01	1.27E+01	4.24E-01
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.38E-01	6.94E+00	2.11E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.48E-01	1.50E+01	4.97E-01
Terrestrial acidification	kg SO_2 eq	3.21E-01	9.06E+00	2.90E-01
Freshwater eutrophication	kg P eq	3.57E+00	1.80E+02	2.99E+00
Marine eutrophication	kg N eq	3.81E-02	1.12E+00	3.35E-02
Terrestrial ecotoxicity	kg 1,4-DCB eq	1.20E+00	5.35E+01	1.04E+00
Freshwater ecotoxicity	kg 1,4-DCB eq	2.43E+01	1.95E+03	1.95E+01
Marine ecotoxicity	kg 1,4-DCB eq	1.86E+01	1.50E+03	1.49E+01
Human carcinogenic toxicity	kg 1,4-DCB eq	5.15E+01	1.27E+03	4.69E+01
Human non-carcinogenic toxicity	kg 1,4-DCB eq	3.33E-01	2.51E+01	2.69E-01
Land use	m^2 yr crop eq	1.49E-02	8.00E-01	1.26E-02
Mineral resource scarcity	kg Cu eq	2.54E-04	2.15E-02	2.02E-04
Fossil resource scarcity	kg oil eq	7.73E-01	2.09E+01	6.86E-01

Impact category	*Unit*	*MA*[d.]	*DI*[e.]	*R*[f.]
Water consumption	m^3	6.24E-02	2.46E+00	5.14E-02

[d.] MA – Module assembly and packaging stage

[e.] DI – Distribution and installation stage

[f.] R – Recycling, material recovery, reuse, repurposing stage

The stage with highest environmental impact is distribution and installation of solar PVs, therefore it is highlighted in the Table 2. The highest normalized midpoint impacts are for freshwater and ecotoxicity, freshwater eutrophication and human carcinogenic and non-carcinogenic toxicity. Results from ReCiPe 2016 endpoint analysis, comparing all six blockchain-based traceability system's stages can be seen in Figure 2.

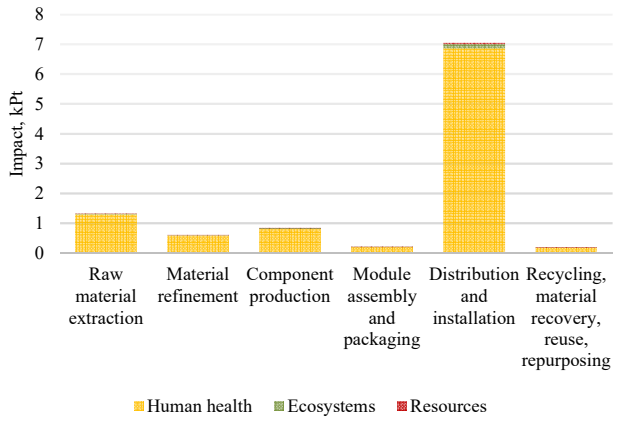


Fig. 2. Endpoint results for all traceability system's stages

Figure 2 clearly illustrates that the largest impact burden lies on the human health in all system's stages. Solar PV distribution and installation is the stage with the highest overall impact. Considering that the system consists of electronic devices, human health risks can be consequently explained by the composition of electronic equipment as such. The main components of these devices are not only plastics, aluminium and steel, but printed circuit boards (PCBs), integrated circuits (microchips), lithium ion batteries, inductors, capacitors and other materials (components) that attribute to the largest accountable impacts. Distribution and installation of 76.15 GWp of solar PVs in a year would require the use of 450 shipping trucks, each of them would be equipped with an IoT sensor and a LoRaWAN gateway for the sensor data transmission – this stage uses the largest number of electronic devices in this system. Results from endpoint analysis therefore explains in more detail the logic behind the fact that this stage has the greatest impacts.

Figure 3 describes impacts on human health more elaborately – the most influential processes from distribution and installation stage are shown. There are mainly three groups of processes that attribute to impact in human health – first, the aforementioned extraction, treatment and associated waste from valuable raw materials (like gold and silver that is used in PCBs and other components), second is the landfilling of industrial waste that is not easily recyclable, and third is the consumption of non-renewable energy (China's energy-mix was used for the analysis). This supports and explains the human non-carcinogenic and carcinogenic toxicity's impacts in this LCA.

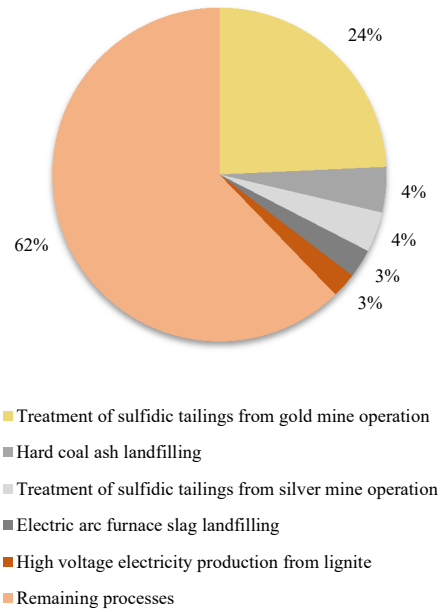


Fig. 3. Human health results specification per most influential processes in distribution and installation stage (cut-off = 1 %)

Overall, the results obtained show that when a private blockchain system is used, energy consumption is not the primary life cycle burden driver, as global warming potential is not the most significant burden in the data obtained. Still, in the light of identified burdens on human health from electricity production from lignite and coal ash landfilling, non-renewable energy should not be used to support the operation of such system. But this aspect can change depending on the energy mix and location used for the assessment. At the same time other, more concerning and seemingly more difficult to change aspects emerge – impacts on human health in the context of raw materials used for the production of electronic devices. It should be noted that these results are influenced by the detailed assumptions made in the study, and the data used for this study might not be directly applicable for studies of other technologies.

IV. Conclusions

The results of this study provide a first insight into the life cycle impacts of blockchain and related IoT sensor and smart meter systems, pointing not so much to energy consumption as previously associated with blockchain technology, but rather to the impact on human health of the extraction of various materials and elements used in electronics. This indicates the need for further research to pay detailed attention to social aspects - occupational safety, workplace conditions, as well as the overall sustainability of resource extraction, options for reusability, recovery from existing devices, and recyclability. Consequently, this research opens up opportunities to conduct a social life cycle assessment to identify more specific social impacts in the life cycle of blockchain-based systems that use smart electronic devices. Also, to make general conclusions on whereas the proposed system should be used to assist in future solar PV LCA preparations (including real-time LCA), further research on how proposed blockchain-based traceability system's impacts

would influence and add up to an individual PV's LCA results should be performed.

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A novel heterogeneous limit analysis framework for the collapse assessment of curved masonry constructions under different loading scenarios

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***Abstract*— This paper presents an innovative computational framework for the collapse assessment of masonry constructions, which seamlessly integrates advanced parametric modeling with Upper Bound Limit Analysis (UBLA). The methodology is built upon the PoliBrick plugin, implemented within the Rhinoceros/Grasshopper environment, which enables the automatic generation of three-dimensional brick assemblages that accurately represent the stereotomy of complex geometries, including arches, vaults, and walls. This geometric output is directly interfaced with a home-made heterogeneous Upper Bound Limit Analysis (UBLA) code implemented in MATLAB. The code models masonry blocks as infinitely resistance units. All nonlinearities are concentrated at the interfaces. These contact surfaces are governed by a rigid-perfectly plastic Mohr-Coulomb criterion. The versatility and accuracy of the proposed framework are demonstrated through its application to two distinct loading scenarios and structural typologies. First, it is validated against an in-situ tested masonry arch subjected to a vertical concentrated load, showing excellent agreement with experimental collapse loads. Second, its efficacy for seismic assessment is proven by analyzing a cross-vault, where the critical influence of stereotomy is systematically investigated across four different brickwork patterns. The results quantify the profound impact of brick disposition on the structural capacity, revealing performance variations of up to 84% in the collapse multiplier. The proposed framework thus provides practitioners with a practical, efficient, and accurate tool for the rapid prediction of collapse mechanisms in a wide range of masonry constructions under diverse loading conditions.**

Keywords*— masonry structures, collapse assessment, limit analysis, parametric modeling, stereotomy, PoliBrick, seismic loads

I. INTRODUCTION

Masonry constructions constitute a significant portion of the global architectural heritage, defining the character of historic urban centers, particularly in European countries [1][2]. Structures such as arches, vaults, and domes are renowned for their efficiency in transferring gravitational loads through compression, a principle masterfully exploited in historical design and construction [3,4]. However, these same structures often exhibit critical vulnerabilities when subjected to horizontal actions, such as those induced by seismic events, presenting a persistent challenge for engineers and conservationists tasked with their preservation [5].

The structural assessment of these historical elements has been profoundly influenced by the principles of Limit Analysis, following Heyman's seminal work [6]. Limit Analysis approach, particularly the kinematic theorem, has become a preferred methodology for estimating the ultimate load-bearing capacity of masonry constructions due to its intuitive application and ability to reliably identify collapse mechanisms [7][8]. Its effectiveness has been further enhanced through computational implementations, such as Upper Bound Limit Analysis (UBLA) approaches [9]-[11] and other energy-based or equilibrium-based methods [12] 13], which allow for a fast evaluation without the need for complex nonlinear dynamic analyses.

A critical, yet often oversimplified, factor governing the structural behavior of masonry is stereotomy – the specific art and arrangement of the stone or brick units. The pattern of the blocks not only affects the aesthetic but fundamentally influences the load bearing capacity and the resulting failure mechanism [14][15]. Despite its importance, a significant gap persists in the available computational workflows. Existing methodologies often struggle to integrate an accurate, automated representation of stereotomy within advanced numerical analysis tools. Manually generating three-dimensional meshes that faithfully represent complex brick patterns on curved surfaces is time-consuming and prone to error, while simplified models that ignore stereotomy lack the fidelity for precise collapse prediction [16].

Bridging this gap is also critically dependent on the high-fidelity measurement of existing structures. The practical application of any advanced numerical tool for heritage assessment begins with digital documentation, typically through 3D laser scanning or photogrammetry. The accuracy of these measurement techniques directly governs the geometric fidelity of the resulting model. The framework presented herein is thus positioned as the crucial next step after measurement, translating raw point-cloud data into a structurally-sound model where the 'as-is' stereotomy is precisely captured.

To bridge this gap, this paper presents a novel, integrated computational framework that seamlessly combines parametric modeling with a heterogeneous Finite Element Limit Analysis. The core of this methodology is the PoliBrick plugin [17], developed within the Rhinoceros/Grasshopper environment, which enables the automatic and parametric generation of three-dimensional masonry assemblages. This tool is directly coupled with a rigorous Upper Bound Limit Analysis (UBLA) code [18][19], where blocks are assumed infinitely resistant and nonlinearities are lumped at the interfaces following a rigid-perfectly plastic Mohr-Coulomb criterion.

The primary contribution of this work is twofold. First, the proposed framework is validated against an in-situ tested masonry arch under vertical loading [20], demonstrating its accuracy in predicting collapse loads and mechanisms.

Second, its versatility is showcased by applying it to the seismic assessment of a cross vault, where the influence of four distinct stereotomy patterns on the collapse multiplier is systematically quantified. The results underscore that the proposed tool is not only robust and accurate but also provides a practical and efficient means for the rapid assessment of a wide range of masonry constructions under different loading scenarios.

II. The Proposed Numerical Framework

The proposed framework for the collapse assessment of masonry constructions integrates two core components to bridge the gap between digital heritage documentation and advanced structural analysis: (i) a parametric tool for the automatic generation of stereotomy-accurate geometries and (ii) a rigorous computational code for heterogeneous Finite Element Limit Analysis.

The computational foundation of this framework is a heterogeneous Upper Bound Limit Analysis (UBLA) code, grounded in the kinematic approach of limit analysis [7][18]. The formulation rests on two fundamental hypotheses: (i) masonry units are discretized using three-dimensional finite elements (e.g., Hexa8, Wedge6) and are assumed to be infinitely resistant, and (ii) all nonlinearities are concentrated at the interfaces between blocks, which are modeled as rigid-perfectly plastic surfaces obeying a Mohr-Coulomb yield criterion. This approach effectively lumps the nonlinear material behavior into the mortar joints, as depicted in Fig. 1. Under these assumptions, the collapse load multiplier and the associated failure mechanism are determined by solving an optimization problem that minimizes the internal power dissipation. A pivotal advantage of this heterogeneous discretization is that the upper bound solution coincides with the lower bound, providing a unique and reliable estimate of the true collapse load [10][18].

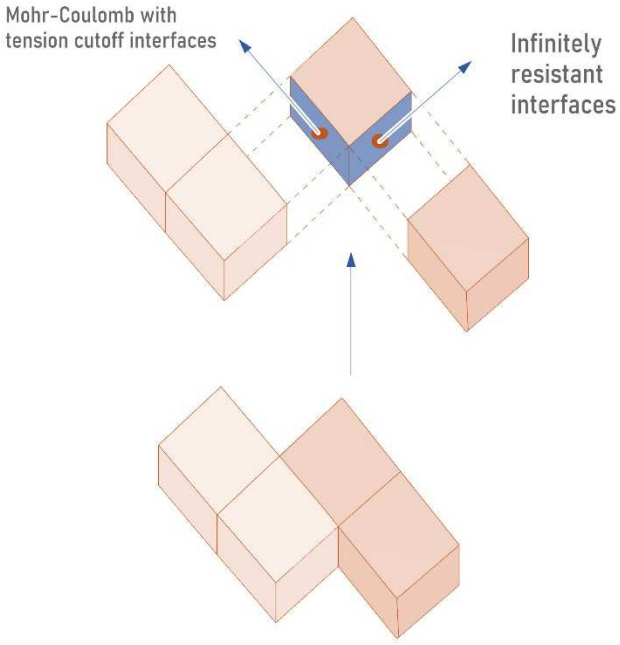


Fig. 1. The typology for defining interfaces, both within single blocks and between adjacent blocks

PoliBrick [17] specifically addresses the critical need for automating stereotomy-aware modeling. Its algorithmic framework utilizes Non-Uniform Rational B-Splines (NURBS) to tessellate complex, free-form surfaces and employs an alphabet-based methodology to generate intricate brick patterns – such as running bond, herringbone, and radial arrangements – while ensuring geometric fidelity through collision detection algorithms. The plugin directly exports the essential data for the UBLA code, namely node coordinates, element topologies, and interface definitions, into a structured text file. This direct export is crucial, as it ensures that the plastic interfaces in the limit analysis perfectly align with the mortar joints of the physical structure, thereby guaranteeing the accuracy of the predicted failure mechanism (see Fig. 2).

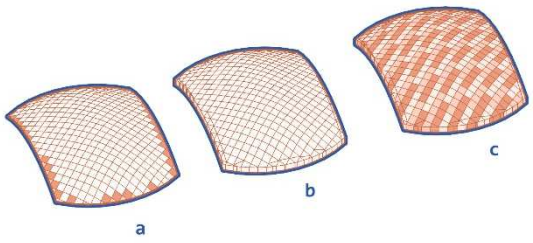


Fig. 2. Mesh optimization process: (a) initial surface tessellation, (b) refinement into Hexa8 and Wedge6 elements via vertex alignment, and (c) a color-coded results evaluation.

The transition from the initial parametric geometry to an analysis-ready mesh requires a refinement process to ensure compatibility with the UBLA code. As depicted in Fig. 3, the unstructured mesh from the CAD environment output is converted into an ordered mesh. This process involves (i) defining only the essential vertices for each element type (e.g., top and bottom faces for hexahedra) and (ii) enforcing strict nodal ordering principles to maintain geometric integrity and prevent element distortion, which is paramount for the stability of the numerical solution.

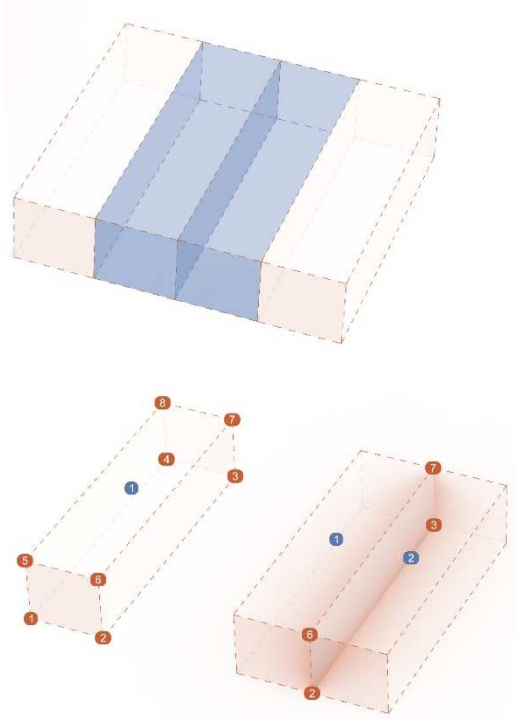


Fig. 3. Establishing a consistent vertex order for adjacent mesh blocks.

III. Validation under Vertical Loading

The accuracy and robustness of the proposed framework are first validated through the analysis of a masonry arch (see Fig. 4) subjected to a vertical concentrated load, a benchmark case for which experimental data and previous numerical results are available in the literature [20]. The structure under investigation is an ancient masonry arch located near Novi Ligure, Italy, characterized by a span of 2555 mm, a rise of 830 mm, and an in-plane thickness of 120 mm. The arch is composed of Italian clay bricks (55 × 120 × 250 mm) laid in alternating stack and header bond patterns with lime mortar joints, as documented in [20].

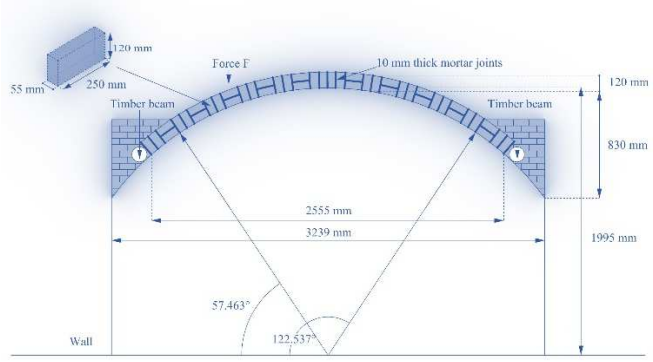


Fig. 4. Geometry and stereotomy of the masonry arch used for validation under vertical loading

The geometric model of the arch, including its precise stereotomy, was generated using the PoliBrick plugin. The two-layer brickwork was accurately represented, and the resulting mesh – comprising nodes, hexahedral elements for the blocks, and interface definitions – was exported for analysis in the UBLA code. The mechanical properties assigned to the interfaces were selected in accordance with the standard assumptions for limit analysis of masonry, featuring a sufficiently high cohesion (c = 0.07 MPa) to preclude sliding and a friction angle of $\Phi = 30°$, while the masonry units were modeled as infinitely resistant.

The analysis successfully identified the collapse mechanism, which is illustrated in Fig. 5. The failure is characterized by the formation of four distinct hinges, a typical mechanism for masonry arches under concentrated loads. The computed collapse load was determined to be 2.04 kN.

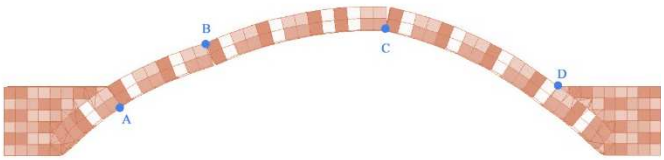


Fig. 5. Predicted failure mechanism for the masonry arch under vertical load, showing the formation of plastic hinges.

To contextualize this result, the predicted collapse load is compared with values from the existing literature in Table 1. The close agreement between the value obtained with the proposed PoliBrick-UBLA framework and both the experimental reference and other numerical simulations confirms the validity of the approach for assessing the stability of masonry structures under gravitational loading.

TABLE I. Comparison of the collapse load for the masonry arch

Source	Type	Collapse Load (kN)
Carozzi et al. [20]	Experimental	~2.10
Bertolesi et al. [21]	Numerical	1.95
Pingaro & Milani [22]	Numerical	2.15
Present Study (PoliBrick-UBLA)	Numerical	2.04

This successful validation under vertical loads establishes a good degree of confidence in the framework core computational engine, paving the way for its application to more complex scenarios, such as seismic assessment where stereotomy plays an even more critical role.

IV. Application to Seismic Loading and the Role of Stereotomy

Following the validation under vertical loading, the versatility of the proposed framework is demonstrated through its application to the seismic assessment of a masonry cross vault, with particular emphasis on quantifying the influence of stereotomy. The approach is first validated against experimental results from a tilting table test conducted on a small-scale cross vault, as documented in [23]. The physical specimen, with a span of 620 mm and a rise of 225 mm, comprised over a thousand dry-joint masonry blocks. For computational efficiency within the UBLA code, a representative model with 188 blocks was utilized, maintaining the critical geometric and mechanical characteristics, including a joint friction angle of $\Phi = 27°$.

The analysis, which considered a G2 horizontal load distribution [24] applied in the plane inclination direction, predicted collapse at a tilting angle of approximately 22°. This shows good agreement with the experimental collapse angle of around 19° reported in [23]. The obtained failure mechanism, illustrated in Fig. 6, reveals sliding at the supports near the hinge of the tilting plane and upward deformation at the same locations – a behavior consistent with an associated plasticity flow rule that cannot be captured under traditional Heyman's hypotheses.

This predicted uplift is a direct consequence of the associative flow rule adopted by the UBLA code, a key point regarding the model theoretical underpinnings. This assumption, which links the plastic flow direction to the gradient of the Mohr-Coulomb yield criterion, is standard for the kinematic theorem as it ensures the computed solution is a unique, true upper bound.

While this rule physically captures dilatancy (uplift), it is known to overestimate the energy dissipation for frictional materials like masonry. This means the computed collapse multipliers in this study are likely an upper-bound overestimation of the true capacity. This overestimation is likely not uniform across the different stereotomy patterns investigated next. The failure mechanisms of the more interlocked patterns (e.g., radial, herringbone) involve significant sliding along inclined joints, where dilatancy would contribute substantially to their computed resistance. Therefore, while the associative rule likely inflates the absolute collapse values for all patterns, it may also exaggerate the percentage of improvement seen in the interlocked patterns. However, the fundamental ranking and

the conclusion that stereotomy is a critical performance parameter remain mechanically sound.

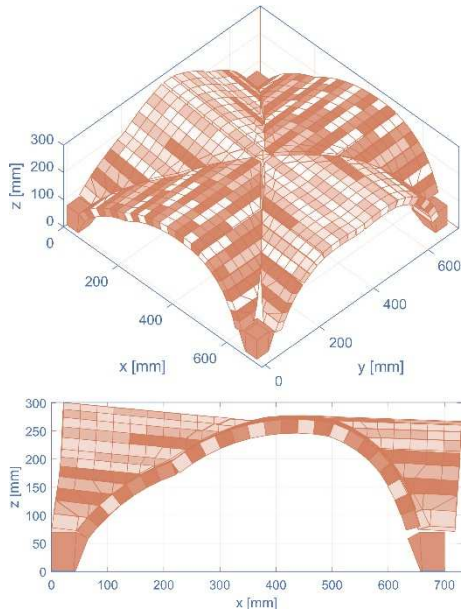


Fig. 6. Collapse mechanism of the cross vault on a tilting plane for a friction angle $\Phi = 27°$.

Having established the model reliability, a parametric study was conducted to systematically investigate the impact of stereotomy on the seismic capacity of a full-scale cross vault (span = 3000 mm, rise = 965 mm). Four distinct brickwork patterns were generated using PoliBrick and analyzed under the same G2 horizontal load distribution, with realistic mortar joint properties (cohesion c = 0.1 MPa, friction angle $\Phi = 30°$). The patterns, shown in Fig. 7, include: (i) running bond perpendicular to the lateral arches, (ii) angular running bonds with 45° convergence at the crown, (iii) a radial arrangement about the center point, and (iv) a herringbone configuration.

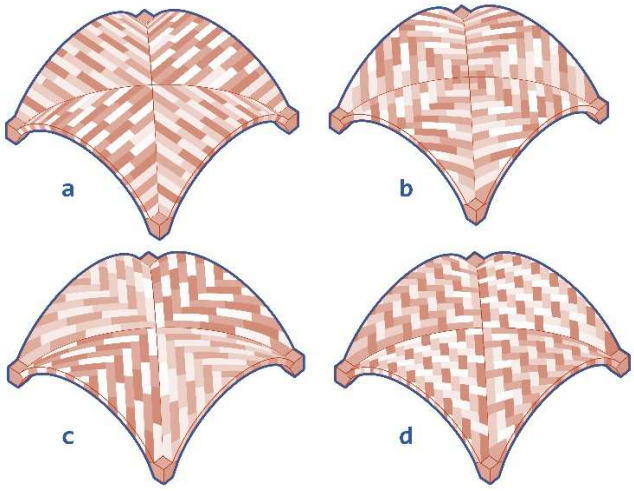


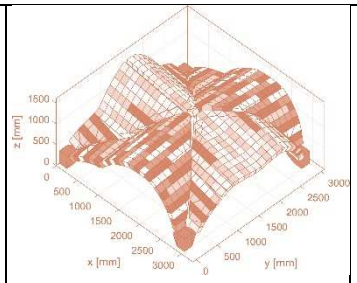
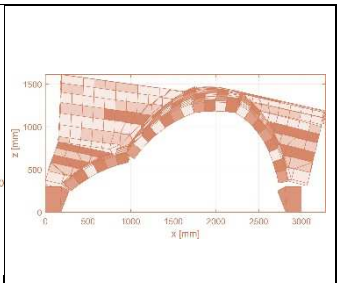
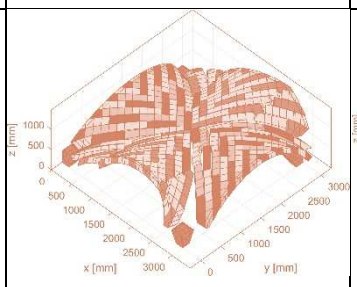
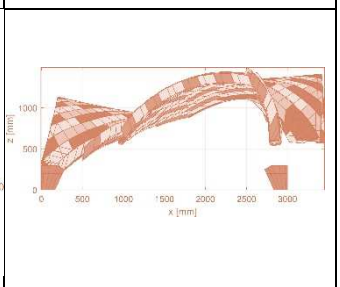
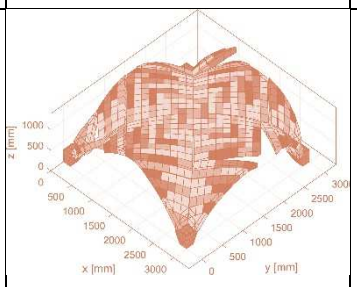
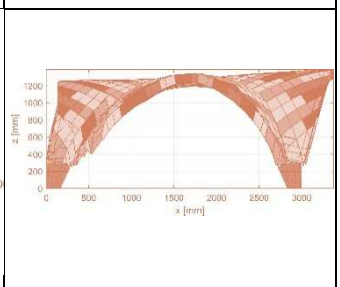
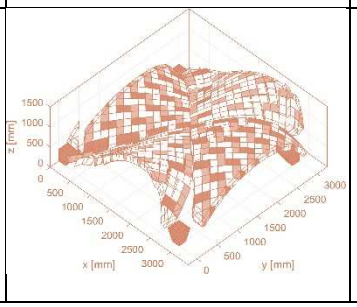
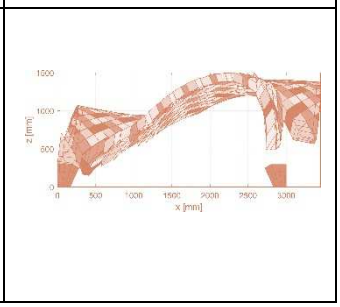
Fig. 7. The four stereotomy patterns analyzed for the cross vault: (a) Running bond; (b) Angular running bonds (45°); (c) Radial arrangement; (d) Herringbone pattern.

The analysis yielded distinct collapse mechanisms and a remarkable variation in the collapse acceleration multiplier, λ, for each pattern, as summarized in Table 2. The radial arrangement ($\lambda = 2.23$) demonstrated the highest seismic capacity, followed closely by the herringbone pattern ($\lambda = 2.21$). The angular running bond ($\lambda = 1.55$) offered intermediate performance, while the traditional running bond ($\lambda = 1.21$) was the least effective. This represents a performance variation of over 84% between the least and most effective patterns. The corresponding failure mechanisms, depicted in Table 3, show how the hinges formation are dictated by the joint alignment, with the radial pattern facilitating a more uniform and efficient redistribution of horizontal forces.

TABLE II. COLLAPSE ACCELERATION MULTIPLIER (Λ) FOR THE FOUR STEREOTOMY PATTERNS

Stereotomy Pattern	Collapse Multiplier (λ)
Running Bond	1.21
Angular Running Bond (45°)	1.55
Herringbone	2.21
Radial	2.23

TABLE III. COMPARISON OF COLLAPSE MECHANISMS FOR THE FOUR CROSS-VAULT PATTERNS UNDER SEISMIC LOADING

Pattern 1 [a_g /g =1.21]		
Pattern 2 [a_g /g =2.23]		
Pattern 3 [a_g /g =1.55]		
Pattern 4 [a_g /g =2.11]		

These results unequivocally demonstrate that stereotomy is not merely an architectural feature but a fundamental

parameter controlling the seismic performance of masonry vaults. The proposed framework proves uniquely capable of quantifying this influence, providing critical insights for both the assessment of existing historical structures and the design of new, seismically resilient masonry constructions.

V. Conclusions

This study has presented a novel and general-purpose computational framework that successfully bridges the gap between advanced parametric modeling and rigorous structural analysis for the collapse assessment of masonry constructions. The integration of the PoliBrick plugin with a heterogeneous Finite Element Upper Bound Limit Analysis (UBLA) code has been demonstrated to provide a robust, efficient, and accurate tool for engineers and conservationists.

The primary contributions and findings of this research are threefold. First, the proposed framework was validated against an in-situ tested masonry arch under vertical loading, with the predicted collapse load showing excellent agreement with experimental data and existing numerical simulations. This confirms the method accuracy for gravity-load scenarios. Second, the framework was successfully applied to the seismic assessment of a cross vault, where its predictive capability was verified against tilting table test results. Third, and most significantly, the systematic investigation of four distinct stereotomy patterns under seismic loading quantified the profound influence of brick arrangement on structural performance. The results revealed a performance variation of up to 84% in the collapse acceleration multiplier, unequivocally demonstrating that stereotomy is a critical design parameter rather than a purely architectural feature. The radial and herringbone patterns exhibited superior seismic capacity, highlighting the importance of joint interlocking and force redistribution.

The practical implications of this work are substantial and tie directly to the field of measurement-based structural assessment. The proposed workflow offers a significant reduction in computational pre-processing time while enhancing the geometric fidelity of numerical models. However, the accuracy of the predicted collapse loads is contingent on the precision of the initial measurements (e.g., from 3D scanning) used to define the stereotomy. Inaccurate measurements of joint thickness or block geometry would directly impact the interface definitions and, consequently, the computed failure mechanism.

Real-world masonry invariably contains non-idealities, such as irregular block shapes, variable joint properties, and pre-existing damage, that are not captured in a "perfect" parametric model. This workflow is therefore ideally suited for integration within a digital twin system for heritage preservation. In such a system, 3D measurement data would create the initial model, which could then be updated by monitoring data. The PoliBrick-UBLA framework would serve as the predictive engine, enabling rapid seismic assessments and promoting the sustainability of heritage structures by ensuring that conservation interventions are minimal, necessary, and based on an accurate understanding of the as-built structure. Future developments will focus on extending the application of this framework to more complex structural typologies, such as domes and entire masonry aggregates.

VI. Acknowledgments

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Sustainability and Equity Challenges of Nuclear Fission and Fusion

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***Abstract*—The sustainability and long-term viability of nuclear fission and fusion as energy sources may be an important topic in view of the recent changes in the political scenario worldwide. This paper provides a framework for comparatively evaluating both technologies vs renewable sources towards a stable and sustainable energy future. We focus on a first quantification of risks, including technological requirements, strategic material demand, energy efficiency and performance metrics, fuel availability constraints, and inherent technical feasibility challenges. Special attention is paid to the scale of infrastructure and research efforts required, and the critical balance between net energy return and total environmental impact.**

***Index Terms*—Nuclear fission, Nuclear fusion, Sustainability**

I. Introduction

The global energy system is undergoing a deep transformation driven by two main goals, climate change mitigation and secure energy supply. During recent decades, renewable energy technologies such as wind, solar photovoltaic (PV), and hydroelectricity have expanded rapidly, becoming widely recognized as the central pillars of decarbonisation strategies worldwide [1], [2]. These sources offer the clear advantage of near-zero operational greenhouse gas emissions and rapidly decreasing costs in many regions.

However, despite these successes, a persistent increase in electrical energy demand stems from conventional growth alongside new requirements, such as those imposed by artificial intelligence. Then, the ambition of an energy transition based exclusively on non-dispatchable Renewable Energy Sources (RES), such as wind and solar photovoltaics (PV), faces significant obstacles that compromise its long-term sustainability, both technically and economically. An analysis of system costs and the impact on grid stability highlights the critical need to integrate stable, dispatchable generation sources, such as nuclear power.

Although the Levelized Cost of Energy (LCOE) of RES is decreasing (projected around 100/MWh by 2025), this metric is insufficient as it neglects system costs—transmission, storage, and network stability—arising from wind and solar intermittency. The IEA/NEA developed the VALCOE (Value-Adjusted LCOE) to include these burdens. VALCOE analysis reveals that when true system costs are considered, nuclear energy (especially the *Long Term Operation* option) is the most economically competitive low-carbon source by 2025, restoring its position of economic leadership due to superior reliability [3]. Indeed, RES exhibit low energy density, spatial intermittency, and, in some cases, modest capacity factors, which complicate the provision of continuous, high-power, and high-reliability electricity services without substantial investments in storage, grid expansion, and system flexibility [4]. Such interventions are technically feasible, but may entail significant additional costs, substantial land-use demands, and long lead times for deployment at the scale required by deep decarbonisation pathways.

The large-scale integration of RES challenges protection systems, traditionally designed for radial power flow, by introducing bidirectional flows and complex fault scenarios. High penetration of Distributed Generators (DGs) causes criticalities like protection blinding, nuisance tripping, and unintentional islanding. Crucially, inverter-based DGs limit the fault current, severely reducing detection sensitivity. Addressing these issues requires expensive modifications, such as Fault Current Limiters or adaptive relays, significantly increasing operational and investment costs [5].

Those technical constraints and the proven increase in system costs (VALCOE) demonstrate that an exclusively intermittent RES grid is unsustainable [3], [5]. Grid stability fundamentally requires the inertial response traditionally provided by large rotating masses (like nuclear synchronous generators). High RES penetration needs complex and costly synthetic inertia techniques (via converters and storage) [6]. However, nuclear energy, by offering intrinsic rotating inertia, superior dispatchability, and VALCOE competitiveness, is the essential element required to balance RES intermittency and ensure an economically and technically robust low-emission transition [7], [8].

Nuclear fission plants provide high energy density and low-carbon dispatchable power, which can contribute to base-load or flexible dispatch when properly designed and operated [9]. Advanced fission technologies, including small modular reactors (SMRs) and generation-IV concepts, offer

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potential advantages in safety, modularity, and capital cost profile that merit serious consideration in near- to mid-term energy planning [10], [11].

Looking further ahead, nuclear fusion, although still in the research and demonstration stage, holds the prospect of very high power densities and inherently low life-cycle emissions, with fuel resources that are abundant and operational risk profiles different from those of fission [12], [13]. Although commercial fusion power is not yet available and significant scientific and engineering challenges remain, continued strategic investment in fusion research could yield transformational options for long-term energy systems.

Here, we emphasise a systems-level perspective that weighs environmental impacts, economic costs, safety considerations, waste management, and public acceptance. This is pursued by considering the following risks [14]:

- Technical risk (TR): Issues related to the technological development of the technique.
- Geological availability risk (GAR): Issues related to the global supply of the elements (resource & reserve base).
- Geopolitical/regional risk (GRR): Issues related to the element supply chain, its geographic distribution, and potential disruptions; vulnerability concerns for meeting demand in specific regions (also affected by price fluctuations).
- Total Equivalent Environmental Impact (TEEI): Issues related to associated air emissions and pollution to water and land or in diverting land use from other primary applications, such as agriculture.

Concerning the adopted method, the risks are normalized to $0-1$ scale, with 1 the highest. The mapping is based on scientific and technical recent sources, available in the literature.

II. Assessment of the Technical Risks

A. Nuclear fission reactors

Energy production through nuclear fission represents an important amount of the energetic mix of Europe (see Fig. 1).

The fission reactors available nowadays are the so-called II and III generation (gen.) reactors [15]. Although these reactors - especially gen. III - have proven to be highly secure and reliable, there is still a resistance from public opinion to their diffusion. On the other hand, the current prediction for the commercial availability of generation IV reactors are of about 5 years from now.

In the framework of the sustainability, it's worth to mention the CANada Deuterium Uranium (CANDU) reactor, a III gen. reactor that can produce energy with natural uranium dioxide with no enrichment required. The cost of natural uranium dioxide is considerably lower then that of enriched uranium [16]. The adoption of natural uranium is made possible by the fact that heavy water (${}^{2}_{1}\mathrm{H}_2O$) is used for both the moderator and the coolant. Another important feature is that they represent the only way to produce tritium (around 130 g/yrs per reactor), via neutron capture in heavy water [17]. Tritium (${}^{3}_{1}\mathrm{H}$) is a radioactive isotope of hydrogen, which is essential component for nuclear fusion fuels.

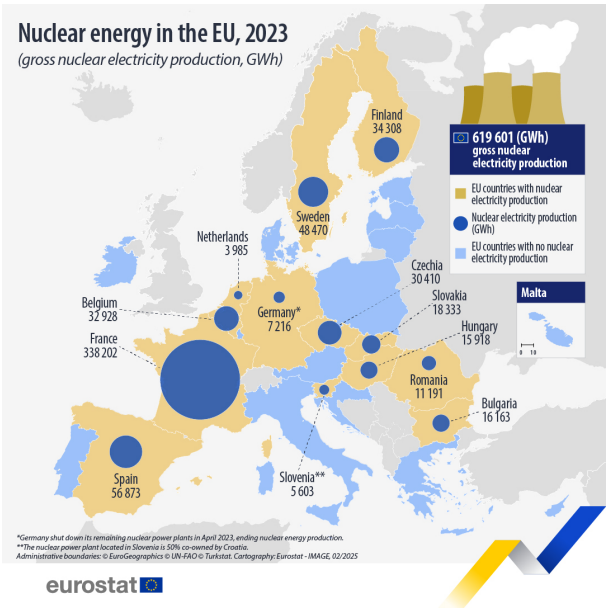


Fig. 1. The European nuclear fission energy map distribution [18].

B. Inertial Confinement Fusion (ICF)

The working principle of ICF is based on the possibility of inducing the formation of thermonuclear conditions, by irradiating a spherical fuel pellet with several High Intensity Lasers (HIL), in the nano-second regime. Among the most promising approaches, direct drive and indirect drive are considered. In direct drive hundreds of laser pulses are symmetrically focused on the target surface. This generates a converging shock wave that lead to an implosion, generating the so-called hot spot, i.e., a region in which nuclear fusions are possible. The hot spot is characterized by high density (10^3-10^4 times the ordinary solid state) and high temperature (10^6 K). The biggest challenges in direct drive are related to the implosion symmetry and to the generation of hydrodynamical instabilities, such as Rayleigh-Taylor instability [19]. To overcome these problems the indirect drive has been proposed. In this case the pellet is placed into a cylindrical gold chamber called hohlraum [12]. The lasers are pointed to the internal surfaces of the hohlraum, leading to the generation of X-rays. This radiation field is close to the *black body* ones, therefore intrinsically isotropic. The radiation pressure exerted on the target surface by the X-rays will generate an implosion able to generate the hot spot minimizing the formation of hydrodynamical instabilities. The main drawbacks of indirect drive are related to the necessity of a more complex target (if compared to the direct drive) and to the laser to X-rays conversion efficiency, which is in the order of 15 %. In both the approaches, the hot spot lasts few ns. However, in 2021, at the National Ignition Facility (NIF), the feasibility of the ICF has been shown [20].

C. A novel approach to ICF: The Microbubble implosion

Microbubble implosion (MBI) is a concept that may be developed to have nuclear fusion [21]. The irradiation with a femto-second high-power laser (HIL) with a micrometric target, that have a spherical empty cavity at center, can redistribute the ionization electrons. The charge unbalance leads the implosion of the cavity walls with a density in the order of 10^{34} m^{-3}. This extreme condition lasts for tens of femtoseconds. Therefore, it is a highly out of equilibrium phenomenon. It is possible to take advantage on this. In thermonuclear plasmas, radiative losses via Bremsstrahlung significantly cool the plasma and can be detrimental. In MBI, the interaction time is so short that Bremsstrahlung are not the dominant loss mechanism. In typical fusion configurations, these losses represent the primary obstacle to the viability of proton-boron as nuclear fuel, due to its high electron density. Concerning the sustainability of the approach, it is highlighted here that the energy per pulse required is in the Joule order and this is already acheived for femto-second laser systems.

D. Principles of Magnetic Confinement Fusion

Magnetic Confinement Fusion (MCF) utilizes the Tokamak reactor design to control extremely hot, low-density plasma [22]. Lacking physical suitable walls, the device employs powerful toroidal and poloidal superconducting magnetic fields to suspend and isolate the plasma within a vacuum chamber, fulfilling the Lawson criterion [22].

Among the main engineering challenges is the management of the extreme thermal conditions to which the tokamak walls are subjected, as they must withstand very high temperatures. Italy, through the DTT (Divertor Tokamak Test) project, focuses its efforts precisely on this issue, known as power exhaust. The main objective of this facility is to study possible techniques—such as alternative magnetic configurations or liquid-metal divertors—capable of mitigating the effects of the enormous thermal loads that impact the in-vessel components exposed to extremely high heat fluxes (orders of magnitude higher than those of a fission reactor) and to neutron bombardment, which degrades the mechanical properties of structural metals. Solving this challenge is crucial for the continuous operation of reactors [23], [24]. Currently, in large experiments such as the International Thermonuclear Experimental Reactor (ITER), the deuterium tritium (D-T) mixture is the one considered. As explained in sec III-E, tritium supply represents a major concern. To make the fusion reactor self-sufficient and sustainable in the long term, it is essential to generate tritium in situ. This will be achieved in future reactors through a "breeding blanket" placed around the reactor core, which will capture the high-energy neutrons produced by the D–T reaction and make them react with lithium (Li) isotopes. Lithium, although not as ubiquitous as water, is also relatively available. [23].

E. Technical Risk (TR)

The definition of a unique TR parameter is not straightforward, the complexity given by the fact that technologies at vastly different stages of industrial maturity needs to be compared. The technical risk for the i-th technology has been defined as follows:

$$\mathrm{TR}_i = \frac{\text{Predicted commercialization year} - 2025}{\text{ICF fusion commercialization} - 2025} \quad (1)$$

ICF has been adopted as normalization. There are several, and not always aligned, opinions about nuclear fusion. On average, 2050 seems to be the most likely commercialization date. MCF and ICF are fundamentally different approaches. The former aims to confine a high-temperature, low-density thermonuclear plasma for long durations using electromagnetic fields. The latter does the opposite: the only confinement is the inertia of the pellet, exploiting a high-temperature and high-density plasma through highly focused laser systems. From a technological point of view, an MCF reactor is an extremely complex machine in which every component is coupled to all others. In ICF, the approach allows for a huge simplification of the apparatus, but this presents trade-offs, as explained in Sec. II-B. Both approaches entail high technical risks, and it is currently impossible to predict which will achieve commercialization first. Historically, however, research has focused predominantly on MCF, particularly in Europe. The primary reason for this preference is the dual-use nature of ICF technology. Most major ICF facilities worldwide have historically been linked to military programs, as the physics of the pellet implosion shares fundamental similarities with the mechanics of thermonuclear weapons. Taking all these aspects into consideration, it is reasonable to conclude that MCF, for energy production, currently holds a slight lead.

Fission plants are in a transition phase. Their diffusion has been limited due to technical and political aspects. For this reason, even if gen. II and gen. III have been commercialized already, there are few hundreds of fission power plants worldwide that, nevertheless, provide about 9 $\%$ of the global energy production, as shown in Fig. 2. The advent of Generation IV reactors, expected by 2030, may significantly alter the current landscape. An estimation of the TR for the considered technology is reported in table I.

TABLE I
TECHNICAL RISK.
*GEN. IV FISSION REACTORS.
**PHOTOVOLTAIC, EOLIC, BIOFUELS, HYDROPOWER

Carbon	**Fission***	**MCF**	**ICF**	**Renewable****
0	0.2	0.9	1	0

III. ASSESSMENT OF THE GEOLOGICAL, GEOPOLITICAL, AND ENVIRONMENTAL RISKS OF ENERGY SOURCES

A. Carbon

The total amount of carbon available on Earth is hard to estimate since most of it is buried underground. Some estimation from the Energy Information Administration (EIA) [25] shows that in the US in 2023 there were about hundreds of trillion tons of carbon left. Such an amount would provide an energy in the order of 10^{24} J. Projections over the years of

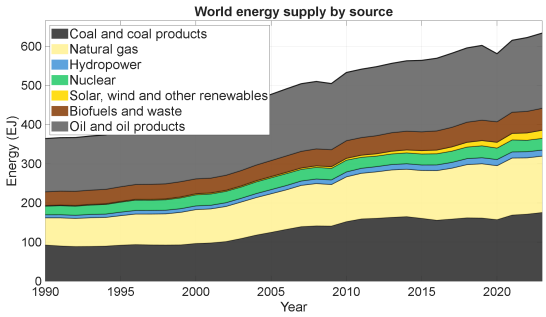


Fig. 2. Data taken from [26].

the world energy demand [26] show that at this rate, assuming $3 \cdot 10^{19}$ J/year, the coal would be completely depleted in about 100000 years. It is clear that the problem is not about its availability but the environmental impact of it.

B. Rare Earth Elements (REE)

REE are vital for modern industry due to their unique chemical properties for permanent magnets, particularly maintaining stable magnetic fields at high temperatures. While not truly scarce, they are highly diluted in the crust, leading to geopolitical constraints: China makes around 37 % of the global production [27] and currently supplies nearly 90 % of the total global demand. REE are essential across the energy sector, used in EV motors, wind turbines, and advanced batteries [28].

C. Uranium and thorium

Uranium is the most used nuclear fuel in fission reactors. It is present in the Earth mostly as ${}^{238}_{92}\mathrm{U}$ (99.3 % of natural uranium) and ${}^{235}_{92}\mathrm{U}$ (0.7 % of natural uranium). The reason for this is that the 235 isotope has a much shorter half-life compared to the 238 isotope. Moreover, the 235 is said to be fissile, i.e., it can undergo fission interacting with low energy neutrons (even a few eV). On Earth, there are currently 6 millions tons of uranium resources in the ground, which would be enough to sustain the current energy demand for 100 years [29] if not recycled [30]. Moreover, this is only a fraction of the real amount of uranium. In fact, it has been estimated that around 4.5 billion tonnes of uranium is actually dissolved in seawater [31]. Numerous efforts have aimed to make uranium extraction from seawater energetically favorable. If this is achieved, uranium could become a widely accessible and reliable energy source, with significant social benefits.

Furthermore, it is worth to mention the role of thorium as nuclear fuel. Thorium is found on Earth crust as ${}^{232}_{90}\mathrm{Th}$. It has been estimated to be more than 3 times as abundant as uranium. It is not fissionable by itself, but, once irradiated by an intense neutron flux, it can produce ${}^{233}_{92}\mathrm{U}$, which is fissionable [32]. There are currently no commercial thorium reactors, but the field has made considerable strides and continues to gain positive momentum worldwide.

TABLE II
GAR PER ENERGY SOURCE: *ONLY THOSE THAT STRONGLY DEPEND ON REE ARE CONSIDERED.

Carbon	**Fission**	**MCF**	**ICF**	**Renewable***
≈0	0.93	1	0.95	0.95

D. Boron and hydrogen

Boron is not a traditional source of energy. However, it can be used in nuclear fusion together with protons from hydrogen. The proton boron (pB) fusion would give no radioactive issues because it does not produce a relevant neutron flux. Boron and hydrogen are cheap and abundant on Earth. The global boron production mostly relies on Turkey (See U.S. GEOLOGICAL SURVEY MINERALS YEARBOOK—2019, Table 5). For these reasons, the possibility of having a nuclear reactor that exploits this type of fusion would be beneficial. On the other hand, the pB fusion cross-section is small compared with the deuterium tritium one [12]. Additionally, it's hard to achieve nuclear ignition because the electrons continuously absorb energy from the ions (collisions), radiating it away (Bremsstrahlung). Therefore, new strategies capable of exploiting pB fusion needs to be developed.

E. Deuterium and tritium

Deuterium and tritium (DT) mixture, ${}^{2}_{1}\mathrm{H}$ and ${}^{3}_{1}\mathrm{H}$ respectively, is considered the most promising fusion fuel for future reactors. In fact, among possible fusion fuels, the DT one has the highest cross-section [12] at low COM (Center Of Mass) energy. Moreover, a DT plasma has considerably fewer electrons than a pB one, and the Bremsstrahlung losses are contained. In addition to the technical problems that prevent nuclear fusion from being achieved, a major concern is the availability of these elements. Deuterium is abundant in seawater, but current technologies makes its extraction expensive, about 10000 $\$/kg$. Moreover, tritium is almost absent in Nature and it must be produced for energy applications. Among all the strategies but, a possible source comes from *heavy water moderated fission reactors*, as explained in sec. II-A. Then, the current price of tritium is one of the most expensive on Earth, about 30 M$\$/kg$.

F. Geological availability Risk (GAR)

A figure of merit capable to summarize all the aspects related to the complex geopolitical and geological situation is proposed. In fact, geological and geopolitical aspects are deeply interconnected. Nevertheless, efforts have been made to separate them and quantify the respective Risk. Moreover, this analysis will reflect the current state of the technology. The geological risk for the i-th resource has been defined as follows:

$$\mathrm{GAR}_i = 1 - \frac{\text{Number of countries owning it}}{\text{Total number of countries}} \qquad (2)$$

The extimated values are reported in table II.

TABLE III
GRR PER ENERGY SOURCE: *ONLY THOSE THAT STRONGLY DEPEND ON REE ARE CONSIDERED.

Carbon	Fission	MCF	ICF	Renewable*
≈0	0.93	≈1	0.98	≈ 1

TABLE IV
TEEI PER ENERGY SOURCE.

Carbon	Fission	MCF	ICF	Renewable
≈1	0.41	0.1	0.09	0.38

G. Geopolitical/regional risk (GRR)

Similarly to GAR, the GRR has been defined for the i-th resource as follows:

$$\mathrm{GRR}_i = 1 - \frac{\text{Number of countries producing it}}{\text{Total number of countries}} \tag{3}$$

The extimated values are reported in table III.

H. Total Equivalent Environmental Impact (TEEI) assessment

Environmental risk assessment provides a quantitative basis for comparing the environmental burdens associated with conventional and alternative energy materials. Exploiting the rationale of the Total Equivalent Warming Impact (TEWI) index, originally developed to account for both direct and indirect greenhouse gas emissions, a broader metric can be formulated to capture the overall environmental impact of the materials considered. While TEWI focuses exclusively on climate effects, the proposed TEEI tries to expand this concept.

To ensure a fair comparison, the TEEI refers solely to the net energy output of the source itself, excluding the contribution of the surrounding infrastructure. It is defined as a weighted sum of normalized impact categories. Each j-th category is scaled to the interval $[0, 1]$ through normalization, so that $N_j = 0$ corresponds to the lowest observed environmental burden and $N_j = 1$ to the highest one within the considered system boundaries. The overall TEEI for the i-th technology is computed as:

$$\mathrm{TEEI}_i = \sum_{j=1}^{n} w_{ij}\, N_{ij}, \qquad \text{with} \qquad \sum_{j=1}^{n} w_{ij} = 1,\ w_{ij} \geq 0. \tag{4}$$

The environmental categories considered are: (1) climate impact, (2) extraction and processing burden, (3) toxicity, (4) radiological risk (when applicable), (5) water use, (6) land use, (7) end-of-life risk, and (8) accident-related environmental hazards. The results reported in table IV are obtained assuming the same weight w_{ij} for each environmental category.

IV. Conclusions and Perspectives

The risk evaluations expressed in tables I to IV, have been summarized in Fig. 3 (left). The contribution of fossil fuels is omitted here, as the ESR constitutes the critical constraint. Although MCF and ICF are not poised for immediate deployment, continued research is crucial. Considering the non-linear relationship between population and energy consumption, fusion stands as the primary long-term solution to ensure universal access to basic needs. Meanwhile, the progressive abandonment of fossil fuels is mandatory. In this context, renewable energy will be pivotal, yet - as noted in the introduction - it cannot realistically supply the entirety of global energy demand alone. Therefore, nuclear fission is an indispensable resource in the transition towards fusion energy.

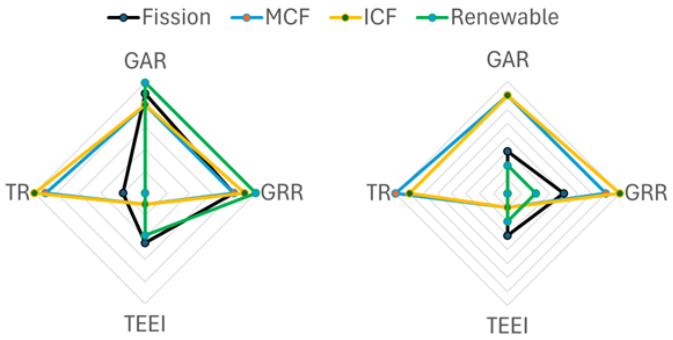


Fig. 3. Plot of the risks in current (left) and in mid-term future (right) scenarios. Risk $= 0 \iff$ center.

Furthermore, Fig. 3 (right) illustrates a near-future, optimistic scenario. In the case of renewable energy, independence from Rare Earth Elements (REEs) has been assumed; currently, dependency on these materials represents a major constraint from both geological and geopolitical perspectives. Regarding fission, the deployment of Generation IV reactors, coupled with viable uranium extraction from seawater the availability of thorium reactors and a spread of spent fuel recycling facilities, is expected to make this energy source significantly more reliable and secure. Furthermore, the ability to extract uranium from seawater would render fission energy accessible to virtually all countries worldwide.

Appendix

To better understand why in nuclear fusion only light elements are used, whereas in nuclear fission only heavy elements are used, the concept of binding energy per nucleon needs to be introduced (see Fig.1.1 [12]).

Consider the general expression for the nuclei mass:

$$M(Z, A) = ZM_p + (A - Z)M_n - |B(Z, A)| \tag{5}$$

Where Z and A the atomic and mass numbers, respectively. M_p and M_n are the proton and neutron masses. Finally, $B(Z, A)$ is the nuclear binding energy. Depending on the nuclear reaction considered, the net energy production, the so called Q-Value, has to be properly evaluated:

$$Q_{fiss} = M_i(Z_1, A_1) - M_{Fiss1}(Z_2, A_2) - M_{Fiss2}(Z, A) \tag{6}$$

$$Q_{fus} = M_1(Z_1, A_1) + M_2(Z_2, A_2) - M_{Fus}(Z, A) \tag{7}$$

If the binding energy of the initial state is lower than the sum of the binding energies of the final states, then the reaction is exothermic ($Q_{fiss} > 0$). In nuclear fusion. If the binding energy of the final state F is higher than the sum of the binding

energies of the initial states, then the reaction is exothermic ($Q_{fus} > 0$). A typical fission reaction is the neutron capture by a U-235 nucleus:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n} \approx 200\,\mathrm{MeV} \quad (8)$$

In the nuclear fusion case, it's worth to mention at least two of the most studied reactions:

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow 3^{1}_{0}n + ^{4}_{2}\mathrm{He} \approx 17.6\,\mathrm{MeV} \quad (9)$$

and

$$^{1}_{1}\mathrm{H} + ^{11}_{5}\mathrm{B} \rightarrow 3^{4}_{2}\mathrm{He} \approx 8.7\,\mathrm{MeV} \quad (10)$$

Compared with carbon combustion, nuclear reactions produce on the order of 10^6 to 10^7 times as much energy per reaction.

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