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GUEST EDITOR

Fabio Fava has been a Full Professor of *Industrial & Environmental Biotechnology* and *Circular Bioeconomy* at the School of Engineering, University of Bologna, since 2005. He has authored around 250 scientific publications, including over 220 papers in international peer-reviewed journals with medium to high impact factors, focusing on industrial and environmental biotechnology and the circular bioeconomy. His work has received more than 12,500 citations, with an H-index of 63 and an i10-index of 150 (Google Scholar), and over 220 publications indexed in Scopus.

His research activities span environmental, industrial, and marine biotechnology, as well as the circular bioeconomy, within several national and European Commission–funded collaborative projects. Among the latter, he coordinated the FP7 collaborative projects **NAMASTE**, focused on the integrated valorization of citrus and cereal processing by-products for the production of food ingredients and novel food products, and **BIOCLEAN**, aimed at developing biotechnological processes and strategies for the biodegradation and tailored depolymerization of waste derived from major oil-based plastics in both terrestrial and marine environments. He also coordinated the University of Bologna's participation in several other FP7 collaborative projects, including **ECOBIOCAP**, **ROUTES**, **MINOTAURUS**, **WATER4CROPS**, **ULIXES**, and **KILL SPILL**.

Fabio Fava served and is serving several national, European and international panels, by covering, among others, the following positions:

• Member of the Scientific Committee of the European Environmental Agency (EEA), Copenhagen, for the "Circular economy and resource use" domain (2021-);

• Italian Representative in the "European Bioeconomy Policy Forum" and the "European Bioeconomy Policy Support Facility" of the European Commission (2020-);

• Senior Expert of the Italian delegation to the Programming committee Horizon Europe, Cluster VI: Food, bioeconomy, natural resources, agriculture and environment (European Commission, DG RTD)(2020-);

• Italian Representative and elected vice chair in the "States Representatives Group" della Public Private Partnership "Circular Biobased Europe" (CBE JU), Brussels (2021-);

• Italian Representative in the "Working Party on Biotechnology, Nanotechnology and Converging Technologies" of the Organization for Economic Co-operation and Development (OECD, Paris) (2008-);

Finally, he is the scientific coordinator of the International Exhibition on Green and Circular economy ECOMONDO held yearly in Rimini (Italy)

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AUTOMATION, DIGITALIZATION, AND HUMAN-CENTRIC RECYCLING: THE BORSOI MODEL FOR PADDED AND UPHOLSTERED TEXTILE WASTE REGENERATION*

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Abstract

The recycling of quilted and padded waste from upholstered products represents one of the most pressing challenges for the textile, furniture, and related industries. These complex materials, often composed of multi-layer fabrics combined with synthetic or natural fillings, are typically excluded from conventional recycling streams due to their structural complexity and the difficulty of separating their components.
In response to this challenge, Borsoi S.r.l., an Italian industrial machinery manufacturer, focused on automation, digitalization, and a human-centric sustainability approach, has developed a comprehensive and innovative recycling solution aimed at transforming padded and quilted textile waste into high-quality secondary raw materials. The primary aim of the innovation is to combine advanced automation, AI-driven material recognition, and digitalization, while embedding the principles of Industry 5.0, which emphasizes human-centricity, resilience, and sustainability.
The developed system covers the full recycling process, from automated waste handling and identification to sanitization, separation, defibering, and upcycling. The main results achieved demonstrate a material recovery efficiency above 95%, with a contamination level consistently below 1%. The recovered fibers meet quality requirements for reuse in industrial applications, for direct textile reintegration and other uses. This modular approach supports local circular value chains and exemplifies Industry 5.0 through traceability, resilience, and low environmental impact.

Keywords: artificial intelligence, circular economy, Industry 5.0, nonwoven regeneration, textile recycling

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1. Introduction

Padded and upholstered textile waste represents one of the most technically and economically challenging streams within post-consumer textile flows. Unlike mono-material garments, these items typically comprise a composite structure of fabrics, foams, adhesives, metal components, coatings, and chemical finishes. This structural complexity renders conventional recycling systems ineffective, contributing to a global recycling rate for mixed textile waste that remains below 1%, and in some cases under 0.5% (Andini et al., 2024).

According to recent assessments, scaling closed-loop textile-to-textile systems for such waste types is hindered by technological bottlenecks in separation and material purity, especially where multilayer compositions and contaminant load are involved (Charnley et al, 2024; Huang et al., 2024). Furthermore, while open-loop recycling has gained some industrial traction, closed-loop systems remain at a pilot or fragmented commercial scale, particularly for padded and upholstered items (Huang et al., 2024).

At the same time, the European Union’s regulatory landscape is evolving rapidly, with incoming mandates around Extended Producer Responsibility[1] (EPR) and separate textile waste collection post-2025. These policy drivers create an urgent need for modular, automated, and human-safe technologies capable of managing complex textile waste streams in a circular and economically viable manner.

In this context, the Borsoi model presents an integrated Industry 5.0-based approach tailored to the needs of this waste segment. The system combines:

- AI-enabled classification and sorting based on spectral imaging and vision technologies, capable of achieving >95% accuracy across mixed input streams (Spyridis et al., 2024; Tsai and Yuan, 2024; Tian et al., 2024).
- Automated delayering, defibering, and contamination removal, addressing the mechanical and material heterogeneity of padded goods.
- Closed-loop sanitization technologies using ozone, UV-C, and supercritical CO_2, ensuring hygienic fiber recovery without water consumption.
- Modular design principles aligned with Industry 5.0, prioritizing human-centricity, resilience, and sustainability through ergonomic interfaces and supervisory roles for operators.

By automating the full spectrum of preprocessing, sanitization, and material regeneration, this model advances the industrial feasibility of circular solutions for complex textile waste. It also responds to literature-identified gaps in large-scale processing, contamination control, and human-machine integration in textile recycling facilities.

2. Materials and methods

The overall recycling system is conceived as a modular, flexible architecture of industrial units, each addressing the specific challenges of padded textile waste through automation, AI-driven sorting, and closed-loop valorization.

Figure 1 illustrates two examples of Borsoi’s modular automation systems: the recycling line for jackets and duvets (left), and the line for mattresses, toppers, and pillows (right). These systems cover all key recycling stages for padded textile products, from loading and unfolding to mechanical opening, emptying, and material separation, facilitating efficient circularity within a single integrated platform (Table 1). A full demonstration of one of these modular recycling lines is available in a recent video by Borsoi S.r.l. (2024) (https://youtu.be/HE0iuy-dsZY) (Fig. 2).

a) **b)**

Figure 1. Borsoi's modular systems for recycling of padded textiles: (a) jackets and duvets; (b) mattresses, toppers, and pillows. The recycling workflow includes: 1. Loading Station (automated or with operator); 2. Loading Conveyor; 3. Compression and Cutting Unit; 4. Delayering, Emptying and Separation Unit; 5. Cover/Shell Discharge Conveyor; 6. Filling Collection Silo

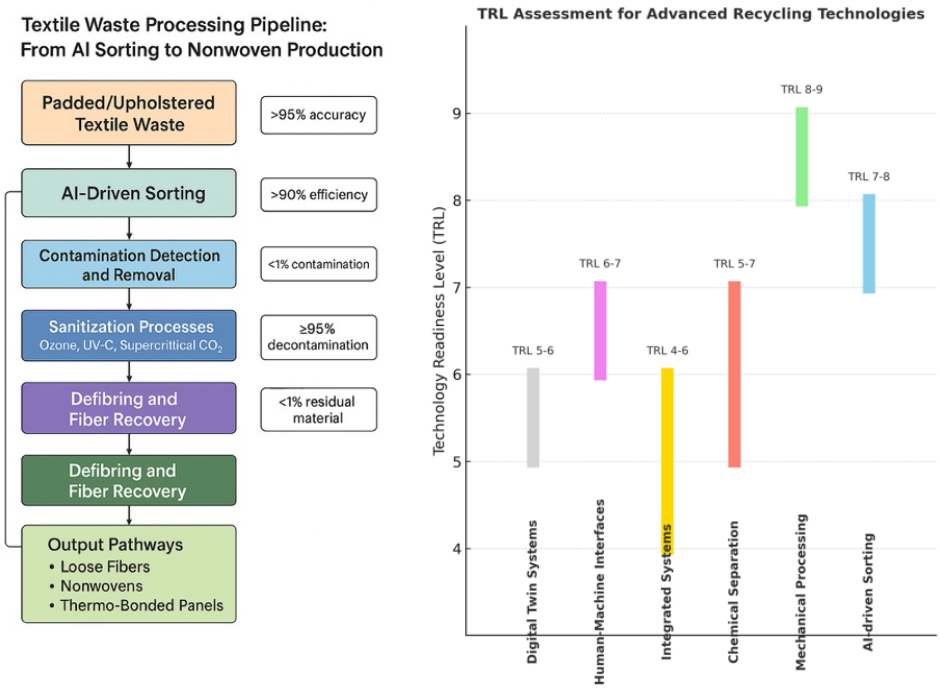
Table 1. Common multilayer textile padded products recycled, and their components

Product components product type	***Outer shell***	***Inner fill***	***Structural components***
Jackets	Nylon / Polyester	Down / Synthetic-Natural fibers	Zippers, snaps, elastics
Pillows & Duvets	Cotton blend / Polyester	Down / Foam / Fiberfill / Waddings	Zippers, piping, inner cases, corners, buttons
Toppers & Mattresses	Poly-cotton /Polyester	Foam / Springs / Fiberfill /Waddings	Metal frame, springs, zippers, piping, straps

The overall workflow encompasses (Table 2):

- Identification and classification via vision systems and AI, achieving >95% accuracy for fiber-type separation (Tsai and Yuan, 2024).
- Mechanical delayering and separation, suitable for disassembling multilayer composites while minimizing fiber damage (Wojciechowska and Kowaluk, 2024).
- Detection and removal of metallic and plastic contaminants through optical and X-ray systems with >99.9% efficiency (Purnell, 2024).
- Sanitization using ozone, UV-C, and supercritical CO_2 dry processes that ensure hygienic quality without the use of water (Karmakar et al., 2024).
- Advanced defibering and fiber recovery lines, optimized for throughput and yield, while mitigating quality loss in foam-contaminated streams (Choudhury et al., 2024).
- Final valorization into loose fibers, nonwovens, and thermo-bonded panels, with applications in insulation, automotive, and packaging (Hazarika and Kalita, 2024; Gaminian et al., 2024).

Data monitoring and process optimization are enabled through a digital twin framework and real-time IoT-enabled sensor arrays, allowing for predictive maintenance, traceability, and adaptive control (Fig. 3). The integration of Industry 5.0 principles, including human-centric roles and system resilience further enhances operational safety, ergonomics, and workforce acceptance (Chivilò and Meneghetti, 2023; Costa, 2024). Table 3 summarizes key sorting and separation technologies benchmarked in the literature.



a) **b)**

Fig. 2. Overview of the Borsoi recycling workflow with validated KPIs (a); TRL assessment for textile recycling technologies (b)

Table 2. Comparison with conventional disposal methods

Parameter	*Borsoi system*	*Landfilling*	*Incineration*
Recovery efficiency	>95%	0%	Energy only
Cross-contamination	<1%	N/A	N/A
Water use	Zero	Low	Low
Energy consumption	0.45 kWh/kg	N/A	High
CO_2 emissions	Low	Very High	High

3. Results and discussion

The integrated textile recycling system demonstrated material recovery efficiencies consistently above 95%, with contamination levels below 1%, aligning with or exceeding benchmarks from the literature (Fig. 4) (Tian et al., 2024; Tsai and Yuan, 2024). AI-enhanced vision and spectral classification tools, including Raman spectroscopy and attention-based deep learning, enable high-resolution grouping of mixed-textile waste into fiber classes, significantly improving feedstock quality for downstream processing (Tsai and Yuan, 2024; Valilai, 2025). These tools reduce dependency on manual sorting and enable cleaner input streams for mechanical and chemical recycling (Table 4).

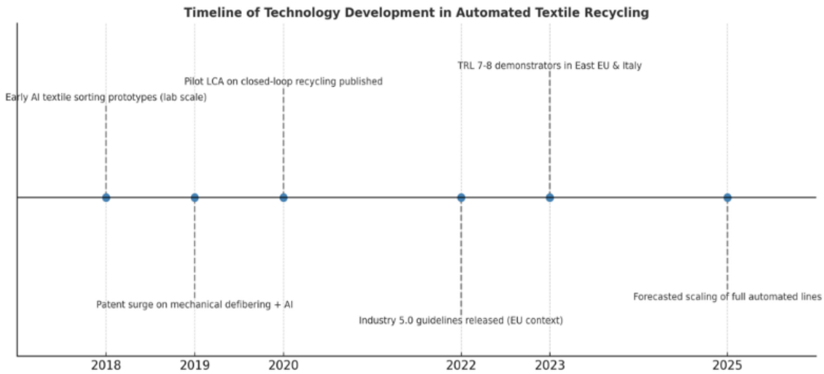


Fig. 3. Overview of the key milestones in the evolution of textile recycling technologies, from early AI tools to expected scaling in 2025 and beyond

Table 3. Comparative overview of sorting and separation technologies

Method	***Reported throughput***	***Reported accuracy/quality***	***Technology readiness (qualitative)***
Raman + ML spectral sorting	~1 piece/s	>95% grouping precision	Prototype / lab-to-pilot (Tsai and Yuan, 2024)
Computer vision + attention nets	Industrial deployment	>90% accuracy	Pilots with deployment stability (Tian et al., 2024)
Spectral imaging + robotics	Not quantified	Preliminary accuracy validated	Pilot-to-demonstrator (Spyridis et al., 2024)
Mechanical shredding + chem. separation	Batch/continuous	Component separation enabled	Patent stage (Speight et al., 2020)

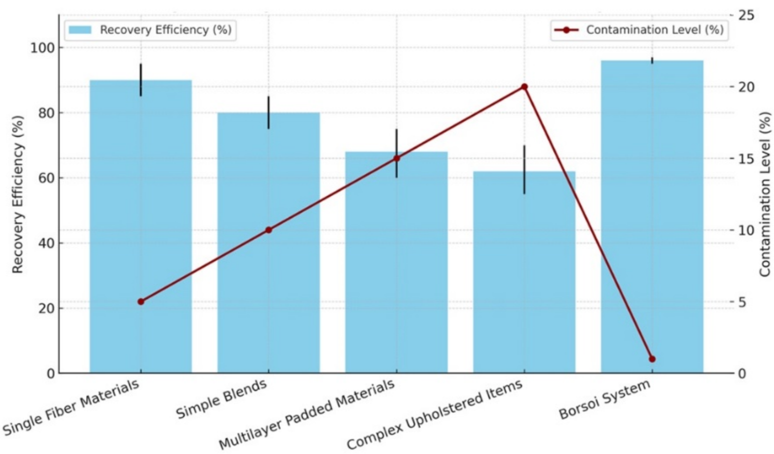


Fig. 4. Material recovery efficiency: literature benchmarks vs. Borsoi system

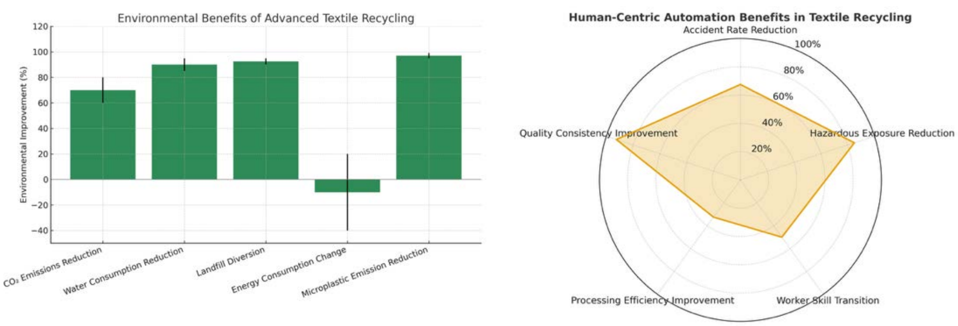
Table 4. Key process parameters in Borsoi's recycling system

Process step	***Technology***	***Parameter (Unit)***
Sanitization	Ozone	5 ppm, 20 min
Sanitization	UV-C	254 nm, high intensity
Sanitization	Supercritical CO_2	70 bar, 35°C
Cutting	Rotary / Guillotine blades	<1 mm fibre cut
Defibering	Tearing drum (2–6 drums, in series)	Feed rate: 50–500 kg/h (depending on material)
Sorting	AI + Vision	Detection speed: 2 items/sec

Mechanical recycling remains the most scalable approach for single-fiber materials, even if closed-loop recycling remains limited in volume and economics (Charnley et al., 2024; Huang et al., 2024). For blended and padded textiles, partial separation via chemical solvolysis (e.g., microwave-assisted glycolysis) has demonstrated rapid processing, high conversion, and techno-economic potential (Andini et al., 2024). When full separation is infeasible, residual-contaminated materials can be valorized into composite boards or nonwovens, retaining function while tolerating residual fillers or adhesives (Wojciechowska and Kowaluk, 2024; Hazarika and Kalita, 2024). These open-loop applications offer near-term circularity pathways and help capture value from difficult waste streams.

Environmental gains are confirmed by multiple LCA studies. For example, recycled denim-based needle-punched nonwovens achieved thermal resistance and tensile strength targets, while reducing GHG emissions and water use compared to virgin alternatives (Karmakar et al., 2024). Yet net impact depends on energy mix, monomer recovery rates, and system integration (Andini et al., 2024).

On the economic front, pilot techno-economic analyses of chemical routes suggest feasible margins under certain feedstock purity and scale assumptions. However, industrial adoption still hinges on overcoming CAPEX/OPEX uncertainties and logistics costs (Andini et al., 2024; Speight et al., 2020). Human-centric automation, a key tenet of Industry 5.0, plays a pivotal role in improving worker safety and system acceptability (Fig. 5). Vision-based sorting, ergonomic workstation design, and collaborative robots reduce exposure to dust and repetitive tasks while supporting workforce reskilling into supervisory roles (Chivilò and Meneghetti, 2023; Costa, 2024).



a) b)

Fig. 5. Key environmental impact metrics comparing advanced textile recycling with virgin material production and conventional waste handling (a); Quantitative improvements enabled by Industry 5.0 principles in textile recycling environments (b)

Despite positive trends, several gaps remain. There is little empirical evidence on robust defibering of multilayer textiles at scale. Few studies provide standardized TRL reporting or system-wide techno-economic models. Real-world pilots integrating AI-sorting, robotic handling, and human-centric operation remain rare, particularly for padded and upholstered items (Spyridis et al., 2024; Chattaraj et al., 2025).

Given the heterogeneity of multilayer waste, hybrid process chains are essential. High-purity mono-materials can be directed to chemical depolymerization, while contaminated or inseparable multilayers are better suited for mechanical defibering and conversion into functional nonwovens or composite boards. The Borsoi model's integration of Industry 5.0 principles, such as human-centric design, collaborative robotics, and adaptive digital twins reinforces its real-world applicability.

To enhance replicability, the literature suggests three key recommendations:

1. *Combine high-precision AI sorting with modular downstream processing tailored to item composition and contamination levels*.
2. *Apply Industry 5.0 design frameworks to ensure ergonomic, safe, and socially acceptable automation environments*.
3. *Prioritize transparent pilot-scale validation with complete LCA and techno-economic assessments (TEA) to guide scale-up*.

4. Conclusions

The Borsoi model offers a modular, scalable solution for recycling padded and upholstered textile waste, combining AI-based sorting, mechanical defibering, and Industry 5.0 principles. High classification accuracy (>95%) and hybrid process chains enable material recovery and valorization, even from complex, multilayer items. Human-centric automation enhances safety and workforce acceptance.

Beyond technical performance, the Borsoi system exemplifies the transition from traditional mechanized recycling toward adaptive, intelligent, and sustainable manufacturing ecosystems. By embedding digital twin architectures, predictive analytics, and real-time data exchange, the platform contributes to the creation of transparent and resilient textile recovery networks. Its modularity allows integration into regional or decentralized recycling infrastructures, promoting short supply chains and strengthening local circular economies.

The environmental implications are equally significant: zero-water sanitization, reduced energy use, and contamination rates below 1% position the system as an eco-efficient benchmark aligned with EU Green Deal targets and forthcoming EPR frameworks. The incorporation of Industry 5.0's human-centric philosophy ensures that automation is balanced with worker empowerment, health protection, and skill enhancement, fostering social sustainability alongside technological innovation.

To support full-scale deployment, future research should validate the model under industrial conditions through long-term pilot trials, comprehensive life cycle assessments (LCA), and techno-economic evaluations (TEA). Further optimization of AI algorithms for mixed-textile recognition and continuous monitoring of fiber quality across reuse cycles will be crucial to confirm durability and market readiness.

Ultimately, the Borsoi platform stands as a pioneering demonstrator of circular textile regeneration, bridging automation, digitalization, and human values, to advance a resilient, inclusive, and economically viable recycling paradigm consistent with evolving policy and market needs.

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References

Andini E., Bhalode P., Gantert E., Sadula S., Vlachos D.G., (2024), Chemical recycling of mixed textile waste, *Science Advances*, **10**, https://doi.org/10.1126/sciadv.ado6827.

Charnley F., Cherrington R., Mueller F., Jain A., Nelson C., Wendland S., Ventosa S., (2024), Retaining product value in post-consumer textiles: How to scale a closed-loop system, *Resources, Conservation and Recycling*, **205**, 107542, https://doi.org/10.1016/j.resconrec.2024.107542.

Chattaraj S., Mitra D., Madan A.K., Pellegrini M., Choudhury T., (2025), *AI Technologies for Enhancing Recycling Processes. Conclusion of AI Technologies for Enhancing Recycling Processes, Advances in Environmental Engineering and Green Technologies Book Series*, ICI Global Scientific Publishing, Hershey, Pennsilvania, USA, On line at: https://doi.org/10.4018/979-8-3693-7282-1.ch022.

Chivilò M., Meneghetti A., (2023), An Industry 5.0 perspective on feeding production lines, *Sustainability*, **15**, 16088, https://doi.org/10.3390/su152216088.

Choudhury K.R., Tsianou M., Alexandridis P., (2024), Recycling of blended fabrics for a circular economy of textiles: Separation of cotton, polyester, and elastane fibers, *Sustainability*, **16**, 6206, https://doi.org/10.3390/su16146206.

Costa E., (2024), Industry 5.0 and SDG 9: a symbiotic dance towards sustainable transformation, *Sustainable Earth Reviews*, **7**, 4, https://doi.org/10.1186/s42055-024-00073-y.

Gaminian H., Ahvazi B., Vidmar J.J., Ekuere U., Regan S., (2024), Revolutionizing sustainable nonwoven fabrics: The potential use of agricultural waste and natural fibres for nonwoven fabric, *Biomass*, **4**, 18, https://doi.org/10.3390/biomass4020018.

Hazarika M.K., Kalita B.B., (2024), Development of nonwoven fabric using textile waste and its characterization, *The Journal of Research ANGRAU*, **52**, 8, https://doi.org/10.58537/jorangrau.2024.52.2.08.

Huang X., Tan Y., Huang J., Zhu G., Yin R., Tao X., Tian X., (2024), Industrialization of open- and closed-loop waste textiles recycling towards sustainability: A review, *Journal of Cleaner Production*, **436**, 140676, https://doi.org/10.1016/j.jclepro.2024.140676.

Karmakar S., Majumdar A., Butola B.S., (2024), A sustainable recycling process and its life cycle assessment for valorising post-consumer textile materials for thermal insulation applications, *Waste Management & Research*, **42**, 734–742.

Purnell P., (2024), Mechanical, chemical, biological: Moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles, *Journal of Cleaner Production*, **385**, 135716, https://doi.org/10.1016/j.jclepro.2021.129325

Speight R., O'Hara I.M., Zhang J.Z., Moller D.E., Jones A., Ross G., (2020), A system and process for the separation and recycling of blended polyester and cotton textiles for re-use, Patent *WO2020252523A1*, Available at: https://patents.google.com/patent/WO2020252523A1/en.

Spyridis Y., Argyriou V., Sarigiannidis A., (2024), Autonomous AI-enabled industrial sorting pipeline for advanced textile recycling, *arXiv / IEEE*, Available at: https://arxiv.org/pdf/2405.10696.

Tian L., Fan V., Wang X., et al., (2024), Qualitative classification of waste garments for textile recycling based on machine vision and attention mechanisms, *Waste Management*, **183**, 74-86.

Tsai P.-F., Yuan S.-M., (2024), Using infrared Raman spectroscopy with machine learning and deep learning as an automatic textile-sorting technology, *Sensors*, **25**, 57, https://doi.org/10.3390/s25010057

Valilai O.F., (2025), Exploring the role of artificial intelligence for pattern recognition of textile sorting and recycling for circular economy, *Procedia Computer Science,* **253**, 346–356.

Wojciechowska M., Kowaluk G., (2024), Challenges and opportunities in recycling upholstery textiles: Enhancing high-density fiberboards with recycled fibers, *Fibers*, **12**, 105, https://doi.org/10.3390/fib12120105.

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BIOFIBRELOOP PROJECT: CIRCULAR BIOBASED TECHNICAL TEXTILES WITH INNOVATIVE BIO-INSPIRED NON-TOXIC FUNCTIONALIZATION*

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Abstract

The textile industry is at a turning point, facing pressure to adopt sustainable production and meet growing demand for smart functionalities. EU policies toward climate neutrality and net-zero emissions require the sector to implement circular and sustainable innovations. Functional textile production often relies on non-recyclable chemicals, creating regulatory and environmental challenges. BioFibreLoop addresses this by developing recyclable textiles from bio-based materials, including lignin, cellulosic and polylactic acid (PLA) fibers. Biomimetic laser-based surface functionalization enables high-performance smart properties, such as hydrophobicity, oil repellence, self-cleaning and antibacterial activity, without hazardous chemicals. Mono-material structures and thermoplastic bio-based coatings further support recycling and a circular product lifecycle. The project will not only deliver technical innovations but also demonstrate how Digital Twins and process models can support life cycle analysis, sustainability assessments, and the efficient development of BioFibreLoop products. In addition, open-source digital tools will further enhance process optimization and scalability.

Keywords: bio-based textiles, biodegradability, biomimetic functionalization, circular process, Digital Twins, safe and sustainable by design framework

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1. Introduction

The textile industry is at a pivotal moment of transformation in response to intensifying environmental challenges, increasingly stringent regulatory frameworks and growing consumer demand for sustainable and high-performance products. Textile manufacturing is one of the most resource-intensive industrial sectors, contributing significantly to global water consumption, greenhouse gas (GHG) emissions and widespread use of hazardous chemicals. In particular, the functionalisation of textiles frequently relies on fluorinated compounds and persistent organic pollutants which not only pose risks to human and environmental health but also compromise the recyclability and circularity of textile products (Niinimäki et al., 2020).

The European Union has introduced a comprehensive policy framework aimed at reshaping the textile value chain. These strategies call for a transition toward climate-neutral, circular and non-toxic textile systems, prioritizing sustainable material use, the elimination of hazardous chemicals and the implementation of safe and sustainable design practices across all product life cycle stages (European Commission, 2023).

In response to these policy and market pressures, the BioFibreLoop project proposes a novel, integrated approach to the development of innovative, circular, safe and high-performance textiles using bio-based and recyclable feedstock. The project focuses on renewable materials such as lignin, cellulose-based and PLA fibres, selected for their compatibility with circular design principles, low environmental footprint, and capacity to replace synthetic fibres in demanding applications including workwear, outdoor clothing, and activewear.

The main objective of this study is to present and critically assess the integrated innovation approach developed within the BioFibreLoop project, which targets the development of circular, bio-based and non-toxic functional textiles. This approach brings together environmental, technical and digital innovations applied across the entire textile value chain, from raw material selection to end-of-life (EoL) strategies, in response to increasing regulatory pressure, ecological challenges and growing market demand for safer and more sustainable textile products within the European Union. In particular, the research aims to investigate how these innovations contribute to advancing sustainable manufacturing practices, while also evaluating the effectiveness of industrial-scale validation activities in demonstrating the performance, durability and scalability of the developed textile solutions under realistic production conditions.

2. Outline of the work

This paper presents the first outcomes of the BioFibreLoop project, covering the development of high-performance textiles derived from renewable and recyclable biomaterials, enhanced with eco-friendly lignin-based coatings functionalised through biomimetic approaches to provide water, oil, UV light and bacteria resistance.

The paper also describes the implementation of advanced digital tools, including Digital Twins (DT) and a Virtual Replication Tool (VRT), designed to support circular design strategies and enable data-driven decision-making across the textile production chain. In parallel, it introduces an integrated safety and sustainability assessment framework, aligned with the Safe and Sustainable by Design (SSbD) principles, to evaluate the environmental, health, economic and social impacts of the developed innovations.

Finally, the study outlines the approach taken to validate these technological advances at industrial scale.

3. Materials and methods

The BioFibreLoop project uses renewable and recyclable materials (lignin, cellulose-based and PLA fibers). Lignin-cellulose blends were melt-spun into multifilament yarns, while PLA and cellulosic fibers were processed into woven, knitted and nonwoven fabrics. Coatings were applied via slot-die extrusion and hot calendering of lignin-cellulose films and biomimetic micro/nanostructures were embossed to impart surface properties, assessed via contact angle. A DT was developed to simulate and optimize production processes (Murzin, 2024), complemented by a VRT for industrial scaling. Sustainability impacts across the value chain are assessed through an integrated framework combining Life Cycle Assessment (LCA), Techno-Economic Assessment (TEA), Social Life Cycle Assessment (S-LCA) and Human and Environmental Risk Assessment (HRA/ERA). LCA is conducted by Next Technology Tecnotessile (NTT) and German Institutes for Textile and Fiber Research (DITF Denkendorf) using SimaPro 10 and Umberto LCA+ respectively, while S-LCA relies on stakeholder surveys and the Social Hotspot Database.

4. Results and discussion

Textile development. BioFibreLoop is developing bio-based functional textiles from renewable and recyclable materials, such as lignin, cellulose and PLA. Protective properties (oil, water, UV and microbial resistance) were enhanced via a thin lignin-based coating, alongside surface modification techniques designed to improve performance without using harmful chemicals.

Multifilament fibers were successfully extruded by DITF Denkendorf via melt-spinning of lignin-cellulose blends. Cellulose improved both flexibility and strength (Jin er al., 2021) while strict control of compound homogeneity and melt rheology ensured continuous fiber production. After several chemical modification attempts, a formulation with adequate elongation at break was obtained. A key limitation was the restricted availability of suitable lignin grades, though improvements in the European biorefinery sector are expected. The resulting filaments were used to produce woven fabrics with satisfactory surface uniformity, smooth texture and a slightly brownish shimmer (Fig. 1).

Fig. 1. Lignin yarn and woven fabric produced by DITF Denkendorf

In addition to the lignin-cellulose fibers, PLA- and cellulose-based fabrics were produced by European partners, such as FreyZein Urban Outdoor GMBH, NTT, and NIL-

Textile SRO, in woven, knitted and nonwoven formats, with controlled variations in composition, grammage, density and mechanical properties. Selected samples with favorable mechanical and structural characteristics were prepared for lignin-based coating trials, including pre-treatment, washing and cutting to suit smaller-scale coating systems at DITF Denkendorf.

Films from compounds with varying lignin/cellulose ratios were developed for textile coating (Fig. 2). European bio-based raw materials were evaluated for film-forming ability, grain size, melt behavior and flexibility, leading to three suitable formulations. With the aim of achieving the highest recyclability of the material, particular emphasis was placed on developing a coating formulation that was chemically compatible and closely similar to the one used for the fibre production. Pursuing a monomaterial configuration enhances EoL sustainability by simplifying recycling logistics, avoiding disassembly. This allows for thermal recycling through melting and subsequent reuse in both coating and fibre production processes. Film production was performed using a lab-scale extruder with a slot die, followed by heated calendering to control thickness and surface homogeneity. Films were applied to textile substrates via thermal lamination, with heat and pressure facilitating layer bonding. Managing thermal compatibility was critical, as lignin-based coatings (~180 °C) closely match or exceed the melting points of the textile materials. Despite this challenge, effective lamination was achieved, ensuring good adhesion while preserving the material's 3D structure.

Fig. 2. Lignin film laminated on a cellulose woven fabric by DITF Denkendorf

Further advances were made in developing functional surface modifications to impart water and oil repellency to bio-based coatings. Nature-inspired micro/nanostructures were embossed onto lignin-based coatings using laser-structured plates (Cai et al., 2014; Darmanin et al., 2015; Latthe et al., 2014; Vorobyev et al., 2015). Replicating these complex structures onto lignin-based coatings remains challenging. A novel laser-based embossing approach is being explored, with experiments at Centre Technologique ALPHANOV and DITF Denkendorf focused on fabricating precision-structured metal plates using two laser types. These metallic masters are then used to thermally emboss micro- and nanostructured patterns onto coated textiles under controlled temperature and pressure (Bouchard et al., 2022). Contact angle measurements, using water, diiodomethane and n-hexadecane, showed enhanced hydrophobic and oleophobic performance (Fig. 3). Current work focuses on lab-scale metallic plates for rapid design and testing, with future scale-up planned via embossing rollers to enable efficient roll-to-roll functionalization of large textile surfaces (Schift et al., 2006).

Digital tools. The BioFibreLoop project addresses the increasing demand for sustainable and digitalized solutions in textile industry by combining sustainable material development with advanced digital tools to support circular value chains (Murzin, 2024). A central component of this effort is the development of DT architecture, providing a dynamic representation of production workflows. Operational parameters were defined following the DT framework (Jørgensen et al., 2023), covering all phases from (i) DT Purposing to (iv) Calibration and Validation. The methodology consisted of three phases: hierarchical decomposition of manufacturing processes to create standardized flow diagrams; impact-driven identification and multi-dimensional classification of parameters by process stage (spinning, weaving/knitting, finishing), material type (PLA, lignin, cellulose), and functional impact (material/process properties, settings, environmental data); multi-level expert validation for lab and industrial relevance.

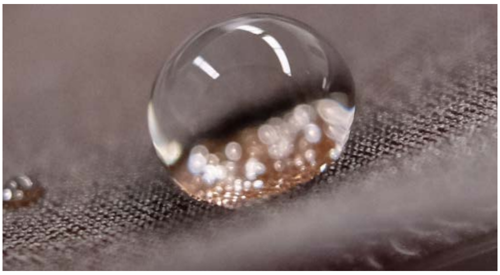

Fig. 3. Water drop on functionalized surface by DITF

This approach identified over 80 operational parameters across three material-specific process flows (Fig. 4), each documented with nominal values, tolerance and partly interdependency mapping. Expert validation confirmed industrial applicability, while highlighting challenges in finishing and recycling stages. This validated dataset establishes the DT baseline, ensuring both scientific robustness and practical relevance for subsequent development phases (Chapman et al., 2000).

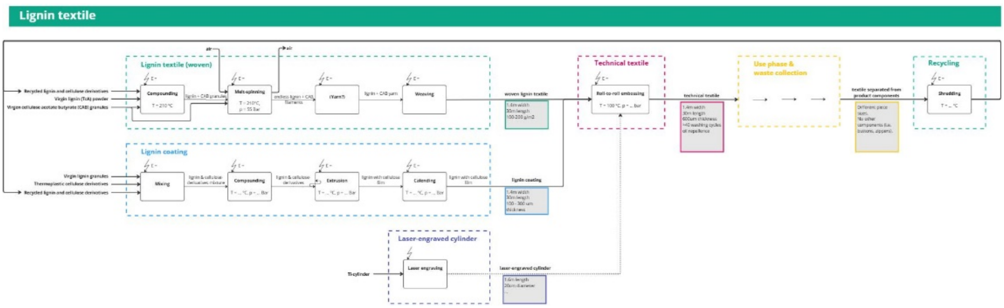

Fig. 4. Process flow of the BioFibreLoop products

A distinctive strength of the DT is its metrics-based decision support. Combined with AI enhancements, it monitors and benchmarks key indicators, such as functionalization efficiency and recyclability performance, against SSbD thresholds (Caldeira et al., 2022), ensuring technical optimization aligns with sustainability goals. To extend its impact, BioFibreLoop is developing a VRT, a digital platform for European textile manufacturers that simulates production scenarios, assesses process modifications and evaluates sustainability outcomes without resource-intensive physical testing, supporting data-driven and low-impact manufacturing.

Safety and sustainability assessment. The National Research Center for the Working Environment (NFA), together with NTT, IDENER Research & Development Agrupacion de Interes Economico and the whole partnership, has developed a life cycle-oriented strategy that integrates environmental, economic, social and health dimensions to assess the overall sustainability of each novel circular textile product. As part of this effort, a dedicated safety and sustainability assessment framework is being established to systematically guide evaluation from the early material and product design through validation and demonstration. The framework is based on core design principles, focusing on material efficiency, reduced hazards, energy, recyclability and life-cycle indicators.

Sustainability performance is systematically assessed across all relevant life cycle stages (material production, manufacturing, use, EoL recovery and biodegradation) from conceptual design to real-world application (Hammar et al., 2024). This integrative approach aligns with key United Nations Sustainable Development Goals (SDGs), including climate resilience, sustainable resource use and human health, while explicitly considering trade-offs such as increased energy demand or material complexity for a balanced evaluation of sustainability impacts. The framework adopts a hybrid approach based on SDGs, SSbD, and established LCA methods (Apel et al., 2024; Caldeira et al., 2022) and is iteratively refined with partner and stakeholder input. The final conceptual model (Fig. 5) is structured around four interrelated sustainability pillars: safety, environmental, social, and economic. Each pillar is assessed using dedicated tools and metrics, including HRA/ERA, LCA, S-LCA, and TEA (Fonseca et al., 2023; Fidan et al., 2025). Combining empirical data with established methodologies, this approach enables robust evaluations and continuous refinement. Although primarily developed to guide sustainability assessments within the BioFibreLoop project, it is designed to be adaptable and aligned with policy frameworks, providing a scalable model to advance safe, circular, and environmentally sustainable textile innovations throughout Europe and beyond.

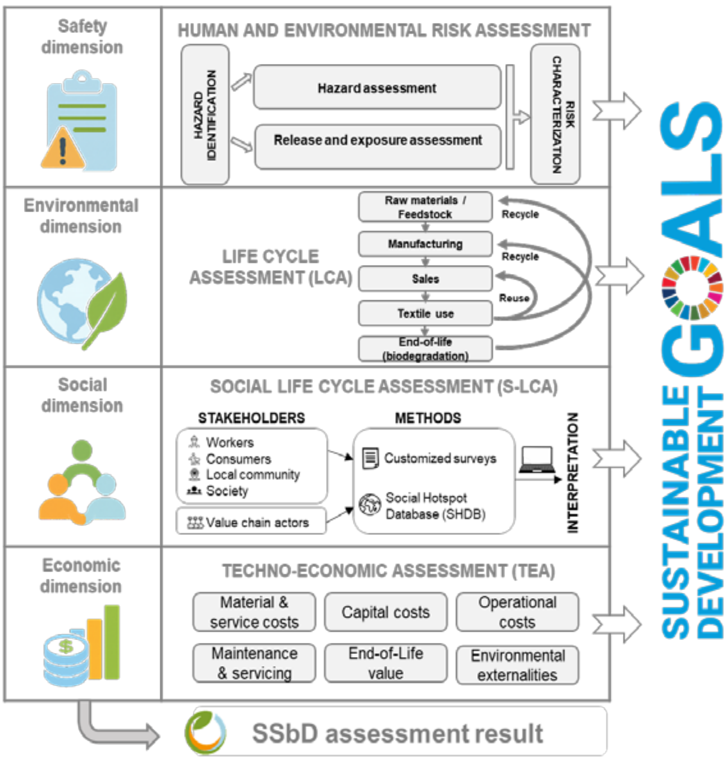

Fig. 5. Conceptual framework for the overall sustainability in BioFibreLoop (Fischer et al., 2025)

5. Concluding remarks

This study demonstrates the potential of bio-based textiles from lignin, cellulose and PLA, where biomimetic surface functionalization enhances water and oil resistance without toxic chemicals. Despite challenges in lignin supply, results confirm technical feasibility and highlight recycling importance.

Future work will address recycling strategies for lignin, PLA and cellulose, alongside biodegradation studies. Digital tools, including DT and Virtual Replication Tool, support optimization and sustainability assessment, while industrial validation is foreseen through demonstrations in Germany, Austria, and Czech Republic, targeting TRL 7.

Disclaimer

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References

Apel C., Kümmerer K., Sudheshwar A., Nowack B., Som C., Colin C., Soeteman-Hernández L.G., (2024), Safe-and-sustainable-by-design: State of the art approaches and lessons learned from value chain perspectives, *Current Opinion in Green and Sustainable Chemistry*, **45**, 100876, https://doi.org/10.1016/j.cogsc.2023.100876

Bouchard F., Wang W., Soldera M., Lasagni A.F., (2022), Influence of structure size and geometry on wetting behavior of PMMA surfaces imprinted with laser-textured stamps, *Journal of Laser Micro Nanoengineering*, **17**, 107-115.

Cai Y., Lin L., Xue Z., Liu M., Wang S., Jiang L., (2014), Filefish-inspired surface design for anisotropic underwater oleophobicity, *Advanced Functional Materials*, **24**, 809-816.

Caldeira C., Farcal R., Garmendia A.I., Mancini L., Tosches D., Amelio A., Sala S., (2022), Safe and sustainable by design chemicals and materials – Framework for the definition of criteria and evaluation procedure for chemicals and materials, *Public Report*, European Commission, On line at: https://publications.jrc.ec.europa.eu.

Chapman P., Clinton J., Kerber R., Khabaza T., Reinartz T., Shearer C., Wirth R., (2000), CRISP-DM 1.0: Step-by-step data mining guide, *Technical Report*, SPSS Inc., Chicago, USA.

Darmanin T., Guittard F., (2015), Superhydrophobic and superoleophobic properties in nature, *Materials Today*, **18**, 273-285.

European Commission, (2023), EU strategy for sustainable and circular textiles, Online at: https://environment.ec.europa.eu/strategy/textiles-strategy_en.

Fidan F.S., Aydoğan E.K., Uzal N., (2025), Comprehensive analysis of social subcategories throughout life cycle assessment approach for the textile industry, *The International Journal of Life Cycle Assessment*, **30**, 1464–1479.

Fischer T., Stegmaier T., Caballero V., Fonseca A.S., Papřok V., (2025), BioFibreLoop: Bio-inspired, laser-based functionalisation on bio-based materials leads to recyclable functional garments, *The Innovation Platform*, **22**, 218-221.

Fonseca A., Ramalho E., Gouveia A., Henriques R., Figueiredo F., Nunes J., (2023), Systematic insights into a textile industry: Reviewing life cycle assessment and eco-design, *Sustainability*, **15**, 15267, https://doi.org/10.3390/su152115267.

Hammar T., Peñaloza D., Hanning A.-C., (2024), Life cycle assessment of a circular textile value chain: The case of a garment made from chemically recycled cotton, *The International Journal of Life Cycle Assessment*, **29**, 1880–1898.

Jin Y., Lin J., Cheng Y., Lu C., (2021), Lignin-based high-performance fibers by textile spinning techniques, *Materials*, **14**, 3378, https://doi.org/10.3390/ma14123378.

Jørgensen B.N., Howard D.A., Clausen C.S.B., Ma Z., (2023), *Digital Twins: Benefits, Applications and Development Process*, In: *EPIA Conference on Artificial Intelligence*, Springer Nature Switzerland, Cham, 511-522.

Latthe S.S., Terashima C., Nakata K., Fujishima A., (2014), Superhydrophobic surfaces developed by mimicking hierarchical surface morphology of lotus leaf, *Molecules*, **19**, 4256-4283.

Murzin S.P., (2024), Digital engineering in photonics: Optimizing laser processing, *Photonics*, **11**, 10, https://doi.org/10.3390/photonics11100935

Niinimäki K., Peters G., Dahlbo H., Perry P., Rissanen T., Gwilt A., (2020), The environmental price of fast fashion, *Nature Reviews Earth & Environment*, **1**, 189-200.

Schift H., Halbeisen M., Schütz U., Delahoche B., Vogelsang K., Gobrecht J., (2006), Surface structuring of textile fibers using roll embossing, *Microelectronic Engineering*, **83**, 855-858.

Vorobyev A.Y., Guo C., (2015), Multifunctional surfaces produced by femtosecond laser pulses, *Journal of Applied Physics*, **117**, 033103, https://doi.org/10.1063/1.4905616

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OPENFOAM-BASED CFD MODELING OF INDOOR AIR QUALITY AND VENTILATION IN SCHOOLS*

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Abstract

Indoor air quality (IAQ) in schools is a critical factor for health, cognitive performance, and air pathogen transmission in school environments. This study presents a computational framework developed within the PNR MISSION project (PREV-A-2022-12377010) to evaluate the effectiveness of cross-ventilation strategies using Computational Fluid Dynamics (CFD) simulations with OpenFOAM v2312. The simulation replicates a real classroom in Palermo, Italy, with a total volume of 213 m3 and 25 students plus a teacher represented using simplified occupant geometries. Exhaled CO_2 is modeled using a sinusoidal function based on a metabolic rate of 1.5 MET. The numerical analysis is supported by an experimental campaign involving continuous monitoring of CO_2, PM2.5, and key microclimatic parameters (temperature, relative humidity). Simulated CO_2 concentrations show good agreement with the measurements, particularly under cross-ventilation conditions, capturing the observed decay trends. The results demonstrate the model's capability to reproduce key airflow dispersion characteristics in naturally ventilated classrooms, providing a basis for further evaluation of IAQ mitigation strategies. And support epidemiological investigations in educational settings.

Keywords: CFD, cross ventilation, IAQ, natural ventilation, OpenFOAM

1. Introduction

Respiratory health is influenced by lifestyle and environmental factors, including smoking and air pollution. Indoor pollutants such as carbon dioxide (CO_2) and particulate matter (PM) are of particular concern. Since Europeans spend about 90% of their time indoors (Harrison et al.,

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2002), exposure in homes, workplaces, and schools is a major public health issue. Indoor concentrations often exceed outdoor levels, in some cases doubling due to indoor sources (Vardoulakis et al., 2015). CO_2, produced by human respiration, indicates insufficient ventilation and high rebreathed-air fractions that may increase airborne infection risk (Lyu et al., 2023; Mendell et al., 2024). This is particularly relevant in classrooms, where high occupancy and limited ventilation cause rapid CO2 accumulation. Children's increased vulnerability further highlights the need for effective mitigation. The PNR MISSION project (Monitoraggio abbattImento riSchi Sanitari InquinamentO iNdoor, PREV-A-2022-12377010) was established to investigate indoor exposures in Italian schools and provide evidence-based strategies to reduce health risks. Within this framework, we focus on a naturally ventilated classroom in Palermo. By combining Computational Fluid Dynamics (CFD) with in-situ monitoring, we evaluate the effectiveness of cross-ventilation in reducing CO_2 buildup. CFD is a valuable tool for resolving airflow, heat transfer, and pollutant transport. It enables simulation of CO_2 spread from respiration and assessment of ventilation strategies at room and occupant scales (Hooff et al., 2018). While several studies of classrooms have examined CO_2 distribution (Aydın and Yılmaz, 2023; Chillon et al., 2021; Ejaz et al., 2024; Mahyuddin and Essah, 2024) many lacked experimental validation, limiting their applicability. The novelty of this study lies in combining detailed CFD with continuous monitoring of CO_2, $PM_{2.5}$, temperature, and humidity, providing a framework to evaluate natural ventilation performance and support epidemiological research in educational settings.

The objectives of this study are:

- Develop an OpenFOAM-based computational framework for simulating airflow and CO_2 dispersion in classrooms.
- Validate the numerical results against experimental monitoring of CO_2.
- Represent occupant emissions using realistic metabolic rates and breathing patterns.
- Assess the effectiveness of cross-ventilation in reducing pollutant buildup and informing strategies for healthier classrooms.

3. Material and methods

The school is in a dense residential area of Palermo with limited green space nearby. Local traffic and household activities are the main external sources of air pollution. The classroom studied is a naturally ventilated elementary school room with a volume of about 213 m^3 (7.3 m × 6.5 m × 4.5 m). It hosts ~25 students and one teacher, with desks arranged in fixed rows. Ventilation is provided through three windows and one door. To ensure realistic conditions, the desk arrangement and occupancy were kept identical to normal teaching practice during the experimental campaign.

Environmental monitoring was carried out with a GrayWolf particle counter ($PM_{2.5}$, PM_{10}) and a DirectSense II multiparametric analyzer (CO_2, temperature, humidity). The instruments were placed near the teacher's desk at 1.5 m height, chosen for power access and safety, since a central position would have interfered with lessons. Such compromises are common in school monitoring and introduce some uncertainty. Students remained seated and engaged in regular classroom activities, corresponding to a metabolic rate of ~1.2 MET.

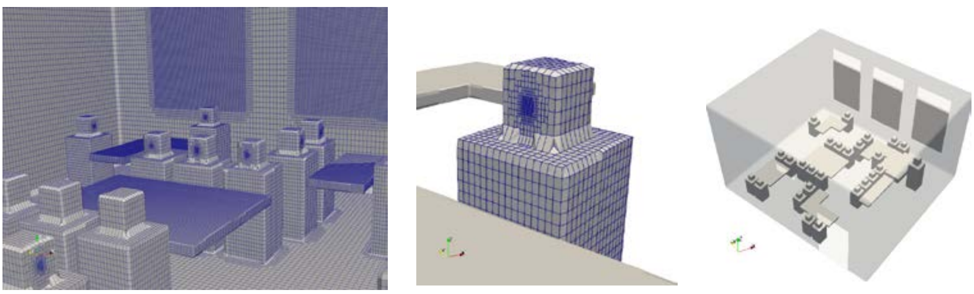
The protocol reproduced typical ventilation practices. These scenarios were tested: (i) stale air, with all windows and door closed, (ii) natural ventilation, with only windows open, (iii) cross-ventilation, with windows and door opened simultaneously once indoor reached ~1000 ppm. Between interventions, the classroom was aired until CO_2 approached background levels (~400 ppm). For the CFD validation, we focus on the cross-ventilation case, while acknowledging that classroom dynamics (e.g, occasional door movements or student activity) prevented perfectly controlled conditions.

These experimental conditions were then reproduced in the CFD simulations, enabling comparison between measured and modeled pollutant dynamics. The simulations were performed with OpenFOAM v2312 using the unsteady Reynolds-averaged Navier–Stokes (URANS) formulation solved with buoyantPimpleFoam[2] Buoyancy was modeled with the Boussinesq approximation, appropriate for small indoor temperature differences. Turbulence was represented with the k–ε model. The equation set included incompressible continuity, momentum, energy, and passive scalar transport for CO_2, with thermodynamic density ρ is provided by the compressible thermophysical model. For the formulation of those the reader can refer to (Mahmoud et al., 2024).

CO_2 was modeled as a passive scalar with a fixed molecular diffusivity ($D_{\text{eff}} = 1.8\ 10^{-5}\ m^2 s^{-1}$). CO_2 sources were limited to occupant mouth patches and window openings; no volumetric sources were included. In addition to CO_2, the Age of Air (AoA) was calculated with the OpenFOAM *airAge* model, representing the average time needed for outdoor air to reach a point in the classroom. Low values indicate well-renewed zones, while high values highlight stagnation. Combining AoA with CO_2 helps identify areas of poor mixing and assess ventilation performance.

3.2. Computational domain and mesh

Geometry was simplified to reduce computational costs. The occupants were represented as simplified cubic blocks with rectangular mouth patches. Figure 1 shows the mesh, the student detail and the layout. The computational grid was generated using *snappyHexMesh*. It is structured and consists of hexahedral cells and some polyhedral near curved surfaces and refinements. The final grid had ~996k cells, with local refinement at windows, the door, and mouth patches to resolve jets and scalar gradients. Mesh quality was within typical indoor-CFD ranges (max non-orthogonality ≈64°, skewness ≈9). Table 2 lists the patch areas and dimensions of the main objects.



a) b) c)

Fig 1. a) Mesh detail b) Mesh student detail c) and geometry layout.

Table 1. Key patch/object sizes used in the CFD domain

Item	***No.***	***Size***	***Note***
Windows (wind-13)	3	2.2×1.5 m (H×W)	Main Openings
Door	1	2.4×1.2 m (H×W)	Outlet / p-ref
Student body (block)	25	1.0×0.5×0.5 m (H×W×L)	Low-poly(seated)
Teacher body (block)	1	1.7×0.5×0.5 m (H×W×L)	Low-poly(standing)
Mouth patches (mo1-26)	26	4.5–6.0×10^{-4} m² (area)	Sinusoidal breathing

3.3. Boundary conditions and computational details

Boundary conditions were set to reproduce the monitored classroom environment. Inflow profiles at the windows were derived from a preliminary façade-scale CFD simulation driven by meteorological observations, with outdoor air fixed at 293 K and 400 ppm CO_2. uring the experiment, the prevailing north-easterly wind (~1 m s^{-1}) produced normal inflow velocities of 0.05, 0.03, and 0.07 m s^{-1} at windows 1–3 The door was modeled as a pressure outlet (p = 1.0×10^5 Pa) using a *pressureInletOutletVelocity* condition, with zero-gradient temperature and CO_2. Walls, desks, ceiling, and floor were treated as no-slip, adiabatic boundaries with zero-gradient CO_2.

Breathing was imposed through sinusoidal velocity inlets at the mouth patches (Umax = 0.4 m s^{-1}, ω = 1.45 s^{-1}, corresponding to 14 breaths·min^{-1}) following (Mahmoud et al., 2024). Exhaled air was set to 310 K and alternated between 27200 ppm (exhalation) and 800 ppm (inhalation) over a 4 s cycle, consistent with a metabolic rate of 1.2 MET. The internal field was initialized with ~1000 ppm CO_2, matching the cross-ventilation case. The simulations were conducted on the Leonardo HPC system at CINECA (Intel Xeon Platinum 8358 CPU, 64 cores), requiring about 6144 CPU-hours to simulate 180 s of classroom dynamics.

4. Results and discussion

4.1 Ventilation scenarios

To create controlled conditions for the experiments, all windows and the door were first opened until indoor CO_2 decreased to ~600 ppm. n the stale-air case, the openings were then closed, leading to progressive accumulation. For cross-ventilation, CO_2 was allowed to rise to ~1000 ppm before windows and door were opened, producing a rapid dilution to ~600 ppm within the first minutes (Fig. 2).

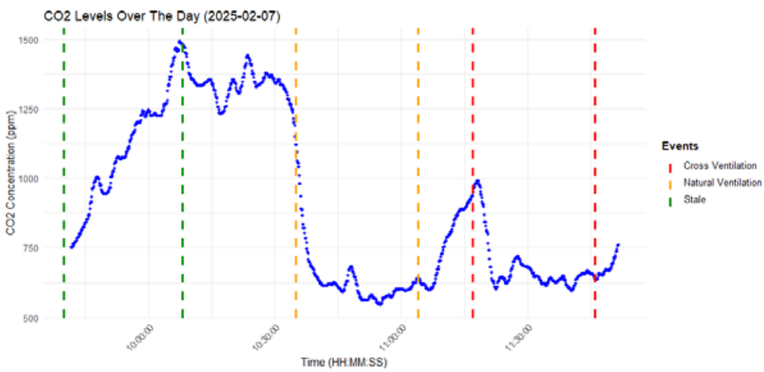


Fig 2. CO_2 concentration vs time during experiments of stale-air (between green lines), natural ventilation (between yellow lines), and cross-ventilation interventions (between red lines)

4.2. Flow field analysis

Airflow patterns were examined on three horizontal slices at 0.9 m (breathing zone), 1.3 m (upper occupied zone), and 3.3 m (near ceiling) above the floor (Fig. 3). At the breathing height, flow was weak and dominated by exhalation jets, while at 1.3 m the inflow spread laterally across the room. Near the ceiling, two counter-rotating recirculation cells developed, one directed toward the windows and the other toward the door. Streamlines confirmed that incoming air rose, circulated at ceiling level, and then descended toward the outlets (Figs 4-5).

Comparison of simulated and measured CO_2 concentrations (Fig. 6) shows the model captured the decay trend well, with differences due to turbulence, breathing variability, and sensor response. The statistical indicators confirm the close agreement (MAPE 3.0%, nRMSE 3.3%, MBE –16.6 ppm).

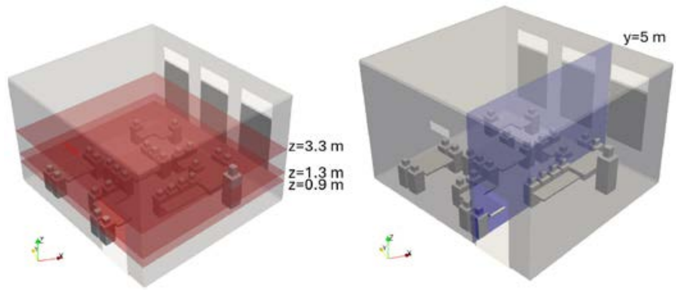


Fig 3. Horizontal slices at 0.9, 1.3, and 3.3 m, and a vertical slice at y = 5 m of the classroom domain used for velocity field analysis

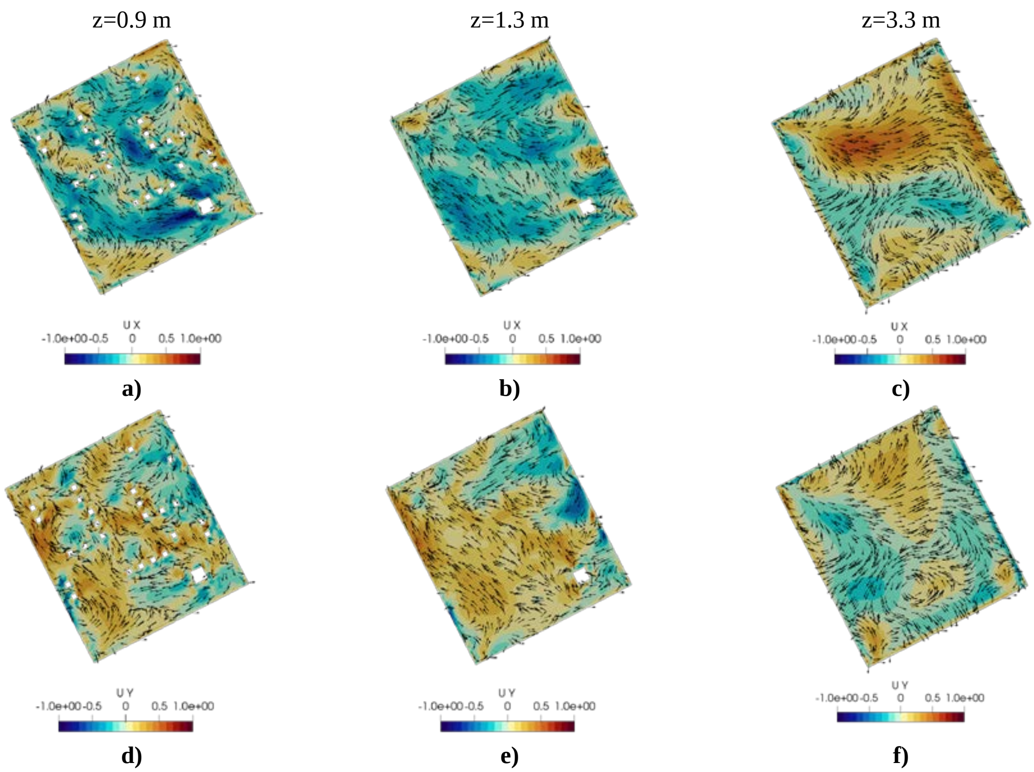


Fig 4. Velocity components at different horizontal slices. Top row: Ux [m/s] (top) and Uy [m/s] (bottom) at 0.9 m 1.3m, and 3.3m

4.4. Impact of ventilation on IAQ

Ventilation performance was further assessed using the age of air (AoA). Under perfect mixing, the air exchange rate is ACH ~ 8.3 h^{-1}, while the CFD solution indicated a faster effective renewal (~4.7 min, 35% shorter). Early snapshots showed rapid refresh near the windows, while the upper corner opposite to the windows required ~460 s, evidencing local stagnation. After 180s, most of the classrom had AoA values below 200 s, though dead zones persisted in recirculating regions (Fig 7).

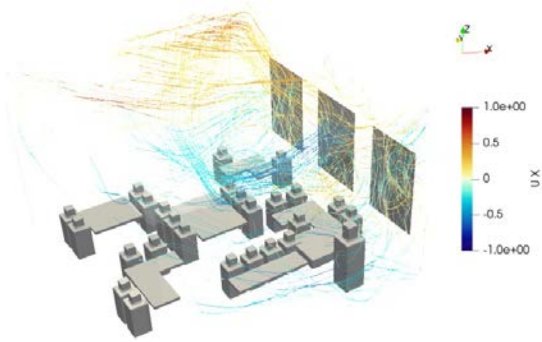


Fig 5. Streamlines visualization of the airflow inside the classroom under cross-ventilation

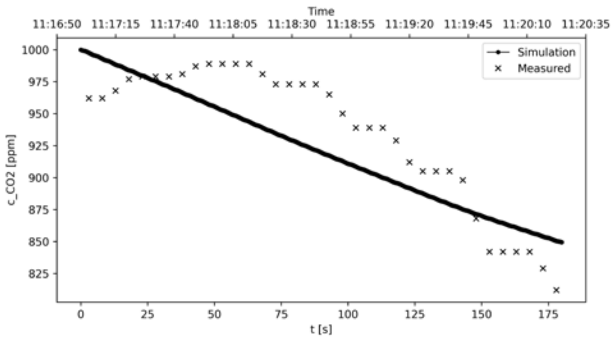
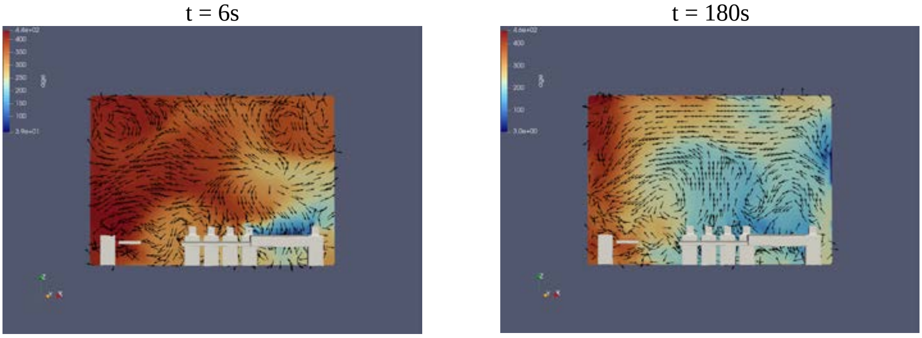


Fig 6. Time series of simulated and measured CO_2 [ppm] decay in the classroom after door and window opening

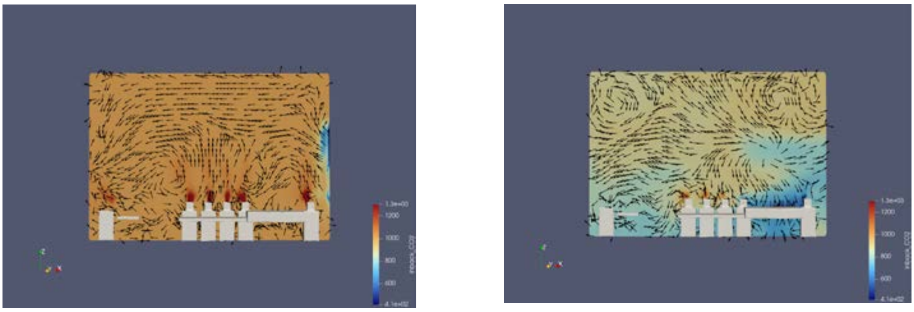
Spatial CO_2 distribution under cross-ventilation (Fig. 8) illustrate the same dynamics: at 6s, fresh air entered from the windows and diluted the frontal area, while plumes and buoyancy carried exhaled CO2 upward, creating higher concentrations near the ceiling. By 180s, concentrations were more homogeneous (400-600 ppm), but local values above 800 ppm remained above occupants. Three-dimensional views (not shown) further confirmed progressive removal, with vertical gradients weakening over time.

t = 6s t = 180s



a) **b)**

Fig 7. Distribution of local time to renewal under cross ventilation: (a) snapshot at t = 6 s, (b) snapshot at t = 180 s t=5s t=180s



a) b)

Fig 8. CO_2 [ppm] Surface contour plot with velocity glyphs projected on the projection on the surface at (a) t = 6 s, (b) t = 180s

5. Conclusions

This study used CFD simulations, validated with in-situ measurements, to assess indoor air quality in a naturally ventilated classroom. Cross-ventilation rapidly diluted exhaled CO_2, with simulations reproducing both decay trends and spatial heterogeneity. Age-of-air analysis confirmed preferential flow paths and dead zones, showing that renewal is not uniform.

The good agreement between measured and simulated CO_2 concentrations demonstrates the robustness of the proposed OpenFOAM-based framework for representing natural ventilation dynamics under real operating conditions. The model successfully captured transient dilution behavior and the spatial variability of pollutants, highlighting its capability to evaluate both global and local air quality indicators. Integrating the numerical and experimental approaches provided complementary insights: while monitoring characterized the overall ventilation efficiency, CFD detailed the spatial structure of airflow and pollutant transport, identifying stagnant regions not detectable by point measurements.

The findings underline the relevance of cross-ventilation as an effective low-cost strategy to enhance indoor air renewal in educational settings. Moreover, the age-of-air analysis revealed that even with open windows and doors, some poorly ventilated areas persist, emphasizing the need to optimize opening configurations and occupant placement.

Beyond validation, the methodology establishes a reproducible computational framework for supporting design and operational decisions in classrooms and other densely occupied environments. The approach can be readily extended to evaluate the interaction between ventilation, occupant-generated pollutants, and thermal comfort, contributing to both epidemiological and energy-efficiency studies.

Future work will address longer monitoring periods under varying meteorological conditions, explore hybrid ventilation scenarios, and couple the CFD framework with dynamic thermal and comfort models. This will enable a holistic assessment of indoor environmental quality, integrating health, comfort, and energy criteria for resilient and sustainable school building design.

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References

Aydın K., Yılmaz B., (2023), CFD-based multi-objective optimization of indoor air quality and thermal comfort in a classroom, *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, **238**, https://doi.org/10.1177/09544089231217960.

Chillon S.A., Millan M., Aramendia I., Fernandez-Gamiz U., Zulueta E., Mendaza-Sagastizabal X., (2021), Natural ventilation characterization in a classroom under different scenarios, *International Journal of Environmental Research and Public Health*, **18**, 5425, https://doi.org/10.3390/ijerph18105425.

Cruz-Octaviano E., Ovando-Chacon G.E., Rodriguez-Leon A., Ovando-Chacon S.L., (2025), Numerical analysis of air quality improvement and thermal comfort in a classroom using organic air cleaners, *Atmosphere*, **16**, 727, https://doi.org/10.3390/atmos16060727.

Ejaz M., Kilpeläinen S., Mustakallio P., Kosonen R., (2024), A CFD study to explore the impact of classroom dimensions and infector location on indoor air quality, *E3S Web of Conferences*, **562**, https://doi.org/10.1051/e3sconf/202456209005.

Franco A., Leccese F., (2020), Measurement of CO_2 concentration for occupancy estimation in educational buildings with energy efficiency purposes, *Journal of Building Engineering*, **32**, 101714, https://doi.org/10.1016/j.jobe.2020.101714.

Harrison R.M., Thornton C.A., Lawrence R.G., Mark D., Kinnersley R.P., Ayres J.G., (2002), Personal exposure monitoring of particulate matter, nitrogen dioxide, and carbon monoxide, including susceptible groups, *Occupational and Environmental Medicine*, **59**, 671–679.

Hooff T., Nielsen P.V., Li Y., (2018), Computational fluid dynamics predictions of non-isothermal ventilation flow – How can the user factor be minimized? *Indoor Air*, **28**, 866–880.

Hwang Y., Gorlé C., (2022), Large-eddy simulations of wind-driven cross ventilation, Part 1: Validation and sensitivity study, *Frontiers in Built Environment*, **8**, https://doi.org/10.3389/fbuil.2022.911005.

Lyu X., Luo Z., Shao L., Awbi H., Lo Piano S., (2023), Safe CO_2 threshold limits for indoor long-range airborne transmission control of COVID-19, *Building and Environment*, **234**, 109967, https://doi.org/10.1016/j.buildenv.2022.109967.

Mahmoud M.M.A., Bahl P., De A. Aquino A.F.V., MacIntyre C.R., Bhattacharjee S., Green D., Cooper N., Doolan C., De Silva C., (2024), A numerical framework for the analysis of indoor air quality in a classroom, *Journal of Building Engineering*, **92**, 109659, https://doi.org/10.1016/j.jobe.2024.109659.

Mahyuddin N., Essah E.A., (2024), Spatial distribution of CO_2 impact on the indoor air quality of classrooms within a university, *Journal of Building Engineering*, **89**, 109246, https://doi.org/10.1016/j.jobe.2024.109246.

Mendell M.J., Chen W., Ranasinghe D.R., Castorina R., Kumagai K., (2024), Carbon dioxide guidelines for indoor air quality: A review, *Journal of Exposure Science and Environmental Epidemiology*, **34**, 555–569.

Park S., Song D., (2023), CO_2 concentration as an indicator of indoor ventilation performance to control airborne transmission of SARS-CoV-2, *Journal of Infection and Public Health*, **16**, 1037–1044.

Respiratory diseases statistics, (n.d.), *Eurostat Statistics Explained*, Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Respiratory_diseases_statistics

Vardoulakis S., Dimitroulopoulou C., Thornes J., Lai K.-M., Taylor J., Myers I., Heaviside C., Mavrogianni A., Shrubsole C., Chalabi Z., Davies M., Wilkinson P., (2015), Impact of climate change on the domestic indoor environment and associated health risks in the UK, *Environment International*, **85**, 299–313.

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STATE OF ART ANALYSIS OF WATER REUSE: CASE STUDIES IN INSTALLATIONS REGULATED UNDER THE INDUSTRIAL EMISSIONS DIRECTIVE*

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Abstract

In Italy refineries and thermoelectric power plants are significant water consumer installations regulated under the Industrial Emissions Directive. In 2023, the country's 13 refineries and 72 thermoelectric plants (≥300 MW) used about 46 million and 2.5 billion cubic meters of water respectively, withdrawal from surface, groundwater and industrial aqueducts. Reclaimed water can be an important alternative to reduce stress on natural sources, especially given Italy's recent water scarcity.

This paper provides an overview of the water reuse strategies adopted in Italian refineries and thermoelectric power plants. It focuses on water consumption and reuse trends over the past three years, as well as the geographical distribution of selected case studies in relation to water scarcity.

As already known, geographic distribution influences water management: for example, many installations are coastal, using desalinated seawater primarily for cooling; others are in the Po Valley, relying on the Po River system. Regarding water scarcity, drought, already experienced in 2022, continued early in the year 2023 across Italy mostly affecting north and center regions. Conditions improved later, but Sicily, Calabria, and parts of the south regions faced extreme drought events in late 2023, which extended into 2024 due to low rainfall. Therefore, reducing water consumption in the installations is essential and requires both minimizing withdrawals from natural sources and reusing wastewater through dedicated treatment facilities. Internal water recycling is widespread in the installations: almost all refineries reuse process water and four of them recover external water from industrial or urban wastewater plants. Among thermoelectric plants, six operate with "Zero Liquid Discharge", about twenty reuse treated water internally and two use rainwater externally for agriculture or aquaculture purposes. It is therefore evident that water reuse is a vital strategy for climate resilience, resource efficiency and securing water availability in the long term.

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Keywords: climate resilience, refinery, resource management, thermoelectric power plant, water reuse

1. Introduction

Water scarcity is increasingly recognized as a major global challenge, with wide-ranging impacts on ecosystems, agriculture and industry. Industrial production is a key contributor to water demand; according to the (FAO, 2022), an estimated 45% of all water withdrawn in Europe is used for industrial purposes. In addition to high consumption, the poor quality of wastewater generated by industrial processes presents significant challenges, particularly in managing freshwater resources and promoting reuse. Therefore, the industrial sector carries a substantial responsibility in addressing these issues through technological innovation (Bikram Jit Singh et al., 2023). Enhancing water efficiency in industrial operations is essential, both for adapting to climate change and advancing the transition to a circular economy.

Several European policy frameworks highlight the role of water reuse as a strategic measure. The Water Framework Directive (EC Directive, 2000), the Strategy on Adaptation to Climate Change (EC, 2021) and the Circular Economy Action Plan (EC, 2020), emphasize sustainable water management, while Regulation (EU) 741/2020 introduces minimum requirements for the safe reuse of treated wastewater in agriculture. Although primarily focused on irrigation, this regulation sets an important step for promoting water reuse in other sectors, including industry. With the adoption of the revised Industrial Emissions Directive, so called IED 2.0 (EC Directive, 2024), circular economy principles and resource efficiency have been fully integrated into the Best Available Techniques (BAT). Water conservation has become a central focus of the Circular Economy Action Plan, which encourages sustainable water management through reuse and resource recovery strategies.

Eco-industrial parks have been designed to encourage water exchange networks among enterprises, minimizing freshwater consumption and wastewater discharge while maximizing reuse. This concept is closely related to industrial symbiosis which involves separate industries collaborating to exchange materials, energy, water, and by-products for mutual advantage (Aussel et al., 2023).

The geographical proximity of the industries is crucial, as transportation is costly and may limit the feasibility of such networks. In Italy, refineries and thermoelectric power plants are key players in the energy sector and rank among the most water-intensive installations regulated under the IED. In 2023, the country's 13 refineries and 72 thermoelectric power plants (≥300 MW) consumed approximately 46 million and 2.5 billion cubic meters of water, respectively, sourced from surface water, groundwater and industrial aqueducts (Stracqualursi et al., 2025).

In compliance with the IED principles, it is increasingly necessary to: (a) efficiently manage freshwater resources without jeopardizing production processes, and (b) treat wastewater streams to enable their reuse, thereby supporting the primary goal of minimizing freshwater withdrawal. Recovering treated water is an important alternative for reducing stress on natural sources, especially given the recent water scarcity in Italy.

Furthermore, the specific configuration and characteristics of each installation influence resource management decisions and water availability is a key factor. The geographical distribution of water-demanding installations has historically favored coastal locations, due to the availability of large volumes of seawater, primarily used for cooling once desalinated and demineralized, then returned to the sea. Other installations are in the Po Valley, where the Po River and its tributaries provide large quantities of surface water for industrial use and discharge, as well as guaranteeing water for agriculture and human consumption.

This paper provides a state of art analysis of sustainable water management actions implemented in the Italian installations regulated under the IED, for enhancing climate resilience and promoting resource efficiency, focusing on water consumption and reuse trends in selected case studies of refineries and thermoelectric power plants over the past three years and their relationship with geographical distribution, regional water scarcity and water availability over the last four years.

2. Research method

2.1. Spatial analysis of industrial installations in relation to water resources

The analysis of the geographical distribution of the installations is based on a georeferenced national-scale database. The geodatabase has been developed through a data acquisition process based on information provided by the operators of the installations, who comply with self-monitoring obligations by submitting annual operational reports (ISPRA, 2025b). The spatial analysis of the installations is carried out to assess their geographical distribution in relation to the availability of renewable water resources and to evaluate their potential environmental impacts on the surrounding areas. This analysis is based on the intersection of the installation map with various geospatial data layers, including:

- ISPRA Land Cover Map (De Fioravante et al., 2021): the land cover class representing surface water bodies is used to generate a 150-meter buffer. This distance aligns with the buffer zones defined under Article 142(a), (b), and (c) of Legislative Decree 42/2004.
- ISPRA Coastline Geodatabase: the national coastline is used to create a 10-kilometer inland buffer, subdivided into three coastal bands (0–300 meters; 300–1,000 meters; 1,000–10,000 meters). This classification facilitates the assessment of pressure from installations located near coastal zones, often characterized by fragile ecosystems and high environmental value.
- Hydrographic Network of the Po River Basin: this layer is included to enable a more in-depth analysis within the Po River Basin, Italy’s largest river basin. The area is particularly sensitive due to the delicate balance between industrial activity, water availability and environmental vulnerability.

2.2. Water stress indicators and integration with spatial data

The spatial analysis of water stress, that is a key indicator for evaluating the pressure on renewable water resources, integrated with additional territorial information (e.g., land use, industrial infrastructure, distribution of surface and groundwater bodies), enables a comprehensive assessment of the interactions between water availability and anthropogenic pressure. The main data sources are:

- BIGBANG Model: a spatially explicit model used to estimate monthly components of the national water balance.
- ISPRA Drought Bulletin: this tool supports monthly monitoring of drought conditions in Italy and Europe using the Standardized Precipitation Index (SPI).
- "Water Stress Status" Web Platform (National Scale): this platform highlights the role of permanent District Observatories for drought monitoring and presents the methodological framework adopted by ISPRA for compiling water stress bulletins.

2.3. Water consumption and reuse trends

Information regarding water consumption volumes, sources and reuse trends in refineries and thermoelectric power plants is available:

- annual report provided by the operator of installations.
- plans and procedures implemented to comply with the provisions of environmental permit for each installation.
- annual inspection report developed by ISPRA.

For plant operators it is mandatory to monitor water consumption. This information is collected and communicated in a periodic report, sent annually to the control authorities.

But the quantitative data analysis for estimating water recovery is very complex, since in many cases the volume of water recovered is not reported by operators in their annual reports; sometimes the data is aggregated and unclear and sometimes only partially reported.

Moreover, data representation across the different installations is not homogeneous, making the methodological approach to data analysis more complicated. This is certainly because the description and representation of the data on water recovery strategies up to now is not mandatory for the operators.

3. Results and discussion

3.1. Geographical distribution

The geographical distribution of water-demanding installations has historically favored coastal locations, due to the availability of large volumes of seawater, primarily used for cooling once desalinated and demineralized then returned to the sea. Among 132 installations subject to national-level Integrated Environmental Authorization (IEA) operating in various industrial sectors, 85 installations are considered in this study, falling into two primary categories: 72 thermoelectric power plants (TPP) and 13 refineries (REF).

Table 1 shows the distribution of these installations in relation to coastal zones, with 48 located within the first 10 km from the coast (Coastal Zones 1–3), confirming a significant concentration in coastal areas. Refineries are predominantly coastal (Farabegoli et al., 2024) while thermoelectric power plants are more prevalent inland, with 32 installations located beyond 10 km from the coast (Coastal Zone 4). Regarding proximity to surface water bodies, only 9 installations (especially TPP) are located within 150 meters of rivers, lakes, or canals, in accordance with the regulatory buffer zone defined by Article 142 of Legislative Decree 42/2004.

Table 1. Distribution of installations in relation to coastal zones

Installation type	***Coastal zone 1 (0-300 m)***	***Coastal zone 2 (300-1.000 m)***	***Coastal zone 3 (1.000-10.000 m)***	***Coastal zone 4 (> 10.000 m)***	***Proximity to surface water bodies (<150 m)***
TPP	13	12	14	32	7
REF	4	4	1	3	2
Total	**17**	**16**	**15**	**35**	**9**

Furthermore, other installations are in the Po Valley where the Po River and its tributaries provide large quantities of surface water for industrial use and discharge, as well as guaranteeing water for agriculture and human consumption (Fig. 1).

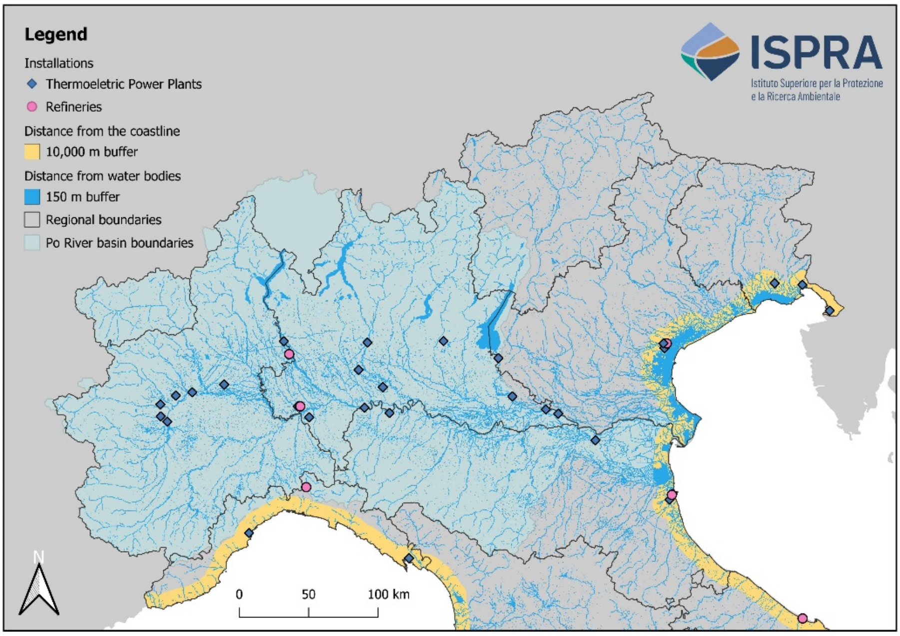

Fig. 1. The map shows thermoelectric power plants (TPP) and refineries (REF) in relation to their distance from water bodies and the coastline. The light blue area indicates the extent of the Po River basin. The corresponding legend is provided in the bottom-right corner

3.2 Freshwater resources

In Italy, the availability of renewable freshwater resources (defined as the portion of precipitation, after accounting for evapotranspiration losses, that is available in the environment for ecosystems and human uses) as assessed by the BIGBANG model from ISPRA (Braca et al., 2024) shows a declining trend. This decline is evident from the statistical analysis of data from 1951 to the present, with a notable decrease in the availability of renewable water resources. Specifically, the annual volume of surface outflow generated from precipitation has been decreasing, influenced by factors like climate change.

The decrease is attributed to a combination of factors, including reduced precipitation in certain regions (especially Central and Southern Italy and the major islands) and increased evapotranspiration. But the decline is not uniform across the country. The northern part of Italy usually experiences higher rainfall compared to the central and southern regions (ISPRA, 2025).

In 2023, the annual availability of renewable water resources reached approximately 373 mm, equivalent to 112.4 billion cubic meters. Although this represents a significant recovery (+68%) from the historic low recorded in 2022, it still marks an 18.4% decrease compared to the long-term annual average (1951–2023) and nearly a 16% reduction compared to the 1991–2020 climatological reference period (Braca et al., 2024; Mariani et al., 2025).

3.3 Water severity data

Water severity, based on the classification of peninsular Italy into four classes, shows in February 2023 (Fig. 2) North (normal), Centre (medium), South (low), Sardinia (medium), Sicily (high) and in December 2024 an increase in medium severity areas, including the south regions, except for Sicily.

Overall, as shown in Fig. 2, drought conditions already experienced in 2022 continued to affect Italy throughout 2023, although with regional variations and lesser extent than in 2022. Extreme and severe drought affected northern and central regions during the early months of the year in areas already impacted by the severe drought of 2022; however, these conditions mitigated as the year progressed. Conversely, in the last three months of the year, which are usually the wettest, a significant precipitation deficit was recorded, especially in Sicily and parts of the Ionian Calabria region. This deficit led to extreme drought conditions, causing severe water stress that extended into 2024, impacting central and southern Italy as well as the major islands. The situation got worse due to continued low rainfall throughout the 2024.

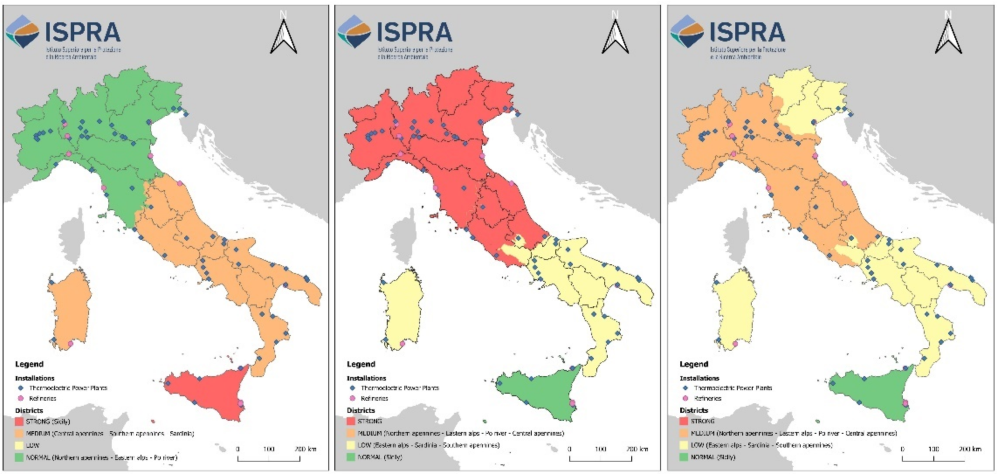

Fig. 2. The maps show the severity of the water crisis on a national scale, along with the location of thermoelectric power plants and refineries. On the left is the situation as of July 2022, in the center February 2023, and on the right the updated scenario as of December 2024

3.4. Water management in refinery plants: current state of implementation and data analysis

Refineries are among the main consumers of water at the industrial level. The sources of water supply are mainly groundwater, surface water and the aqueduct network; in refineries located on the coast, significant quantities of water are withdrawn from the sea. Due to the growing problem of water scarcity, as well as the application of the IED, 11 of the 13 Italian refineries have already implemented water reuse practices (mainly internal reuse and in some cases reuse of water recovered from other plants). Internally reused treated water is mainly used as industrial process and cooling water, to produce demineralized water and firefighting water (Blesi et al., 2024). Data on water recovery has been analyzed and refers to the three-year period 2022-2023-2024 for each installation. The reused water mainly comes from the wastewater treatment plants of the refinery.

Six of the 13 refineries also reuse contaminated groundwater from on-site ongoing remediation activities, previously pre-treated using dedicated treatment plants (Farabegoli et al., 2024). The data analysis showed, over the three-year period considered, that the 11 refineries using recovered water were able to cover on average 30% of their water needs (excluding seawater). Specifically, in 2024, out of the 11 installations analyzed, 5 installations used more than 50% of recovered water to cover their consumption, 3 between 50% and 20% and 3 less than 10%.

3.5 Water management in thermoelectric power plants: current state of implementation and data analysis

The substantial water consumption in energy production is primarily associated with cooling processes and the generation of steam, making this industrial sector the largest consumer of water resources (EEA, 2022). Data on water recovery of 72 thermoelectric power plants in Italy (≥300 MW) have been analyzed. Half of them have already implemented water reuse practices (internal reuse, reuse of water coming from outside or external reuse). Specifically, 20 practice internal reuse, about 15 reuse waters recovered from other plants outside the plant for internal use, mainly as cooling and processing water and 2 reuse rainwater outside the plant for agricultural greenhouses and as cooling water for fish farming. It is also worth noting that 6 thermoelectric power plants implement the "Zero Liquid Discharge" strategy, that aims to eliminate the discharge of liquid waste from an industrial plant into the environment through the recovery and recycling of all treated wastewater.

Only a sample of 19 installations provided consistent data that could be analyzed. The data analysis showed, over the three-year period considered (2022-2023-2024), a significant variability in the water recovery rates, ranging from a minimum value of 5% to a maximum value of 96.5%. The average value is about 50%. Specifically in 2024, 6 installations used more than 80% of recovered water for their consumption, 4 between 80% and 50%, 6 between 50% and 10%, and 3 less than 10%. The percentages do not change significantly over the three-year period. It is worth noting that the higher recovery percentages are distributed in the central-southern part of the Italian territory, that has been more affected by severe issues related to water scarcity.

3.6. Real case studies

Six installations were selected as representative case studies to analyze the percentages of reused water: 2 of them reuse water for external purposes while in 4 of them water is supplied from both traditional surface or groundwater sources and from wastewater coming from treatment/reclamation plants. In the latter case studies, the percentage of reuse was calculated considering the amount of reused water in relation to the total water consumed for the process and for other purposes, such as sanitary and firefighting uses.

The consumption of seawater for cooling was always excluded in the calculation of water reuse percentages. Figure 3 shows the water reuse percentages in the six case studies over the years 2022, 2023 and 2024.

3.6.1. Torrevaldaliga Nord Thermoelectric Power Plant

The power plant is located on the Tyrrhenian Sea, approximately 6 km from the city of Civitavecchia (Rome), Coastal Zone 1. In this case, study water reuse is performed diverting a portion of treated seawater used for cooling to a nearby aquaculture facility. To determine the water reuse percentage, the volume of water for external reuse is calculated in relation to the total volume of water used in the process. The resulting percentages are 87.3% in 2022, 77.7% in 2023, and 70.5% in 2024.

3.6.2. Candela thermoelectric power plant

This cogeneration plant is in a predominantly agricultural area within the municipality of Candela in the Apulia region, Coastal Zone 3. Rainwater collected in the plant is treated and subsequently redirected to a nearby greenhouse complex. The water reuse percentages are calculated based on the total volume of rainwater collected by the drainage system and supplied for external use. The resulting values are 100% in 2022, 76.2% in 2023, and 97.3% in 2024.

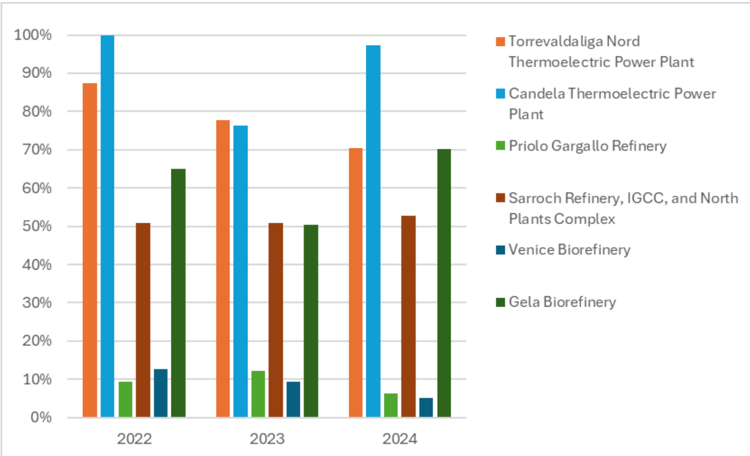

Fig. 2. Water reuse percentages by installation and year

3.6.3. Priolo Gargallo Refinery

The refinery is located within the Syracuse petrochemical complex, Coastal Zone 1. The installation is divided into two main sections: the North and South plant. Water reused for internal purposes comes from the South plant, whose water is supplied from wells, seawater, aqueduct and demineralized water provided by the nearby power plant. The percentage of reuse is approximately 10–12% in both 2022 and 2023, while a slightly lower value of 6% was recorded in 2024.

3.6.4. Sarroch Refinery, IGCC, and North Plants Complex

The Sarroch Refinery, IGCC, and North Plants Complex are located on the southern coast of Sardinia, Coastal Zone 1. In terms of production capacity, it ranks among the largest facilities in the Mediterranean region and is considered one of the most complex in Western Europe. Water is not only supplied from the aqueduct and the sea but also from an internal treatment plant and an external wastewater treatment plant (WWTP). The calculated reuse rates for the three-year period consistently averaged around 55%.

3.6.5. Venice Biorefinery

The biorefinery is in the industrial zone of Porto Marghera, within the municipality of Venice, Coastal Zone 1 and represents the first industrial-scale application of innovative technology to producing biofuels from biomass.

Water sources used in the process include lagoon water – which is fully returned to the water body and excluded from reuse calculations – along with aqueduct water and recycled industrial water supplied by the nearby consortium WWTP. The percentage of reused water from the WWTP in relation to the total water consumption is: 12.7% in 2022, 9.3% in 2023 and 5.1% in 2024.

3.6.6. Gela Biorefinery

The biorefinery is located on the southwestern coast of Sicily, in a flat area of the Gulf of Gela, Coastal Zone 1. Water sources used for processing and cooling include water from a reservoir, the municipal biological treatment plant and the groundwater treatment plant. The percentage of reused water is: 64.9% in 2022, 50.4% in 2023 and 70.1% in 2024.

4. Conclusions

This study highlights the importance of water reuse for resource efficiency and climate resilience in Italian refineries and thermoelectric power plants, especially in areas affected by recurrent water scarcity. Case studies show high reuse rates in thermoelectric facilities, while refineries exhibit greater variability, ranging from 10% to 70% depending on process complexity, treatment infrastructure, and local freshwater availability. These results confirm that the industrial water reuse potential in Italy is significant, yet unevenly implemented across sectors and regions.

The analysis underscores persistent challenges in data consistency and transparency. Although self-monitoring is mandatory under the Industrial Emissions Directive, reporting practices differ among operators, limiting the comparability of water recovery data. Establishing standardized monitoring protocols and harmonized reporting frameworks would enable more accurate assessment of national water reuse performance and facilitate benchmarking across installations.

The forthcoming implementation of the revised Industrial Emissions Directive (IED 2.0) provides an important policy opportunity to improve data collection, integrate reuse performance indicators into permit requirements, and foster best available techniques for circular water management. Expanding the use of advanced treatment technologies—such as membrane filtration, reverse osmosis, and zero liquid discharge systems—can further enhance recovery efficiency and reduce pressure on natural resources.

In addition to technological advances, a systemic perspective is essential. Encouraging inter-plant water exchange within industrial clusters and eco-industrial parks could create synergies between refineries, thermoelectric plants, and nearby industries, optimizing resource use at a territorial scale.

Future efforts should therefore focus on consolidating reliable data collection, promoting knowledge sharing, and aligning economic and regulatory incentives to scale up water reuse. Through such coordinated actions, Italy can strengthen the resilience of its industrial sector, mitigate the impacts of drought, and advance toward a more circular and sustainable use of water resources.

References

Aussel D., Cao Van K., Salas D., (2023), Optimal design of exchange water networks with control inputs in eco-industrial parks, *Energy Economics,* **120**, 106480, https://doi.org/10.1016/j.eneco.2022.106480.

Bikram Jit Singh, Chakraborty A., Sehgal R., (2023), A systematic review of industrial wastewater management: Evaluating challenges and enablers, *Journal of Environmental Management*, **348**, 119230, https://doi.org/10.1016/j.jenvman.2023.119230.

Blesi F., Cortese M., Farabegoli G., Giorgioli P., Giuliani C., Spuri S., (2024), Pratiche di "water reuse" nelle raffinerie (in Italian), *Ecoscienza Sostenibilità e Controllo Ambientale*, **3**, 48–50.

Braca G., Mariani S., Lastoria B., Tropeano R., Casaioli M., Marchetti G., Bussettini M., (2024), Bilancio idrologico nazionale: stime BIGBANG e indicatori sulla risorsa idrica. Aggiornamento al 2023, *Rapporti ISPRA*, **401**, Roma, Italy.

De Fioravante P., Luti T., Cavalli A., Giuliani G., Dichicco P., Marchetti M., Chirici G., Congedo L., Munafò M., (2021), Multispectral Sentinel-2 and SAR Sentinel-1 integration for automatic land cover classification, *Land*, **10**, 611, https://doi.org/10.3390/land10060611.

EC, (2020), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A new Circular Economy Action Plan for a cleaner and more competitive Europe, COM/2020/98 final, Brussels,

EC, (2021), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Forging a climate-resilient Europe – The new EU Strategy on Adaptation to Climate Change, COM/2021/82 final, Brussels.

EC Directive, (2000), Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, *Official Journal of the European Union*, **L 327**, 1–73.

EC Directive, (2010), Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (Integrated Pollution Prevention and Control), *Official Journal of the European Union*, **L 334**, 17–119.

EC Directive, (2024), Directive 2024/1785 of the European Parliament and of the Council of 24 April 2024 on Industrial and Livestock Rearing Emissions Directive (IED 2.0), *Official Journal of the European Union*, Brussels.

EC Regulation, (2020), Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse, PE/12/2020/INIT, Brussels.

EEA – European Environment Agency, (2022), Water abstraction by economic sector in the 27 EU Member States, 2000–2019, *European Environment Agency*, Copenhagen, Denmark.

FAO, (2022), *The State of the World's Land and Water Resources for Food and Agriculture 2021 – Systems at Breaking Point: Main Report*, Food and Agriculture Organization of the United Nations, Rome, Italy.

Farabegoli G., Blesi F., Cortese M., Giorgioli P., Giuliani C., Spuri S., (2024), I consumi idrici nelle raffinerie e le potenzialità del water reuse per fronteggiare la crisi idrica alla scala nazionale (in Italian), *Proc. of RemTech Expo 2024*, Ferrara, Italy, 16–20 September 2024.

Farabegoli G., Blesi F., Cortese M., Giorgioli P., Giuliani C., Spuri S., (2024), Sustainable water management in Italian oil refineries related to climate change, *Procedia Environmental Science, Engineering and Management*, **11**, 521–530.

ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale, (2025), *Ambiente in Italia: uno sguardo d'insieme. Annuario dei dati ambientali 2024*, Roma, Stato dell'Ambiente, Rapporto 102/2025, ISBN 978-88-448-1254-6.

ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale, (2025b), *Rapporto annuale sul Geodatabase delle Installazioni AIA. Edizione 2025*, Roma.

Legislative Decree, (2004), Decreto Legislativo 22 gennaio 2004, n. 42. Codice dei beni culturali e del paesaggio, ai sensi dell'articolo 10 della legge 6 luglio 2002, n. 137 (in Italian), *Gazzetta Ufficiale n. 45 del 24 febbraio 2004, supplemento ordinario n. 28.*

Mariani S., Braca G., Lastoria B., Tropeano R., Casaioli M., Piva F., Marchetti G., Bussettini M., (2025), Drought and water resource assessment at the national level in Italy from 1951 to today, *Proc. of EGU General Assembly EGU25-2062*, Vienna, Austria, 27 April – 2 May 2025.

Stracqualursi A., Mauro F., Borghesi R., (2025), The water–energy nexus in thermoelectric power plants: A focus on Italian installations regulated under the Integrated Emission Directive, *Water*, **17**, 1285, https://doi.org/10.3390/w17091285

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INDOOR MONITORING OF MUSEUM ENVIRONMENTS: STRATEGIES FOR COLLECTIONS' CONSERVATION AND VISITORS' WELL-BEING*

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Abstract

The correct conservation of art collections within an adequate management of the museum environment is a complex problem to address, considering that exhibition spaces are often located within historic buildings that may themselves be subject to protection constraints. It is, therefore, necessary to promote maximum accessibility to the artworks, ensuring the well-being of visitors, and at the same time protecting the artifacts from the impact of environmental factors that can lead to their degradation. These factors, in turn, are also influenced by the length of stay of visitors.
Art objects are diverse in nature, complex, and composite, and the environmental conditions appropriate for their correct conservation vary in relation to the materials they are made of. Consequently, these conditions may not always coincide with those ideal for ensuring microclimatic comfort for visitors. A unique solution for all situations is therefore not feasible and, often, compromises must be made. For this purpose, a first methodological approach, integrated, interactive, and aimed at acquiring useful data to improve the conservation and enjoyment of artworks, was tested at the Pinacoteca Provinciale of Potenza within the Basilicata Heritage Smart Lab Project (PO FESR Basilicata 2014).

Keywords: heritage conservation, microclimate monitoring, well-being monitoring

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1. Introduction

The United Nations' 2030 Agenda for Sustainable Development clearly acknowledges the role of culture in sustainable development, particularly in Target 11.4: "Strengthen efforts to protect and safeguard the world's cultural and natural heritage", part of the Sustainable Development Goal (SDG) 11, focused on Sustainable Cities and Communities. Beyond this direct reference, highlighting the importance of cultural heritage for creating inclusive, safe, resilient, and sustainable human settlements, also SDG 4 (Quality Education), SDG 10 (Reduced Inequalities), and SDG 12 (Responsible Consumption and Production) refers to heritage in terms of learning opportunities, equitable access, empowerment of marginalized groups and sustainable heritage management (UN, 2015). Cultural heritage fosters social cohesion and belonging, connecting people to their past, traditions, and shared values. Engaging local communities in heritage conservation also empowers them and enhances their well-being. Economically, the rehabilitation and adaptive reuse of historic buildings can revitalize urban centers, attract investment, and support local businesses.

There is growing consensus, particularly from UNESCO, that culture, including cultural heritage, can play a crucial role as a transversal enabler for the traditional three pillars on which sustainable development is grounded: environmental, economic, and social. Then, an effective management of cultural heritage is required, considering economic, social, and environmental factors in an integrated approach. In this perspective, Indoor Air Quality (IAQ) in museums becomes a critical factor for cultural heritage conservation, as it directly affects the long-term preservation of collections and the health of staff and visitors (Ilieș et al., 2022; Schito et al., 2018). Museum artifacts, in fact, are highly susceptible to deterioration: fluctuations in temperature (T) and relative humidity (RH) can cause physical damage like cracking and warping, while high humidity can promote the growth of mold and bacteria, which directly damage organic materials and produce their own harmful secondary byproducts. Gaseous pollutants like sulfur dioxide (SO_2), nitrogen oxides (NO_x), ozone (O_3), and various Volatile Organic Compounds (VOCs) can cause chemical degradation, leading to weakening and corrosion of materials. Particulate matter (PM10, PM2.5) can cause physical damage through abrasion or by forming hard-to-remove deposits (Camuffo, 2019; Gysels et al., 2004).

Pollutants inside the museum environment can be from both external sources, like particulate matter and gaseous pollutants from the urban environment, traffic, and industry, and internal sources. Internal sources include off-gassing from building materials, furnishings, and cleaning products and activities. Human presence, such as visitor and staff movement, can re-suspend dust and emit CO_2 and VOCs. Even museum collections themselves can be sources of pollutants as they degrade. Moreover, Heating, Ventilation, and Air Conditioning (HVAC) systems (Brimblecombe, 1990; Pavlogeorgatos, 2003), particularly if improperly maintained, can distribute pollutants and dust and promote their deposition. The ongoing climate changes make this scenario even more complex and urgent to manage, since variations in temperature and humidity are becoming wider, more frequent, and unpredictable, significantly affecting the conservation of artworks.

The monitoring and control of these parameters is therefore crucial to ensure that the environment remains stable and protective, for the proper preservation of museum collections, and does not generate discomfort for visitors, compromising the enjoyment of the artworks. However, universally recognized international standards to refer to are currently not available. Thus, preservation efforts must rely on recommendations and guidelines developed by different institutions, which vary across regions and depend on the materials that should be preserved (Elkadi et al., 2021; Tetreault, 2018). Table 1 presents some examples of recommended environmental parameters for the conservation of paintings on canvas, which are commonly displayed inside museums and object of this research.

Table 1. Recommended T and RH values for the conservation of paintings on canvas (Aghemo and Guarnerio 1997)

Institution	***T (°C)***	***ΔT_{max} (°C)***	***RH (%)***	***ΔRH_{max} (%)***
MiC (2001)	19-24	-	35-60	-
UNI (1999)	19-24	±1.5	40-55	±6
ICCROM	-	-	50-65	-
ICC/CCI (Canadian Conservation Institute)	-	-	47-53	±2

While the primary focus of these recommendations is on the conservation of collections, it must also be considered that a poor IAQ can also affect the health and comfort of museum personnel and visitors, eventually leading to respiratory issues, headaches, and other discomforts (Goulding, 2000). The World Health Organization (WHO) provided in 2021 updated Air Quality Guidelines (AQGs) for indoor environments, based on new scientific evidence showing adverse health effects at even lower pollutant concentrations, primarily focusing on indoor air quality due to its significant impact on human health (WHO, 2021). Although AQGs are not legally binding, they provide a scientific basis for policymakers to set out national standards and policies to reduce air pollution and its associated health burden. The thresholds established by the WHO for indoor well-being in standard environments are shown in Table 2 and they are suitable in case of long stay (e.g., residential buildings and working places).

Table 2. Recommended T and RH values for human well-being

Institution	***T (°C)***	***RH (%)***
Summertime	20-24	30-70
Wintertime	23-26	30-70

As can be easily noticed from the comparison between the parameters listed in Table 1 and those in Table 2, the issue within a museum environment lies in the fact that the conditions required for the proper conservation of collections may, in some cases, differ from those considered ideal for visitor well-being, and balancing these instances is a challenging task. In fact, compliance with environmental standards is essential to prevent the rise of deterioration phenomena but, at the same time, focusing on visitors' well-being is fundamental to encouraging their continued presence in exhibition spaces, contributing to a more enjoyable and relaxed museum experience (Aversa et al., 2025). Moreover, the presence of visitors can significantly affect the indoor air quality, often causing dangerous sudden fluctuations in temperature and humidity, and an increase in CO_2 concentration.

Balancing these two needs requires a deeper understanding of what happens within museum environments: on-site monitoring is the most reliable way to know the actual environmental conditions of a room, identify risk factors for both artworks and visitors, and measure the effectiveness of any corrective actions undertaken (Centorrino et al., 2021; Ryhl-Svendsen, 2006; Uring et al., 2020). The preliminary monitoring methodology proposed here, carried out within the framework of the Basilicata Heritage Smart Lab (BHSL) project, Work Package 1 “Monitoring Basilicata Heritage”, involved the installation of a compact wireless sensor network for measuring physical and chemical parameters, both inside and outside the museum environment. Furthermore, to explore any cause-and-effect relationships between visitor presence and environmental conditions, a new way to capture visitors' perceptions was exploited. To this purpose, a small museum, such as the Pinacoteca Provinciale di Potenza, was the perfect case study.

2. Materials and methods

To thoroughly investigate the issue of balancing the different needs for collection conservation and visitors' well-being within museum environments, the methodology below was designed and developed. It combines a network of sensors for indoor and outdoor microclimate monitoring with the analysis of visitor presence and behavior, using QR codes placed next to selected exhibited artworks that link visitors to designated web pages.

This methodology was tested at the Pinacoteca Provinciale of Potenza, established in 2000 and selected as a pilot site for the research activities (Fig. 1). The gallery hosts a permanent exhibition of 19th-century artworks by Lucanian artists (Room 2), as well as more contemporary works by Luigi Guerricchio, Vincenzo Claps, and Italo Squitieri. These are displayed in the 20th-century room (Room 1) alongside works by renowned Italian artists such as Carlo Levi, Fausto Pirandello, and Renato Guttuso. Five paintings from the collection were selected as case studies for the research.

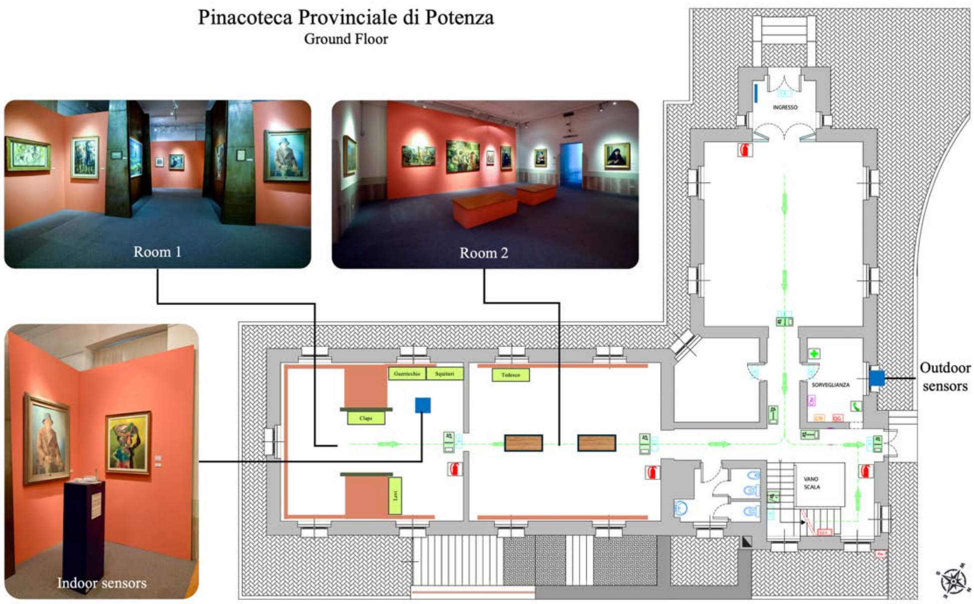


Fig. 1. Plan of the ground floor of Pinacoteca Provinciale di Potenza

The monitoring system selected for microclimate evaluation, on the basis of previous experiences carried out in classrooms (Aversa et al., 2019; Aversa et al., 2020) is compact, minimally invasive, and easy to install. It consists of two subsystems: the first employs a wireless sensor network to simultaneously measure illuminance (Lux), air flow (Flux), temperature (T), relative humidity (RH%), and indoor carbon dioxide concentration (CO_2). An additional sensor is dedicated to recording outdoor temperature and relative humidity. All devices are managed by a central unit that enables remote data acquisition: the data acquisition interval for all parameters was set at 15 minutes. Table 3 lists the sensors used and the corresponding measured parameters. The indoor sensors (blue square in Fig. 1) were placed within the space close to the paintings, to create good conditions for the correlation between sensor-derived and QR code-derived information. The outdoor sensors were placed outside a window on the northern side of the building. Visitor behavior was analyzed by designing the visit to the gallery as an interactive experience. It begins with a welcome panel that informs visitors that the museum has been selected as a pilot site for a research activity and invites them to take part in the study by scanning QR codes placed next to selected paintings throughout the exhibition. Each QR code is accompanied by a short message intended to trigger the visitor's curiosity. Upon scanning the QR code, the visitor is directed to a webpage dedicated to the specific artwork, organized into four sections: an image of the painting, a description of the work, a brief biography of the artist, and a survey.

Table 3. Sensors used

Device	***Function***	***Range and accuracy***
MWDG-GSM-B	modular wireless Datalogger Gateway	-
WSD00THCOP	T_{in}, RH_{in}, and CO_2 wireless Sensor and smart Datalogger	-10/+60°C; ±0.2°C 0/100%; ±2% 0/5000ppm; ±1ppm
WSD00TH2L	T_{in}, RH_{in}, Lux wireless Sensor, and smart Datalogger	-10/+60°C; ±0.2°C 0/100%; ±2% 0/16KLux; ±1Lux
EE07 KIT	T_{out}, RH_{out} Sensor (Outdoor)	-30/+60°C; ±0.1°C 0/100%; ±2.5%
WSD12-THEE	wireless smart Datalogger to combine with EE07 KIT	-

This approach serves a dual purpose: on the one hand, it offers visitors an engaging service by providing real-time access to in-depth information on the artworks; on the other, it provides museum staff with valuable feedback on the public's appreciation of the works and, through the survey, on the exhibition environment and overall visitor comfort. A web analytics tool was installed on each page to collect information on the number of daily visits, access time, and visit duration. These data were then compared with the total number of visitors recorded by the museum to estimate the percentage of visitors who accessed the website.

3. Results and discussion

The monitoring system, placed within the space close to the paintings in Room 1, and the additional sensors, installed on the north-west façade of the building, allowed measuring internal air quality and internal and external microclimatic parameters for almost five months (between the late spring and the beginning of autumn of 2024). In Fig. 3, the trends of indoor Temperature and Relative Humidity are compared to the corresponding outdoor values, showing that internal microclimatic parameters are smooth in the face of significant external variations. The indoor Temperature maintains between 17°C and 28°C, whereas the outdoor Temperature oscillates, reaching a minimum of 2°C and a maximum of 39°C. Similarly, indoor Relative humidity stays between 37% and 69% despite the minimum and the maximum values, 14% and 100% respectively, recorded outside.

This occurs in the absence of an air conditioning system, highlighting that the building has good thermo-hygrometric insulation properties. The behavior may be due to the presence of interior panels which generate a crawlspace of almost 35cm with respect to the perimeter's walls. However, a museum building is a complex place where works of art and people coexist, each requiring different environmental conditions, as shown in Figure 4, where thresholds established for cultural heritage conservation and human well-being are superimposed on microclimatic measurements.

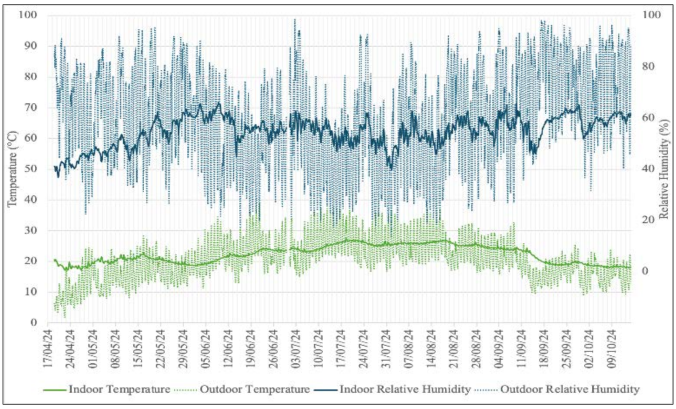


Fig. 3. Comparison between indoor and outdoor temperature (green lower charts) and between indoor and outdoor relative humidity (blue higher charts).

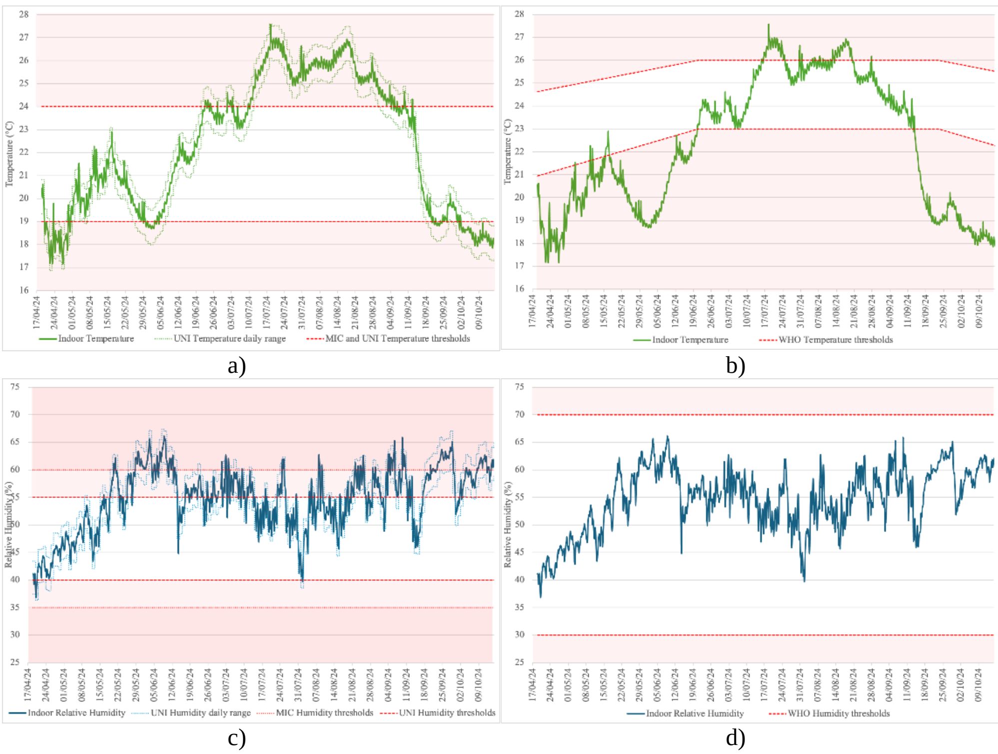


Fig. 4. Comparison between: a) indoor Temperature and MiC and UNI threshold values; b) indoor Temperature and WHO threshold values; c) indoor Relative Humidity and MiC and UNI threshold values; d) indoor Relative Humidity and WHO threshold values.

The Ministry of Culture and the Italian Standard Organization, from here on out referred to as MiC and UNI respectively, provide thermo-hygrometric limits (MBAC, 2001, and UNI, 1999) for paintings on canvas. According to them, Temperature (Fig. 4a) should remain between 19°C and 24°C. Moreover, UNI establishes that daily variation does not exceed ±1.5°C, also when visitors are present. While the daily range is always respected, Temperature rises above the maximum for most of the summer season and falls below the minimum for short periods in spring and autumn. Different thresholds are given by the World Health Organization (WHO), which recommends indoor Temperature between 23°C and 26°C during summertime and between 20°C and 24°C during wintertime. These limits, shown in Fig. 4b, highlight that visitors' well-being is generally guaranteed only in the summer season, whereas the Temperature falls below the minimum for most of the monitored period. Regarding Relative Humidity, MIC thresholds (35%÷60%) are met for most of the observation period. On the other hand, UNI thresholds are more conservative (40%÷55%) and the upper value is frequently crossed. Daily oscillation range, set equal to ±6 %, is sometimes achieved (Fig. 4c). Recommendations provided by WHO are always largely satisfied with Relative Humidity being far from limit values (30%÷70%) as shown in Figure 4d. To summarize, needs in terms of Temperature are hard to reconcile since, when the visitors' well-being is satisfied, the upper limit given for paintings on canvas is exceeded and, when the values satisfy painting conservation requirements, visitors' well-being is disregarded. On the other hand, the trend of Relative Humidity generally meets visitors' and painting demands as well.

Over the same observation period, the Internal Air Quality (IAQ) has also been monitored. Results in terms of the trend of CO_2 are displayed in Fig. 5, where limits given by UNI (UNI, 2019) for Category I and Category II are superimposed.

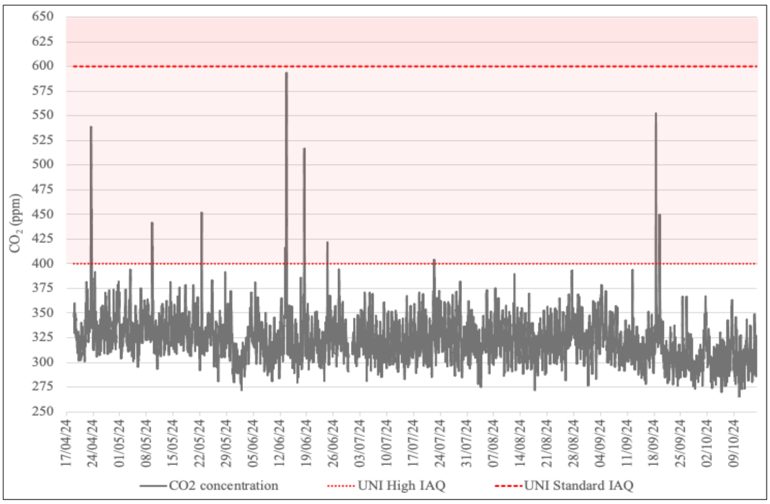
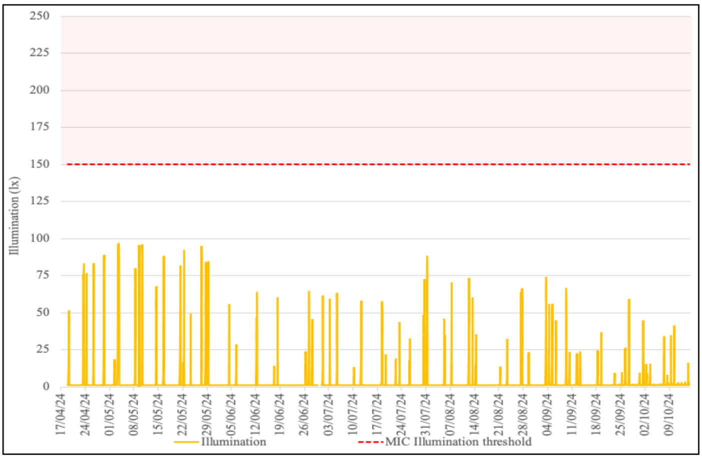
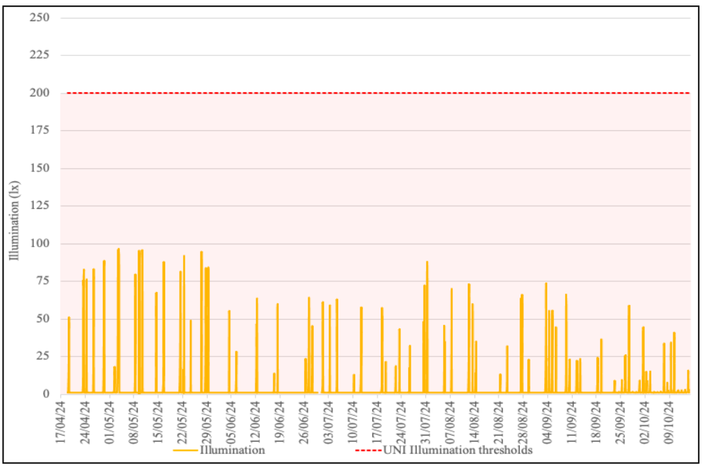


Fig. 5. Comparison between the trend of measured CO2 and the limits given by UNI for High and Standard IAQ

Values of CO_2 lower than 400ppm, which characterize the Category I, indicate high indoor air quality and are recommended for environments in the presence of sensitive people (children, elderly, people with diseases). Values of CO_2 lower than 600ppm, which characterize the Category II, indicate medium indoor air quality and are considered the standard for residential, working and school environments. Throughout the monitoring period, sensors recorded values of CO_2 oscillating around 330 ppm, and then a high indoor air quality was generally encountered. Some peaks are evident; however, they represent rare instances, and their values are contained within the standards. Moreover, the level of CO_2 characterizing the Category II is adequate for painting conservation, and then what is required for people's well-being also respects artworks demand. Among the monitored values, air flow, with a constant value of 0.03 m/s, resulted in being largely compliant with the suggested thresholds, 0.15 and 0.17 m/s in wintertime and summertime, respectively, both for cultural heritage conservation and visitors' well-being. Figure 6 shows the values of Illumination recorded inside Room 1. Once again, threshold values established by regulation are superimposed. For the proper conservation of painting on canvas, the Italian Ministry of Culture (MBAC 2001) suggests a maximum Illumination value of 150 lx, which is largely satisfied in Room 1 as shown in Fig. 6a.



a)

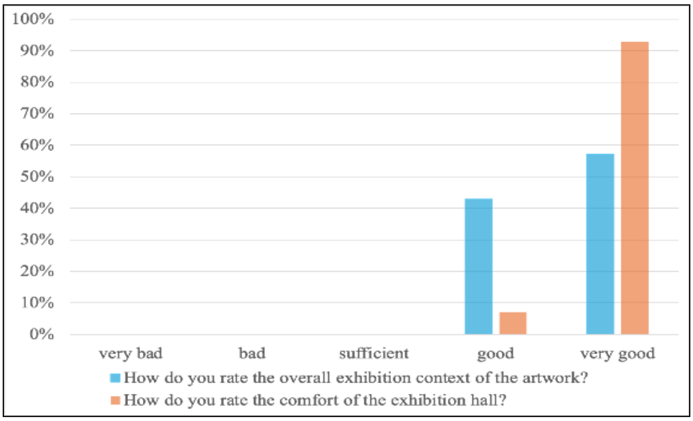


b)

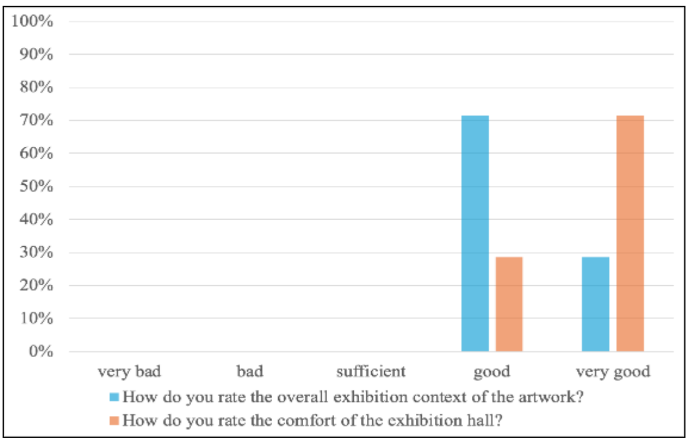
Fig. 6. Comparison between: a) indoor illumination and MiC maximum threshold for painting on canvas; a) indoor illumination and UNI minimum threshold

On the other hand, the WHO doesn't give recommendations about indoor Illumination levels for people's well-being. The UNI EN 12464-1:2021 standard (UNI 2021), which deals with working places, also doesn't provide Illumination levels for museum environments, giving priority to the conservation needs. However, it establishes a minimum level of illumination for continuous workplace occupancy of 200lx (Fig. 6b). Once again, the requirements for cultural heritage conservation don't meet the needs for people's well-being, although for a short visit period a low Illumination value can be accepted.

While the chemical-physical environmental parameters above were being recorded by the monitoring system, giving an objective measure of them, sensations perceived by visitors were being acquired through the QR-code method. These virtual links, positioned next to the artworks along the exhibition path, allowed people to express in real time how they were perceiving the quality of the surrounding environment, giving a subjective evaluation. Answers to the questions of the survey linked to the QR-codes are summarized in Fig. 7, grouped for exposition Rooms (1 and 2), in terms of the percentage of users who expressed each judgement (Fig. 7). All visitors judged both the exhibition context and the comfort of the halls positively, rating them as "good" or "very good".



a)



b)

Fig. 7. Results of survey: a) Room 1, b) Room 2

To transform these judgements into synthetic and processable data, two indices, $i_{context}$ and $i_{comfort,}$ and their mean value i_{mean} have been defined as shown in Eq. (1).

$$i_{context} = \frac{\sum_{k=1}^{5} g_k \cdot n_{cont\_k}}{N}; \; i_{comfort} = \frac{\sum_{k=1}^{5} g_k \cdot n_{comf\_k}}{N}; \; i_{mean} = \frac{i_{context} + i_{comfort}}{2} \quad (1)$$

where: g_k = (0, 0.25, 0.5, 0.75, 1) is the weight given to each of the five selectable judgments, increasing from 0, corresponding to "very bad", to 1, corresponding to "very good"; n_{cont_k} is the number of users who expressed the k judgment as regards the exhibition context; n_{comf_k} is the number of users who expressed the k judgment as regards the comfort of the hall; N is the total number of users who filled in the questionnaire.

The three indices have been computed separately for each Room, and the results are summarized in Table 4. Values are very high, in some cases they are almost one, and consistent with results in terms of air quality and microclimate parameters, which had established suitable conditions for visitors' wellbeing. Indices still allow comparing the two Rooms with each other. As it is evident values which characterize Room 1 are greater than those characterizing Room 2 in terms of context, comfort, and mean. This circumstance highlights a different perception of the environments from visitors who seem to prefer overall one of the two halls, giving useful food for thought to the museum curators.

Table 4. Summary of the results of the survey in terms of indices

	$i_{context}$	$i_{comfort}$	i_{mean}
Room 1	0.89	0.98	0.94
Room 2	0.82	0.93	0.88

4. Conclusions

A complex scenario frames the issue of Indoor Air Quality control in museum environments, marked by unique and specific needs, quite different from those of general indoor settings occupied by workers or visited by the public. In this context, while the primary goal must remain the preservation of artwork collections, it is equally necessary to strike a balance with the comfort requirements of both visitors and, above all, staff, since working time longer than visit time.

The monitoring protocol proposed aims to reach this goal through a multidisciplinary approach for collecting data, so as to inform considerations on current guidelines and contribute to their possible revision. Many environmental parameters have been monitored using devices that are cost-effective, easy to install, and minimally invasive. Moreover, a QR code access system allowed for the correlation of sensations perceived by visitors with instrumental measurements. This methodology is neither conclusive nor exhaustive; rather, it is intended as a reference for conservation professionals, recognizing that standardized procedures cannot be universally applied across all museum environments due to the heterogeneity of the exhibition rooms and of the artworks' materials.

Because of the deleterious effects of certain pollutants on human health, future studies should focus on the development of a robust methodology and experimental setup, including the detection and quantification of fine particulate matter (PM 2.5). Furthermore, the implementation of people counting systems would facilitate the acquisition of valuable insights into the impact of visitors' presence on microclimatic parameters inside the museum environment and enable a more comprehensive analysis of their mutual interaction.

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References

Aghemo C., Guarnerio G., (1997), *Valutare il costruito: la qualità ambientale di una biblioteca universitaria*, Alinea, Firenze, Italy.

Aversa P., Settimo G., Gorgoglione M., Bucci E., Padula G., De Marco A., (2019), A case study of indoor air quality in a classroom by comparing passive and continuous monitoring, *Environmental Engineering and Management Journal*, **18**, 2107–2115.

Aversa P., Diana M., Amato A., Settimo G., (2020), *Actions to Boost Energy Efficiency and Indoor Air Quality: Case Studies in Italian Schools*, Proc. of BEHAVE 2020 – 6th Conference on Behaviour and Energy Efficiency, Copenhagen, Denmark, 21–23 October 2020.

Aversa P., Innella C., Marghella G., Marzo A., Tripepi C., (2025), Monitoring for the preservation of cultural heritage and visitor satisfaction, *Lecture Notes in Civil Engineering (LNCE)*, **1**, 406–414.

Brimblecombe P., (1990), The composition of museum atmospheres, *Atmospheric Environment Part B: Urban Atmosphere*, **24**, 1–8.

Camuffo D., (2019), *Microclimate for Cultural Heritage: Measurement, Risk Assessment, Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments*, Elsevier, Amsterdam, The Netherlands.

Centorrino P., Corbetta A., Cristiani E., Onofri E., (2021), Managing crowded museums: Visitors flow measurement, analysis, modeling, and optimization, *Journal of Computational Science*, **53**, 101357.

Elkadi H., Al-Maiyah S., Fielder K., Kenawy I., Martinson D.B., (2021), The regulations and reality of indoor environmental standards for objects and visitors in museums, *Renewable and Sustainable Energy Reviews*, **152**, 111653.

Goulding C., (2000), The museum environment and the visitor experience, *European Journal of Marketing*, **34**, 261–278.

Gysels K., Delalieux F., Deutsch F., Van Grieken R., Camuffo D., Bernardi A., Sturaro G., Busse H.J., Wieser M., (2004), Indoor environment and conservation in the Royal Museum of Fine Arts, Antwerp, Belgium, *Journal of Cultural Heritage*, **5**, 221–230.

Ilieș A., Caciora T., Marcu F., Berdenov Z., Ilieș G., Safarov B., Hodor N., Grama V., Shomali M.A.A., Ilieș D.C., (2022), Analysis of the interior microclimate in Art Nouveau heritage buildings for the protection of exhibits and human health, *International Journal of Environmental Research and Public Health*, **19**, 16599.

MBAC, (2001), *Atto di indirizzo sui criteri tecnico-scientifici e sugli standard di funzionamento e di sviluppo dei musei*, D.Lgs. n. 112/98 art. 150 comma 6, Ministero per i Beni e le Attività Culturali, Roma, Italy.

Pavlogeorgatos G., (2003), Environmental parameters in museums, *Building and Environment*, **38**, 1457–1462.

Ryhl-Svendsen M., (2006), Indoor air pollution in museums: Prediction models and control strategies, *Studies in Conservation*, **51**, 27–41.

Schito E., Conti P., Testi D., (2018), Multi-objective optimization of microclimate in museums for concurrent reduction of energy needs, visitors' discomfort and artwork preservation risks, *Applied Energy*, **224**, 147–159.

Tetreault J., (2018), The evolution of specifications for limiting pollutants in museums and archives, *Journal of the Canadian Association for Conservation*, **43**, 21–37.

UN, (2015), *Transforming Our World: The 2030 Agenda for Sustainable Development*, A/RES/70/1, United Nations, New York, USA.

UNI, (1999), *Works of Art of Historical Importance – Ambient Conditions for the Conservation – Measurement and Analysis*, UNI 10829:99, Ente Nazionale Italiano di Unificazione (UNI), Milan, Italy.

UNI, (2019), *Energy Performance of Buildings – Ventilation for Buildings – Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics – Module M1-6*, UNI EN 16798-1:2019, Ente Nazionale Italiano di Unificazione (UNI), Milan, Italy.

UNI, (2021), *Light and Lighting – Lighting of Work Places – Part 1: Indoor Work Places*, UNI EN 12464-1:2021, Ente Nazionale Italiano di Unificazione (UNI), Milan, Italy.

Uring P., Chabas A., Alfaro S., Derbez M., (2020), Assessment of indoor air quality for a better preventive conservation of some French museums and monuments, *Environmental Science and Pollution Research*, **27**, 42850–42867.

WHO, (2021), *Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*, World Health Organization, Geneva, Switzerland.

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EVALUATION OF INDUSTRIAL WASTE: THE INTEGRATED ENVIRONMENTAL AUTHORIZATION AS A TOOL FOR THE CIRCULAR ECONOMY IN BASILICATA REGION[*]

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Abstract

Circular economy applied to industry creates a remarkable set of benefits, both environmental and socio-economic. Within the framework of the circular economy, while the industrial sector is already undergoing a shift toward structural changes and toward greater sustainability, an obstacle to its full development is still represented by a bureaucracy that is perhaps not yet adaptive enough, potentially slowing down the adoption of innovative and sustainable practices. The Environmental Compatibility Office of the Directorate General for Environment, Territory, and Energy of the Basilicata Region is the competent authority for issuing the Integrated Environmental Authorization (IEA), which allows for the construction and operation of industrial plants. By adopting an integrated - or better yet, holistic - approach, the Integrated Environmental Authorization makes it possible to evaluate and optimize the life cycle of materials, promoting practices of reuse and recycling of industrial waste that convert them into resources. In this way, waste generation will reduce and the environmental impact of industries will minimize. Through the authorization of activities such as the use of products classified as End of Waste (EoW) in production processes, the competent authority can promote synergies between industries and facilitate the matching of supply and demand. The Basilicata Region has authorized, as non-substantial modifications of the Integrated Environmental Authorization, the introduction of materials classified as EoW into the production cycle of cement plants; following the implementation of the modification, savings in natural resources (materials extracted from quarries located within the regional territory) are expected, amounting to tens of thousands of tons per year. Ultimately, by working within the framework of the institutional mission of the regional administration, and in accordance with the principle of sustainable development, the aim is to demonstrate how the IEA can represent a significant tool capable of synergistically integrating environmental protection, innovation, and economic growth.

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1. Introduction

The transition toward an industry based on a sustainable approach and aiming for climate neutrality - promoted at the EU level by the European Green Deal and subsequently reinforced through the Clean Industrial Deal - imposes, as a global environmental challenge, a deep revision of traditional production models. In this context, the promotion of the circular economy represents a fundamental strategic opportunity to combine the decarbonization of industrial processes with economic growth.

The key objectives for the industry of the Old Continent, also in light of the growing challenges regarding the supply of raw materials, have become, among others, the following:

- the rationalization of production cycles;
- the valorization of industrial waste through reuse, recycling, and recovery practices;
- the extension of the materials' life cycle;
- the improvement of resource-use efficiency.

In this way, it is possible to foster a transition toward more efficient and resilient production models.

From a regulatory perspective, the Integrated Environmental Authorization, established by Directive 2010/75/EU and transposed into the Italian legal framework by Legislative Decree No. 152/2006 (specifically, Title III-bis of Part II), constitutes the key permitting tool for the control and integrated management of emissions generated by industrial plants with high environmental impact. The Integrated Environmental Authorization is an autonomous permit governed by a specific regulatory framework that enables the operation of an industrial facility under precise imposed conditions.

The integrated approach of the authorization makes it possible to systematically and holistically consider interactions among different environmental sectors (air, water, soil, waste), fostering optimized and sustainable technical solutions. Within the circular paradigm, such authorization can play an enabling role in facilitating the reuse of materials classified as "End of Waste" (EoW), promoting the substitution of virgin raw materials with certified secondary resources.

This work aims to analyze - through the experience of the Basilicata Region (where responsibility for environmental authorizations lies with the Environmental Compatibility Office of the Directorate General for Environment, Territory, and Energy) - the role of the Integrated Environmental Authorization as a technical-administrative lever for integrating the principles of the circular economy into the region's industrial cycles.

In particular, it illustrates the process of amending the authorization in relation to the use of End of Waste materials, highlighting the relevant regulatory, procedural, and evaluation aspects, with the primary objective of showing how the adoption of a holistic approach - such as that of the Integrated Environmental Authorization - can generate measurable positive impacts, both in terms of reducing the ecological footprint of industrial plants and in terms of saving natural resources.

Through the description of the administrative procedures adopted and the examination of concrete cases - including the authorization of non-substantial modifications aimed at introducing EoW materials into the production cycle of a clinker and cement manufacturing plant - the study seeks to demonstrate how the Integrated Environmental Authorization can foster synergies among businesses and facilitate the meeting of supply and demand for secondary resources, while also contributing to the achievement of the Minimum Environmental Criteria (CAM) required by sustainable public procurement policies.

2. Materials and methods

This work is based on a qualitative and regulatory methodological approach, complemented by an applied analysis of concrete cases of non-substantial modifications of the Integrated Environmental Authorization (I.E.A.) concerning the introduction of materials classified as “End of Waste” (EoW) into the production cycle of a cement plant operating in the Basilicata Region.

The sources used include European and national regulatory references, regional technical documentation, ministerial guidelines, and scientific and technical literature on both the cement production sector and the treatment and recovery of industrial waste.

The regulatory framework of reference consists of:

- Directive 2010/75/EU of the European Parliament and of the Council of 24.11.2010 on industrial emissions (integrated pollution prevention and control), which defines the principles of the Integrated Environmental Authorization and the framework for issuing, renewing, and amending authorizations;
- Legislative Decree No. 152 of 03.04.2006, “Environmental Regulations,” Part Two, Title III-bis, which transposes the aforementioned Directive and details the authorization procedure in Italy;
- Regulation (EU) No. 305/2011 on construction products, which sets out compliance requirements for placing construction materials on the market;
- Ministerial Decree No. 264 of 13.10.2016, which establishes the criteria for determining when a waste ceases to be considered as such pursuant to Article 184-ter of Legislative Decree No. 152/2006.

In addition, the following were consulted:

- the document containing the BAT Conclusions for the cement production sector;
- the Minimum Environmental Criteria for public procurement of cement and construction materials (Ministerial Decree of 23.06.2022).

Reference was also made to the guidelines drafted by the Environmental Compatibility Office, aimed not only at defining the criteria for identifying whether or not modifications are substantial, but also at recognizing certain types of interventions that do not affect the prescriptive framework nor the management of the authorization. For the cases identified - including the replacement of raw and auxiliary materials with others of equal or lesser impact, such as in the case under discussion - the Environmental Compatibility Office deemed it advantageous to streamline the administrative process. This was done with a view to simplification, seeking to accelerate innovative and sustainable practices, provided it can be demonstrated that such practices improve, or at least do not alter, the emission performance of industrial plants.

The analysis focused essentially on reviewing the technical files related to requests for non-substantial modifications of the Integrated Environmental Authorization, particularly those concerning the introduction of End of Waste materials into the clinker and cement production cycles. The methodology included:

- regulatory and technical review: mapping of relevant regulations and applicable technical references;
- procedural analysis: description of the stages of the technical review carried out by the Environmental Compatibility Office of the Basilicata Region;

- case study: detailed description of the modifications requested by a cement production plant authorized in Basilicata, with reference to the type of EoW material used, the quantities, the expected benefits, and the anticipated environmental impacts;
- comparative evaluation: comparison between the consumption of traditional raw materials (from quarries) and substitute materials (EoW), in terms of environmental savings and economic sustainability.

3. Case study

An interesting case concerns a cement plant operating in the Basilicata Region, which requested authorization to introduce and increase the use of materials classified as End of Waste (EoW) in its production cycle, specifically:

- to introduce 50,000 tons/year of the product commercially known as "Base marna," an EoW material intended to replace the natural marl used as a base component of clinker;
- to introduce 35,000 tons/year of the material known as "Pellet gypsum," also classified as EoW, aimed at replacing the natural gypsum used in the final stage of cement production;
- to increase from 16,000 to 50,000 tons/year the use of the product "Matrix," an EoW already previously authorized, serving primarily as a corrective agent for chemical composition.

These interventions are part of an industrial strategy aimed at gradually reducing the use of natural raw materials (limestone, clay, gypsum), while at the same time enhancing the valorization of materials derived from recovery operations. The operator's declared objective is twofold: on the one hand, to promote a circular economy based on the reuse of by-products and waste; on the other, to increase commercial competitiveness through the production of cements with a high recycled content, in line with the Minimum Environmental Criteria for public procurement (Ministry of the Environment, 2022). From an environmental standpoint, the introduction of these materials enables overall savings of approximately 119,000 tons/year of quarry-derived raw materials. From a regulatory and procedural perspective, the modification was considered not only non-substantial under Article 29-nonies, paragraph 1, of Legislative Decree No. 152/2006 - since it does not entail significant changes to the plant or its emissions (both channeled and diffuse) - but it was also treated as an intervention subject to the simplified administrative procedure. The technical-administrative review was conducted by the Environmental Compatibility Office of the Basilicata Region, which verified the compliance of the EoW materials with environmental standards and safety requirements (Directive 2010/75/EU; Basilicata Region, 2023).

The technical assessments included:

- analysis of the physico-chemical composition of the proposed materials to verify their suitability as functional substitutes for traditional raw materials (BAT Conclusions for the cement industry, 2013);
- verification of the absence of hazardous substances or residual contaminants in the EoW materials, based on analytical certifications provided by the producers;
- comparison between the estimated post-modification emissions and the authorized limit values, which proved favorable, i.e., with no exceedances or additional risks for environmental matrices.

From an industrial perspective, the use of EoW materials also translates into operational benefits: "Base marna" and "Matrix" have a stabilized and consistent composition, which facilitates quality control of the clinker produced. "Pellet gypsum," thanks to its regular form and controlled sulfate content, allows for greater precision in regulating cement setting time.

4. Results and discussion

The analysis conducted on the case study of a cement plant in the Basilicata Region highlighted how the introduction of materials classified as End of Waste (EoW) into production cycles can achieve significant environmental and economic results.

In quantitative terms, the overall savings in natural raw materials from quarries is estimated at approximately 119,000 tons/year, directly reducing the impact associated with extraction activities and transportation. This reduction translates into a significant decrease in the environmental footprint linked to the extraction, transport, and preliminary treatment of natural materials (European Cement Association, 2021). The reduction in climate-altering emissions, estimated at around 5,000 tons/year of CO_2, reflects both lower road transport needs and reduced energy consumption in grinding and kiln operations, given that EoW materials feature more favorable granulometric and reactive properties (ISPRA, 2020). This demonstrates that the adoption of secondary resources can serve as an effective tool for decarbonizing the sector.

From an operational standpoint, the introduced materials proved suitable for the functional replacement of conventional raw materials, ensuring stable and controlled clinker composition and greater precision in regulating cement setting time. This generates direct benefits for production process management, with reduced operational variability and improved quality of the final product.

On the regulatory side, the type of intervention enabled a fast and effective administrative process, without increasing environmental risks. The checks carried out confirmed the absence of additional critical issues for air, water, and soil, demonstrating the compatibility of EoW materials with the standards established by current legislation.

Overall, the results confirm that integrating End of Waste materials into the cement production cycle not only reduces the ecological footprint of plants but also contributes to achieving resource efficiency and circular economy goals, while strengthening industrial competitiveness.

5. Conclusions

In the cement production sector, End of Waste (EoW) materials represent a valid alternative to the exclusive use of raw materials extracted from quarries: this approach saves natural resources while reducing the energy and environmental costs associated with their extraction and transport. Thus, adopting a circular approach in the cement industry can generate concrete and measurable environmental benefits.

The analyzed experience demonstrates how the Integrated Environmental Authorization, when interpreted proactively, can serve as an enabling tool for the effective implementation of circular economy principles in the cement sector. The introduction of materials classified as End of Waste has led to significant savings in natural raw materials and measurable reductions in climate-altering emissions, without producing negative impacts on environmental standards or product quality.

Beyond environmental benefits, the use of secondary resources has generated tangible industrial advantages, such as greater stability in the production process and compliance with the requirements of the Minimum Environmental Criteria, with positive repercussions in terms of industrial competitiveness and access to the public procurement market.

The added value of the activity examined in this study lies in the synergy between circular economy, technological innovation, and environmental sustainability - elements that also have positive commercial implications. Through the effective and flexible use of the

Integrated Environmental Authorization, it is therefore possible to transform a permitting process into a driver of ecological transition, while still ensuring rigorous and integrated control of environmental impacts.

Looking ahead, the model adopted by the Basilicata Region shows how the integration of regulatory instruments, administrative capacity, and sustainable industrial strategies can accelerate the path toward climate neutrality and enhance the resilience of the production system.

References

Basilicata Region, (2024), *Regional Government Resolution No. 547 of September 13, 2024.* Basilicata Regional Government, Potenza, Italy.

European Cement Association, (2021), *Environmental Report 2021.* CEMBUREAU, Brussels.

European Commission, (2013), *Commission Implementing,* Decision 2013/163/EU, Official Journal of the European Union, Brussels.

European Parliament & Council of the European Union, (2010), *Directive 2010/75/EU on Industrial Emissions (Integrated Pollution Prevention and Control),.* Official Journal of the European Union, Brussels.

ISPRA, (2020), *National Report on Greenhouse Gas Emissions,* Italian Institute for Environmental Protection and Research, ISPRA, Rome.

Ministry of the Environment and Protection of Land and Sea, (2016), Ministerial Decree of October 13, 2016, No. 264 – End-of-Waste Criteria, Rome: Official Gazette of the Italian Republic.

Ministry of the Environment and Protection of Land and Sea. (2022). *Minimum Environmental Criteria for construction materials and cement.* Rome: Official Gazette of the Italian Republic.

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SUSTAINABLE REMEDIATION OF CONTAMINATED SITES: THE CASE STUDY OF THE MAR PICCOLO OF TARANTO*

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Abstract

The Charter for Sustainable Remediation, signed by the Minister of the Environment, is a declaration of principles that recognizes the centrality of sustainable development objectives in the characterization and remediation of contaminated sites. The remediation of polluted marine sediments is a complex process, often necessary to recover areas of socio-economic interest. In recent years, remediation efforts have focused on the physical removal of contaminants or their immobilization, frequently employing techniques that can negatively affect the ecosystem. Sustainable remediation, by contrast, refers to an environmental restoration process aimed at removing or reducing pollutants through less invasive and ecologically compatible solutions. This work illustrates and discusses the case of the Mar Piccolo of Taranto: a basin that, due to its morphological and ecological characteristics, represents a particularly intricate environmental ecosystem, yet one of extraordinary naturalistic value. Unfortunately, the Mar Piccolo has been included in the "Taranto National Interest Site" due to the accumulation of toxic substances in its sediments. Nevertheless, thanks to its remarkable resilience, the basin has preserved a unique natural heritage of biodiversity. In this context, it is essential to consider its recovery through sediment remediation techniques with minimal ecological impact, such as bioremediation using natural or genetically modified microorganisms, monitored natural attenuation, and similar approaches, while limiting waste production and promoting recycling. A sustainable remediation strategy can therefore serve not only as an effective environmental solution but also as a catalyst for revitalizing socio-economic activities, both traditional (e.g., mussel farming) and innovative, based on environmentally responsible processes.

Keywords: Mar Piccolo, recovery ecosystem, sediments, sustainable remediation

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1. Introduction

Sustainable remediation acknowledges the central role of sustainable development objectives in the characterization, safety, and functional redevelopment of contaminated sites, with the aim of safeguarding biodiversity and protecting natural resources. Effective remediation fosters well-being, reduces poverty, promotes environmental sustainability, restores trust in institutions, enhances growth opportunities, and improves business competitiveness. It also supports approaches that prioritize biodiversity conservation, the self-purifying capacity of ecosystems, climate impact mitigation, and potential carbon sequestration. Sustainable remediation promotes new circular economy models capable of reducing emissions and increasing ecosystem resilience (Colglazier, 2015; Uricchio, 2020).

Marine sediments can accumulate persistent organic and inorganic contaminants, posing risks to both human health and the environment. As a result, sediment remediation is a complex process and presents significant challenges from both environmental and technological perspectives. Historically, efforts have focused on the physical removal of contaminants through dredging or their immobilization, methods that often have adverse effects on benthic ecosystems and filter-feeding organisms due to the resuspension of polluted sediments (Cooper et al., 2011). The seas of Taranto (Mar Piccolo and Mar Grande) constitute a coastal marine ecosystem whose biological equilibrium has been progressively altered by human development, particularly due to large-scale industrial activities (Cardellicchio et al., 2016). The Mar Piccolo, in particular, exemplifies a Mediterranean coastal ecosystem whose ecological balance has been compromised by significant environmental stress linked to industrial expansion (Petronio et al., 2012). This situation has led to the accumulation of pollutants in the sediments, although the basin still retains a high level of biodiversity, notable resilience, and supports important mussel farming operations. Over the years, several sediment characterization programs have been undertaken to assess contamination levels and pollutant dispersion. The resulting data have further highlighted the basin’s complexity and dynamic nature, underscoring the need for targeted remediation strategies to protect ecological biodiversity and sustain existing socioeconomic activities.

Therefore, in the case of the Mar Piccolo of Taranto, it is essential to consider ecological, economic, and social factors when defining sustainable remediation goals. The primary objective of this work is to explore the prospects for remediation and redevelopment of the Mar Piccolo basin, where the unique ecological features of the marine environment call for alternative solutions to dredging and the development of cost-effective sediment management strategies, including in-situ treatment options.

2. Study area

The Mar Piccolo is a typical semi-enclosed basin of the Mediterranean Sea (Fig. 1), characterized by limited water circulation (De Serio et al., 2007). This condition promotes the sedimentation of organic matter, which plays a key role in the transport and accumulation of pollutants within the sediments. The Mar Piccolo hosts the largest mussel farm in Italy. The high degree of urbanization and industrialization in the Taranto area has led, over the years, to sediment contamination by toxic organic compounds and heavy metals, with concentrations often exceeding legal limits. Consequently, contaminated sediments in the basin represent a significant source of pollution for both the water column and biological organisms.

The surrounding areas are home to major industrial facilities, including the Acciaierie d'Italia steel plant, an ENI oil refinery, and two thermoelectric power stations. Additionally, the city of Taranto hosts a major commercial port and the principal naval base of the Italian

Navy. For these reasons, the area was designated a "Site of National Interest (SIN)" under National Law No. 426 (1998) and included in the National Environmental Remediation Program. Chemical characterizations carried out over time (ARPA Puglia, 2014; ISPRA, 2010), along with research conducted by various Extraordinary Commissioners for remediation since 2013, have confirmed the presence of high levels of priority contaminants in the sediments, including heavy metals (lead, cadmium, mercury, copper, zinc, etc.) (Calace et al., 2005, 2008; Petronio et al., 2012) and organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-dioxins and dibenzofurans (PCDDs/Fs), and polychlorinated biphenyls (PCBs) (Cardellicchio, 2020) (Fig. 2). Moreover, elevated concentrations of organic compounds (e.g., PCBs) have also been detected in farmed mussels, posing a significant risk to human health.

Regarding organic pollutants, the exceedance of the limits established by European Commission Regulation (EC, 2011) for dioxins and dioxin-like PCBs has led, since 2011, to a ban on the marketing and consumption of adult mussels from the first inlet of the Mar Piccolo. Several studies have also identified the presence of protected species within the basin, in accordance with the Barcelona Convention protocol (United Nations, 1977). In light of this scenario, and to support the basin's environmental recovery, it is essential to consider environmentally sustainable sediment remediation strategies, identifying low-impact technologies that safeguard biological communities and promote the revival of mussel farming.

Fig. 1. The coastal area of Taranto

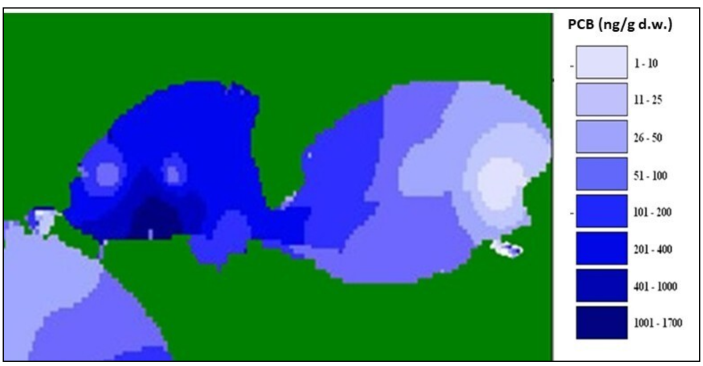

Fig. 2. Distribution of PCBs in the Mar Piccolo basin of Taranto

3. Results and discussion

3.1. Scenarios of remediation in Mar Piccolo

The environmental picture emerging from the various sediment characterizations in the first inlet of the Mar Piccolo highlights the complexity of the remediation challenge: the resuspension of contaminated sediments represents a significant secondary source of pollution. Therefore, any seabed disturbance operations must be carefully evaluated. The conceptual model of the basin (ARPA Puglia, 2014) revealed the presence of areas with varying levels of contamination and the need to adopt differentiated intervention strategies, taking into account the simultaneous presence of mussel farming activities and important biological communities. These strategies also require coordination with various stakeholders and a clear definition of the intended use of the areas to be remediated, in order to meet sustainability and cost-effectiveness criteria (Extraordinary Commissioner, 2018).

Given the basin's unique ecological conditions, dredging operations can have several negative impacts on the biological component, not only due to increased turbidity in the water column but also because of the potential dispersion of toxic contaminants, with adverse effects on mussel farming. In this context, the remediation project for the first inlet of the Mar Piccolo must incorporate a range of technological approaches: environmental dredging or capping for the most contaminated areas, and non-invasive techniques such as bioremediation, phytoremediation, and monitored natural attenuation for less contaminated zones. In recent years, more effective eco-dredging systems have been tested in several port areas. These systems are capable of operating in accordance with Circular Economy principles and allow sediment removal without direct contact with the seabed. By maintaining a low-pressure field above the sediment, they prevent material leakage and subsequent resuspension. This enables operations even in protected areas, avoiding turbidity in the water column (Decomar: https://www.decomar.it/index.html).

ENEA and CNR, through the Life 4 Mar Piccolo project (Life 4 Mar Piccolo, 2016), have proposed an alternative methodological approach to traditional remediation techniques for the Mar Piccolo. A pilot plant was tested, based on the controlled resuspension of fine particles of polluted sediment and a membrane-based micro- and ultrafiltration system to separate suspended particles from the water. This remediation process is effective because it targets the most contaminated portions of sediment while minimizing impacts on biocenosis. The approach involves selectively removing contaminants suspended in the water or adsorbed onto suspended solid particles. This methodology thus helps preserve the unique characteristics of an environment designated by the European Union as a Site of Community Importance (SCI) under the Habitats Directive 92/43/EEC (European Commission Directive, 1992). Capping is a sediment isolation technique that involves covering contaminated sediments with a layer of suitable material to prevent contact between pollutants and the surrounding aquatic environment (Förstner and Apitz, 2007; Palermo et al., 1998).

An innovative variant, known as "reactive capping," includes not only layers of clean materials but also adsorbents designed to reduce or eliminate the diffusion of contaminants. In general, capping is an effective technology for contaminants strongly associated with sediments, including hydrophobic organic compounds such as high molecular weight polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), dioxins, and heavy metals (Gomes et al., 2013). Heavy metals are typically present in sediments as insoluble sulfides under strongly reducing conditions. Since oxygen penetration into the capping layer is usually limited, capping promotes reducing conditions in the underlying contaminated sediment, facilitating the formation of insoluble metal sulfides (Peng et al., 2018).

The low solubility of these sulfides enhances metal retention, making capping an extremely effective technique for sediments with high concentrations of heavy metals, such as those found in the southern part of the first inlet of the Mar Piccolo.

3.2. Challenges for in situ bioremediation

In situ bioremediation employs biological processes to degrade environmental pollutants. However, the complexity of the sediment–water ecosystem can often limit the effectiveness of these processes, which tend to be more successful when environmental conditions are carefully defined and controlled to enhance biotransformation. Various approaches have been adopted to evaluate natural bioremediation in contaminated sediments (Perelo, 2010), including Monitored Natural Recovery (MNR), biostimulation of microbial populations, the introduction of non-native species with high degradation capacity, and phytoremediation using macrophytes and/or algae. The MNR technique relies on natural degradation processes that occur spontaneously in a given environment and can reduce or even eliminate the bioavailability and toxicity of contaminants. In sediments, the affected portion is primarily the surface layer, although the effect can extend up to one meter deep in marine estuarine environments. The importance of these processes lies in the fact that reducing the bioavailability of a contaminant also decreases its exposure to and accumulation in organisms, a concern that particularly affects bioaccumulator species such as mussels farmed in the first inlet of the Mar Piccolo. For about a decade, many countries have explored the potential of MNR, which is often considered a viable alternative to traditional remediation methods for contaminated sites. Perelo (2010) studied the in situ bioremediation of organic pollutants in sediments, highlighting its lower environmental impact and more favorable cost-benefit ratio in terms of waste production compared to conventional management strategies. Nevertheless, in situ bioremediation requires longer timeframes (ranging from months to several years), and its success is less predictable than traditional methods, making it a suitable option primarily for sites with low levels of contamination.

In this regard, it is essential to assess the ability of natural processes to achieve remediation goals without human intervention (Prabhakar et al., 2002). The application of MNR in the less contaminated marine areas of the Mar Piccolo of Taranto, however, requires the elimination of residual active sources of contamination and continuous monitoring to evaluate the progress of sediment remediation (Cardellicchio and Cardellicchio, 2022). MNR can also be combined with other technologies described above (e.g., capping) and applied to more contaminated areas. However, natural recovery must be constantly monitored over time to ensure that degradation processes, especially those targeting persistent organic pollutants are proceeding at the expected rate. It is important to note that natural degradation can sometimes lead to the formation of secondary compounds that remain toxic. Therefore, the processes governing the environmental fate of pollutants must be thoroughly understood, including the estimation of the time required to achieve remediation objectives. The adoption of these technologies for the restoration of the Mar Piccolo basin must be based on a comprehensive preliminary analysis of the ecosystem and, above all, on the degradation capacity of the specific biological and microbial communities present.

Biocenotic surveys conducted in the Mar Piccolo over the years have revealed that sediments in the first inlet are almost uniformly covered by macroalgae such as the green alga *Caulerpa prolifera*, the red alga *Gracilaria dura*, and the brown alga *Dictyota dichotoma*. Along the northern coast, the seabed is also colonized by the seagrass *Cymodocea nodosa*. Even in the second inlet, there are areas with dense algal vegetation composed of *Cladophora prolifera*, *Gracilaria dura*, and *Dictyota dichotoma*, with *Cymodocea nodosa* present on sandy bottoms (ARPA Puglia, 2014) (Fig. 3).

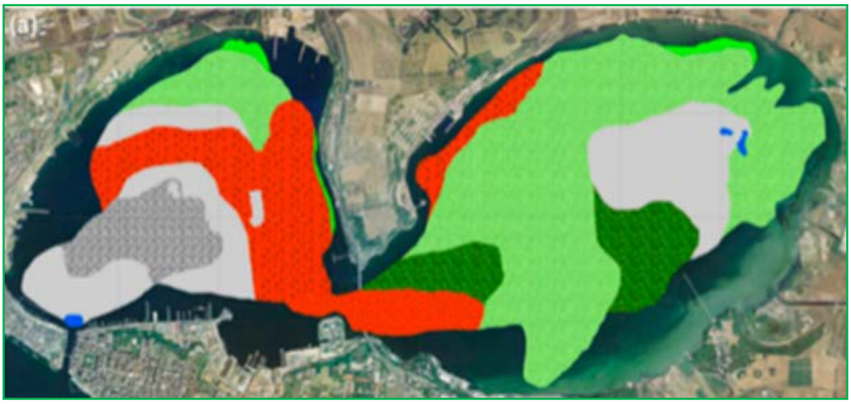

Fig. 3. Phytocoenosis of the Mar Piccolo of Taranto: Light green area: *Cymodocea nodosa*; Dark green: *Caulerpa prolifea and racemosa* and green algae (Arpa Puglia, 2014)

The presence of algae and seagrasses clearly suggests the role of plant communities in seabed phytoremediation. The phytoremediation of organic contaminants in sediments occurs in distinct compartments: (a) the plant compartment, consisting of roots and shoots; and (b) the root zone compartment, comprising the sediments surrounding the plant roots. In these compartments, various mechanisms of contaminant removal and transformation have been observed, including passive absorption into root biomass, active translocation from roots to shoots, accumulation in roots, and chemical transformation within plant cells (Cheto et al., 2004; Zeeb et al., 2006; Whitfield-Aslund et al., 2007).

In the rhizosphere, organic contaminants are transformed and removed through two main mechanisms: chemical transformation by enzymes (e.g., peroxidases and dehydrogenases) secreted by plant roots (Cheto et al., 2004), and biotransformation, including complete mineralization, by rhizosphere microorganisms. Their growth and metabolic biodegradation activity are stimulated not only by root exudates, which contain a wide range of organic and inorganic substrates, but also by improved sediment oxygenation. In fact, submerged aquatic macrophytes (such as seagrasses) are known to oxygenate the root zone to protect themselves from the harmful effects of phytotoxins formed under anaerobic conditions. An increased oxygen flux from plant roots to the sediment should, in principle, enhance the removal rate of organic contaminants susceptible to aerobic biodegradation, such as polycyclic aromatic hydrocarbons (PAHs) (Huesemann et al., 2004). In contrast, for PCBs, increased sediment oxygenation is unlikely to contribute significantly to their removal. This is not surprising, as anaerobic conditions are required for the dechlorination of higher molecular weight PCBs, and only biphenyls with lower chlorine content are subject to aerobic mineralization (Vasilyeva and Strijakova, 2007). Therefore, PCB biodegradation by plant communities can only be attributed to the stimulation of microorganisms via root exudates. Analyses of PCB congener distribution in sediments have provided evidence of degradation processes occurring naturally within ecosystems. This degradation has been interpreted as the result of reductive dechlorination mediated by different populations of anaerobic bacteria, each species exhibiting its own selectivity pattern for various congeners. It is thus evident that PCB molecules, despite their high chemical stability and low bioavailability, are naturally subject to biological degradation processes.

Experimental tests conducted on marine sediments from the Mar Piccolo in Taranto have confirmed the involvement of the native microbial community in the degradation of high molecular weight PCBs under strictly anaerobic incubation conditions, without the addition of amendments. Microorganisms of the genus *Dehalococcoides* are involved in this reductive dechlorination of PCBs and are characterized by PCB dechlorinases that play a key role in the process. Accordingly, the results of various investigations suggest that the native microbial community inhabiting the Mar Piccolo sediments is capable of effectively supporting PCB biodegradation under anaerobic conditions (Matturro et al., 2016). The creation of microbial consortia with biodegradation capacity therefore represents a promising approach to addressing the challenge of environmental restoration, contributing to the expansion of tools for effective in situ bioremediation strategies.

4. Concluding remarks

From the analysis of the various remediation technologies, it emerges that, depending on the characteristics of the marine areas and the sediments of the Mar Piccolo, different types of remediation can be adopted, particularly in relation to the intended use of each area. Sustainable dredging or capping can be effectively applied in highly contaminated zones, provided that the dispersion of pollutants during operations is carefully avoided.

Therefore, the selected technologies must not only meet sustainability and cost-effectiveness criteria, but also aim to safeguard and revitalize the ecological environment. This is especially true for the Mar Piccolo in Taranto, which has long served productive purposes and whose restoration must necessarily respect and reflect its existing ecological values. Assessing the degradative capacity of plants and microorganisms thus becomes a key factor in the implementation of conservation techniques, which should also be supported by continuous monitoring of natural recovery processes.

References

Arpa Puglia, (2014), The Mar Piccolo of Taranto: Technical-scientific study on the interactions between the environmental system and the flows of contaminants from primary and secondary sources: Elaboration of a conceptual site model, Technical Report,.

Calace N., Cardellicchio N., Ciardullo S., Petronio B.M., Pietrantonio M., Pietroletti M., (2008), Metal distribution in marine sediments of the Mar Piccolo in Taranto (Ionic Sea, Southern Italy), *Toxicological & Environmental Chemistry*, **90**, 549–564.

Calace N., Ciardullo S., Petronio B.M., Pietrantonio M., Abbondanzi F., Campisi T., Cardellicchio N., (2005), Influence of chemical parameters (heavy metal, organic matter, sulphur and nitrogen) on toxicity of sediments from the Mar Piccolo (Taranto, Ionian Sea, Italy), *Microchemical Journal*, **79**, 243–248.

Cardellicchio F., (2020), A critical evaluation of washing methods for heavy metal remediation of dredged sediments, *Procedia Environmental Science, Engineering and Management*, **7**, 53–60.

Cardellicchio N., Cardellicchio F., (2022), Management strategies of contaminated sediments in a site of national interest (SIN), *Procedia Environmental Science, Engineering and Management*, **9**, 891–899.

Cardellicchio N., Covelli S., Cibic T., (2016), Integrated environmental characterization of the contaminated marine coastal area of Taranto, Ionian Sea (Southern Italy), *Environmental Science and Pollution Research*, **23**, 12491–12494.

Cheto T., Lester R., Vough L.R., Chaney R.L., (2004), Phytoremediation of polychlorinated biphenyl-contaminated soils: The rhizosphere effect, *Environment International*, **30**, 799–804.

Colglazier W., (2015), Sustainable development agenda: 2030 – Building knowledge-based societies is key to transformative technologies, *Science*, **349**, 1048–1050.

Cooper K.M., Curtis M., Wan Hussin W.M.R., Barrio Froján C.R.S., Defew E.C., Nye V., Paterson D.M., (2011), Implications of dredging-induced changes in sediment particle size composition for the structure and function of marine benthic macrofaunal communities, *Marine Pollution Bulletin*, **62**, 2087–2094.

De Serio F., Malcangio D., Mossa M., (2007), Circulation in a southern Italy coastal basin: Modeling and field measurements, *Continental Shelf Research*, **27**, 779–797.

Decomar, (n.d.), *Decomar S.r.l.*, Available at: https://www.decomar.it/index.html.

EC, (2011), Regulation No 1259/2011 amending Regulation (EC) No 1881/2006 as regards maximum levels for dioxins, dioxin-like PCBs and non-dioxin-like PCBs in foodstuff, Online at*:* https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32011R1259.

European Commission Directive, (1992), Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, *Official Journal of the European Union*, L 206, 7–50.

Extraordinary Commissioner, (2018), *Remediation, environmentalization and redevelopment of the Taranto area*, Summary Report, On line at: http://www.cotecchia.associates/portfolio/study-taranto-area.

Förstner U., Apitz S.E., (2007), Sediment remediation: U.S. focus on capping and monitored natural recovery, *Journal of Soils and Sediments*, **7**, 351–358.

Gomes H.I., Dias-Ferreira C., Ribeiro A.B., (2013), Overview of in situ and ex situ remediation technologies for PCB-contaminated soils and sediments and obstacles for full-scale application, *Science of the Total Environment*, **445-446**, 237–260.

Huesemann M.H., Hausmann T.S., Fortman T.J., Thom R.M., Cullinan V., (2009), In situ phytoremediation of PAH- and PCB-contaminated marine sediments with eelgrass (*Zostera marina*), *Ecological Engineering*, **35**, 1395–1404.

ISPRA, (2010), *Evaluation of characterization results for the Identification of Appropriate Actions for Remediation of Site of National Interest of Taranto*, Technical Report, Joint Research Centre, Ispra, Italy.

Life 4 Mar Piccolo, (2016), *LIFE+ Project: Remediation and reuse of sediments of Mar Piccolo*, Available online: http://www.lifemarpiccolo.it/.

Matturro B., Ubaldi C., Grenni P., Caracciolo A.B., Rossetti S., (2016), Polychlorinated biphenyl (PCB) anaerobic degradation in marine sediments: Microcosm study and role of autochthonous microbial communities, *Environmental Science and Pollution Research*, **23**, 12613–12623.

National Law No. 426, (1998), *New interventions in the environmental field*, *Gazzetta Ufficiale della Repubblica Italiana*, Ordinary Supplement No. 12., Rome, Italy.

Palermo M., Maynord S., Miller J., Reible D., (1998), *Guidance for in-situ subaqueous capping of contaminated sediments*, USEPA Report 905-B96-004, On line at: https://www.epa.gov/superfund/superfund-contaminated-sediments-guidance-and-technical-support.

Peng W., Li X., Xiao S., Fan W., (2018), Review of remediation technologies for sediments contaminated by heavy metals, *Journal of Soils and Sediments*, **18**, 1701–1719.

Perelo L.W., (2010), In situ and bioremediation of organic pollutants in aquatic sediments – Review, *Journal of Hazardous Materials*, **177**, 81–89.

Petronio B.M., Cardellicchio N., Calace N., Pietroletti M., Pietrantonio M., Caliandro L., (2012), Spatial and temporal heavy metal concentration (Cu, Pb, Zn, Hg, Fe, Mn, Hg) in sediments of the Mar Piccolo in Taranto (Ionian Sea, Italy), *Water, Air, and Soil Pollution*, **223**, 863–875.

Prabhakar C.T., Truex M.J., Lee P., (2002), A case study for demonstrating the application of U.S. EPA's monitored natural attenuation screening protocol at a hazardous waste site, *Journal of Contaminant Hydrology*, **59**, 133–162.

United Nations, (1977), *Barcelona Convention for the Protection of the Mediterranean Sea against Pollution and related Protocols*, *Official Journal of the European Union*, L 240, 3–50.

Uricchio A.F., (2020), Le bonifiche sostenibili nella nuova carta di principi presentata dal Ministro dell'Ambiente (in Italian), *Rivista Giuridica Ambiente & Diritto*, **20**, 525–532.

Vasilyeva G.K., Strijakova E.R., (2007), Bioremediation of soils and sediments contaminated by polychlorinated biphenyls, *Microbiology*, **76**, 639–653.

Whitfield Åslund M.L., Zeeb B.A., Rutter A., Reimer K.J., (2007), In situ phytoextraction of polychlorinated biphenyl (PCB)-contaminated soil, *Science of the Total Environment*, **374**, 1–12.

Zeeb B., Amphlett J.S., Rutter A., Reimer K.J., (2006), Potential for phytoremediation of polychlorinated biphenyl (PCB)-contaminated soil, *International Journal of Phytoremediation*, **8**, 199–221.

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FROM CIRCULAR ECONOMY TO REGENERATIVE AGRICULTURE: THE CASE OF POLLINA PAV*

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Abstract

The document presents the development and application of POLLINA PAV, a novel biofertilizer/biostimulant derived from poultry manure via a patented enzymatic biological treatment, aligning with circular economy and regenerative agriculture principles. The process involves a low-energy maturation of poultry manure heaps using a vegetal enzymatic preparation that fosters both aerobic and microaerophilic conditions, resulting in a stabilized product rich in stable organic matter and essential nutrients, including nitrogen, potassium, and phosphorus predominantly present in struvite form.

Characterization of the final pellets revealed an almost neutral pH, reduced salinity, and absence of pathogenic bacteria, confirming hygienic safety. Organic matter content exceeds 70%, with total organic carbon above 35%, and approximately 8% humic substances, indicating maturity and stability. Nitrogen content is significant (>3.5%), with about 30% in water-soluble forms, enabling both immediate and slow-release fertilization. Phosphatase enzymatic activity in the biofertilizer reaches 10-15 µmol PNP/g h, enhancing soil phosphorus bioavailability by catalyzing organic phosphorus mineralization and thus reducing dependence on critical raw material phosphorus inputs. Urease activity declines during maturation, indicating moderated nitrogen mineralization. Basal respiration measurements demonstrate microbial viability, supporting soil biological activity upon application.

The POLLINA PAV biofertilizer offers multifunctionality: nutrient supply, soil organic matter restoration, microbial stimulation, and enhanced phosphorus cycling, coherent with regenerative agriculture objectives of soil health improvement and ecosystem service provision. The technology provides an effective strategy for poultry manure valorization, reducing greenhouse gas emissions compared to synthetic fertilizers and supporting sustainable crop production systems.

Keywords: biofertilizer, enzymatic preparation, phosphatase, poultry manure, regenerative agriculture

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1. Introduction

The need for food and feed increases with population growth, and it is often associated with increase in by-products and waste generation. Poultry manure and litter represent the main by-product in poultry cycle, both for meat and egg production. In Europe, poultry manure production accounts for 25-30 Mt/y and Polland with 4.5 Mt/y is the main producer (Drozdz et al., 2020). According to the EUROSTAT data, the principal poultry producers in the EU-28 in 2018 were: Poland (16.8%), UK (12.9%), France (11.4%), Spain (10.7%), Germany (10.4%) and Italy (8.5%, with about 2 Mt/y manure). These by-products need proper collocation and recycling, according to Circular Economy strategy to conserve resources. Their final utilization or disposal is in soil, for agricultural purposes.

Agriculture is facing important challenges: soils degradation, difficult economic sustainability for farmers, with increased cost for energy and fertilizers, generational turnover, the effects of climate change. Currently over 60% of soils in Europe are unhealthy, according to the 19 indicators defined by European Soil Observatory (https://esdac.jrc.ec.europa.eu/euso), in particular connected to SOM (Soil Organic Matter) depletion, erosion: the supply of Organic Matter (OM) is crucial for fertility, physical and biological, for the maintenance of ecosystem services, and for C sequestration to mitigate climate change, soil as a sink for Carbon.

The need for agriculture that allows for the maintenance of resources and productivity, as well as income for farmers. New business models have been developed. Currently, Regenerative Agriculture (RegenAg) is recognized as a tool for soil health and the maintenance of agricultural productivity and natural capital. Pillars of Regenerative Agriculture are the use of organic fertilization for restoring soil fertility leading to broader ecosystem benefits including water quality, biodiversity, and carbon sequestration

This paper presents the first application of a new biological treatment of poultry manure (PM) to obtain biofertilizer/biostimulant POLLINA PAV in the Organic supply chain. Innovation is focused on technical tools/products that combine both economic and environmental aspects. Pollina PAV is obtained according to new patent (Dall'Ara, 2025), as a further step beyond EP 1314710, which had demonstrative application in LIFE12 ENV/IT/356 RESAFE and LIFE17 ENV/IT/POREM (Strafella et al., 2021). From the results of LIFE POREM project, the fertilizer from PM recycling has lower emissions in comparison with NPK fertilizers for indicator climate change (LIFE POREM Handbook, 2021).

The goal is to develop flexible and versatile techniques and products that can be applied in conventional agriculture, in the organic sector, and in new scenarios such as RegenAg.

Particular attention was then given to P, recognized as a critical raw material, CRM (https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials). The technique was developed to obtain a biofertilizer/biostimulant that provides nutrients but also has the capacity to enhance the availability of nutrients present in the soil. In fact, P is often present in soil, but only a small fraction is available for plants. It was investigated the presence of phosphatase, a group of enzymes that catalyse the hydrolysis of esters and anhydrides of phosphoric acid, releasing inorganic P and phosphate ions, assimilable by plants. This can improve soil P availability, to reduce P input needs.

3. Experimental design

Pilot tests were carried out at Agrofertil plant: two piles of about 15 tons each undergone a maturation process for 100 days as described in patent, to obtain an organic fertilizer/biostimulant. It is a simplified and energy saving treatment. Treatment is based on the use of vegetal enzymatic preparation (adaptive complex system) inserted inside heap during its formation, in dose of about 0.5 kg/ton PM and subsequent biostabilization in batch static pile. It is simplified composting, with aeration via natural convection (Fig. 1).

The "microenvironmental" conditions induced by the activation process lead to the creation of at least two zones within the pile: a surface layer, in contact with the air, in completely aerobic conditions, and an internal zone, in microaerophilic conditions, i.e., with a reduced O2 concentration, where the processes of intense mineralization, which require a lot of oxygen, are therefore slowed. Two different raw materials were tested: poultry manure from laying hens (PM1) and poultry litter from broilers (PM2), both in organic farming. Final products were pelleted at low temperature.

4. Materials and methods

The. process was monitored by automatically acquiring the temperature on the surface of the pile and at a depth of 1 m inside it (4 acquisitions per day, i.e., every 6 hours), as shown in Fig. 1.The measurements were taken using IoT devices, which allow them to be used in complex environments (IP57 rating) and without infrastructure thanks to their internal rechargeable battery and GSM technology. The devices measure the temperature inside the pile using a dedicated 1-meter-long probe. The data is sent to the server and displayed on the system dashboard. The data is stored and can be viewed over time, and the graphs allow temperature trends to be determined throughout the process. Substrate evolution during treatment have been analyzed via periodical sampling and subsequent analyses. Substrate was sampled at t= 0, after 75 days maturation and final pelletized biofertilizer (100 d). Each sample consisted of 4 sub-samples.

The matrices were subjected to chemical-physical, physical and biological characterization. pH and CE were measured at a 1:5 solid: liquid ratio and then measured, after centrifuging and filtering through ash-less filter paper (Albet 145 110). Volatile substance/Organic Matter was determined via calcination (550°C for 6 h). TOC (Total organic C) e Ntot were measured with elemental analyzer LECO C, N, S. TOCsol e Nsol: on the same extraction, were quantified with a TOC analyzer (TOC- 5050A, Shimadzu). Macro and Microelements were determined using an inductive optical emission spectrometer (ICP-OES, model ICAP 6500 DUO THERMO).

Biological characterization included respiration and enzymatic activities, especially connected to C, N and P cycle (β-Glucosidase, Urease and Phosphatase). β-glucosidase activity was determined by the method of Tabatabai (1982) and Eivazi and Tabatabai (1988). Urease activity was determined by the buffered method of Kandeler and Gerber (1988). Phosphatase activity was determined by the method of Tabatabai and Bremer (1969).

a) **b)**

Fig. 1. Poultry manure: a) manual insertion of Vegetal enzymatic preparation (complex adaptative system), during heap formation and b) final heap, in evidence temperature monitoring system

Basal respiration was analyzed by placing 15g of each sample, moistened to 50-60% of the WHC, in a hermetically sealed flask equipped with a rubber septum for glass sampling. The samples were then incubated at 28ºC for 22 days and the CO_2 evolved was measured at given time intervals, with an infrared gas analyzer (PBI-Dansensor, CheckMate II)) (Hernandez and Garcia, 2003).

5. Results and discussion

The main results of chemical-physical characterization are reported in Table 1. They show that the final biofertilizer is a mature product, with almost neutral pH and low salinity, similar to cattle manure. It is hygienically safe, as confirmed by the absence of *Salmonellae* and *E. coli*. Process monitoring showed a profile of T > 65°C required for sanitization for a few weeks (Fig. 2). It presents:

- a high content of stable organic matter (TOC > 35% and organic matter over 70%), with 8% humic matter and only 8% immediately available,
- high nitrogen content (N > 3.5%), of which approximately 30% is water-soluble, immediately available (nitrates and ammonium) and the large organic part which can be mineralized and used by plants and microorganisms over time, is compatible with slow-release N.
- good content for K and P; P is contained also in struvite compound NH_4MgPO_4* $6H_2O$, evidenced by XRD diffraction.

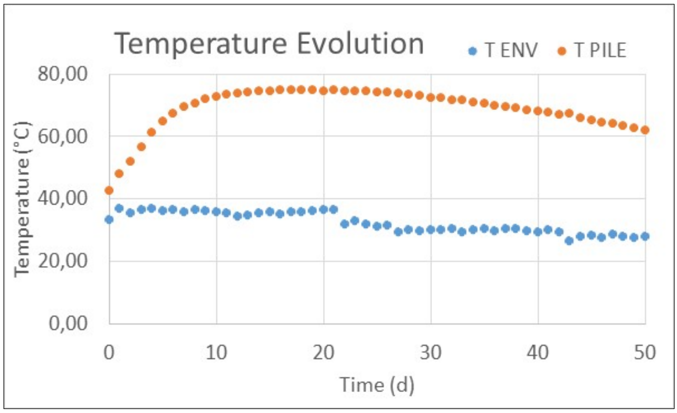
The main result of enzymatic characterization is reported in Fig. 3. Phosphatase in final pellets reaches 10-15 µmol PNF/ g*h, useful to interfere with P present in soil to transform into compound available for plants. The reduced value of urease activity confirms the slowing down of nitrogen release, as already seen in the application of previous EP 1314710 (LIFE POREM Handbook, 2021). β-Glucosidase shown a decline from initial to final figures, from 0.6-1.6 to 0.15 µmol PNF/ g ss h, as indicator of a more stable C fraction in pellets. Basal respiration shows that it is a "living" product (2300-2600 mg C-CO_2/kg*g for pellets), that will adapt to the soils to which it is added.

Table 1. Chemical - physical characterization of initial Poultry manure and final biofertilizer pellet

Parameter	***Measure unit***	***PM F 1 t=0***	***PM F 2 t=0***	***PELLET 1 t=100 d***	***PELLET 2 t=100 d***
pH		6.89	7.33	7.50	7.53
CE	mS/cm	4.19	4.00	3.56	3.52
Humidity	%	48.14	32.74	16.58	14.43
Organic Matter	% DM	79.38	79.73	72.34	75.78
TOC	g/100g	36.62	37.44	33.63	38.78
Cws	g/100g	7.94	8.15	8.24	8.61
Chumic	g/100g	4.80	6.27	7.74	8.32
Ntot	g/100g	6.11	3.53	5.62	4.74
Nws	g/100g	1.62	1.50	1.48	1.34
P2O	g/100g	1.95	2.09	1.99	1.64
$Pwsol^-$	g/100g	-	-	0.22	0.18
Ktot	g/100g	1.57	1.94	1.42	1.64

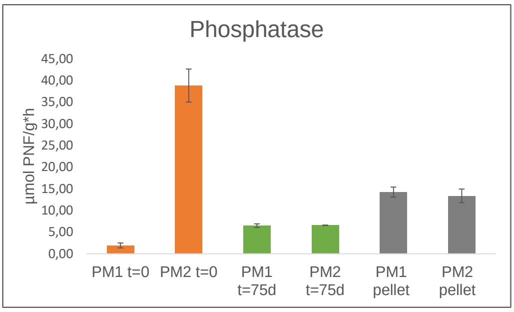
Final fertilizers are very rich in Organic Matter in both cases, with all nutrients and micronutrients (data not shown) to prevent deficiencies of elements that can affect production. Special features are connected to P: it contains about 2% of P_2O_5, mainly in the struvite form, which has low hydrosolubility but is available for plants, so that to reduce leakage; furthermore, there is phosphatase, a group of enzymes that catalyse the hydrolysis of esters and anhydrides of phosphoric acid, releasing inorganic P and phosphate ions, assimilable by plants. This can improve soil P availability, to reduce input needs for P, a critical raw material (4) (CRM).

a)

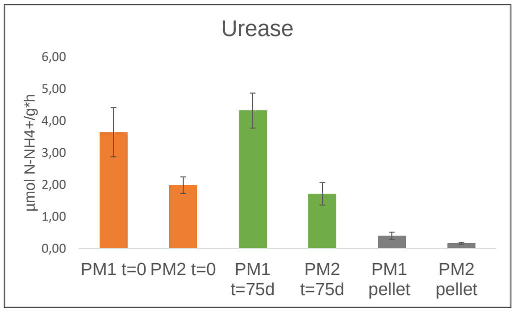


b)

Fig. 2. Biofertilizer pellets a) and b) Temperature evolution during first 50 days treatment



a)



b)

Fig. 3. Evolution of main enzymatic activities a) Phosphatase and b) Urease for PM1 from laying hens' manure and PM2 from broiler litter

6. Conclusion

The final organic fertilizer/biostimulant POLLINA PAV, obtained through a low-energy circular economy process, represents a sustainable and regenerative alternative to conventional fertilizers. Its high content of stable organic matter, enzymatic activity, and balanced nutrient profile supports the fundamental pillars of Regenerative Agriculture (RegenAg) by fostering soil regeneration, enhancing biodiversity, and improving soil physical and biological fertility, while simultaneously reducing greenhouse gas emissions and dependency on synthetic fertilizers.

The product contributes to the long-term restoration of soil health by stimulating microbial communities and promoting efficient nutrient cycling, particularly of nitrogen and phosphorus through biological mineralization and enzymatic activation. Its dual functionality as a nutrient source and biostimulant enables gradual nutrient release, reduced leaching risks, and improved soil structure and water retention capacity. These properties translate into resilient agroecosystems capable of maintaining productivity with reduced external inputs.

To consolidate these results, field-scale validation is essential to monitor nutrient release dynamics, crop productivity, and soil biological responses across different pedoclimatic conditions and cropping systems. Such studies should integrate life cycle, carbon footprint, and biodiversity assessments, as well as the evaluation of carbon credit generation potential, thus linking soil improvement practices to measurable environmental and economic benefits.

Moreover, incorporating POLLINA PAV within RegenAg-oriented business models aligns with the transition toward sustainable competitiveness, an agricultural paradigm where profitability derives not only from yield but also from ecological integrity, carbon sequestration, and reduced input dependency. In this perspective, soil health becomes a strategic asset for both farm resilience and environmental stewardship, reinforcing the convergence between circular economy and regenerative agriculture for a truly sustainable food system.

References

Dall'Ara A., (2025), *Biostimolante edafico organico naturale. Procedimento di preparazione e suo uso per migliorare la disponibilità di nutrienti confinati nel suolo*, Italy, Patent Application No. IT102025000008460. Available at: https://esdac.jrc.ec.europa.eu/euso; https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials.

Drozdz D., Wystalska K., Malinska K., Grosser A., Grobelak A., Kacprzak M., (2020), Management of poultry manure in Poland – Current state and future perspectives, *Journal of Environmental Management*, **264**, 110327.

LIFE POREM, (n.d.), *Handbook – New strategies for better soil management via remediation with poultry manure-based bioactivator*, On line at: https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE17-ENV-IT-000333/poultry-manure-based-bioactivator-for-better-soil-management-through-bioremediation.

Strafella A., Salernitano E., Bezzi F., Delise T., Leoni E., Magnani G., Dall'Ara A., Folini T., Dradi D., Fontana F., Minerva N., (2021), The POREM bio-activator as a solution for degraded soils: Results of first Italian trial, *Environmental Engineering and Management Journal*, **20**, 1673–1681.

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ECO-SUSTAINABLE PHOTOLUMINESCENT EPOXY COMPOSITES INCORPORATING ETNA VOLCANIC ASH AS A NATURAL WASTE FOR DECORATIVE BUILDING APPLICATIONS*

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Abstract

This research presents the development of composite materials based on epoxy resin, enriched with volcanic ash from Mount Etna and photoluminescent additives, intended for decorative applications in the construction sector. The dual objective is to repurpose a naturally abundant by-product, often treated as waste and to promote sustainable and functional solutions for contemporary architecture. Experimental formulations incorporated both raw and ground volcanic ash, highlighting how particle size directly influences the photoluminescent properties of the materials. Notably, untreated and non-powdered ash proved more effective in maintaining luminous intensity.

The integration of volcanic ash increases the overall mass of the composite while reducing the amount of polymer required, enhancing production efficiency and supporting a circular approach. The developed prototypes, in the form of mosaic tiles, demonstrate the ability to store solar energy and release it in low-light environments, contributing to passive illumination. The innovation lies in the synergy between natural resources and low-impact technologies, opening new perspectives for eco-compatible building materials and responsible design.

Keywords: architectural materials, circular economy, epoxy composites, photoluminescence, volcanic ash

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1. Introduction

The construction sector, long scrutinized for its environmental impact, is now undergoing a transition toward more sustainable practices and innovative technologies. With nearly 39% of global CO_2 emissions attributed to the building industry, there is an urgent need to rethink the materials used and the production processes, favoring solutions that reduce the consumption of natural resources and promote circular economy approaches. Several recent studies have confirmed the effectiveness of recycled, bio-based, and industrial by-product materials in improving the environmental performance of construction products (Iluyomade and Okwandu, 2024; Saini and Ledwani, 2024; Wu et al., 2025). The increasing use of fly ash, reclaimed wood, volcanic soils, and functional pigments is finding applications in coatings, concretes, adhesives, and decorative components. Creative reuse of residual materials has also been explored using multilayer composites such as Tetra Pak in insulating panels, employing heat-based processes without traditional chemical binders (Buonocore and De Luca, 2022). Recent contributions have also emphasized the potential of agricultural and food-processing residues in green building applications, such as the recovery of vegetable fibers from licorice waste for use in sustainable composites (Madeo et al., 2025)

Moreover, Loise et al. (2024) demonstrated the functional value of bio-additives derived from agricultural residues in modifying the rheology of bitumen, with tangible improvements in mechanical performance and durability. Volcanic ash plays an especially promising role in this context. As a natural material rich in silica, it has been the subject of numerous academic studies for its pozzolanic and structural potential. López Gómez and Cultrone (2025) highlighted its effectiveness in producing improved clay bricks, while Bernardo et al. (2022) developed porous glass-ceramics by combining Etna ash with glass waste, yielding results notable for strength and lightness. Cascone et al. (2025) explored its use in green roofs, showcasing properties such as water retention and thermal regulation. These contributions support the transformation of volcanic ash from environmental burden to functional resources within circular construction systems. In parallel, photoluminescent materials, capable of absorbing and re-emitting visible light in darkness without electric power are gaining ground in building and urban environments, where energy efficiency, nighttime visibility, and aesthetics converge. The synthesis of advanced compounds such as $SrAl_2O_4$: Eu^{2+}/Dy^{3+} has enabled persistent luminescence lasting up to 12 hours, and according to DataIntelo (2025), the global market for photoluminescent products is expected to exceed $1.4 billion by 2032. Rodionova et al. (2024) showed how these materials enhance not only visibility but also aging resistance, due to photon interaction with microstructural features. This research builds on these perspectives by developing a composite material based on epoxy resin, Etna volcanic ash, and photoluminescent additives.

The objectives include characterizing luminous properties, assessing the effect of volcanic ash, identifying decorative applications for both indoor and outdoor environments, and evaluating the contribution of this technology to sustainable building practices. The proposed approach aims to create innovative, high-performance, and environmentally responsible materials aligned with current advances in construction research.

2. Materials and methods

2.1. Materials

The materials used in this experiment are described below.

2.1.1. Etna Volcanic ash

The volcanic ash used in this study originates from the eruptions of Mount Etna, one of the most active volcanoes in Europe (Fig.1a). Below is reported the grain size distribution curve of the volcanic ash used (Fig.1b).

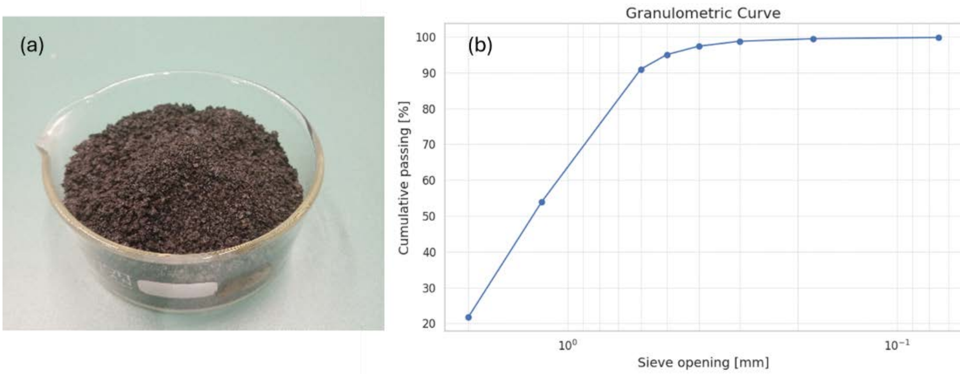

Fig. 1. (a) Sample of volcanic ash from Mount Etna; (b) Particle size distribution curve of the volcanic ash sample

The granulometric curve reveals a well-graded soil material, characterized by a smooth and continuous increase in cumulative passing percentage, indicating a wide range of particle sizes. Fine fractions dominate the composition: over 90% of the sample passes through the 0.60 mm sieve, suggesting a significant presence of fine sand and silt. Coarse gravel components are minimal, as only 21.76% of the material passes through the 2.00 mm sieve. A steep segment of the curve between 1.20 mm and 0.60 mm reflects a high concentration of particles within that size range. Overall, the curve is regular and uninterrupted, with no abrupt horizontal or vertical sections, which confirms that the material is well-graded and not uniform or single-sized. The soil sample can be classified as a well-graded fine sand, with a continuous particle size distribution and minimal coarse content. This type of material is generally suitable for engineering applications where good compaction and moderate permeability are required. Some samples were prepared not only using the raw volcanic ash, but also with the same ash finely ground using a Pulverisette Reset (Fig. 2a) to achieve a more uniform and controlled particle size distribution (Fig. 2b).

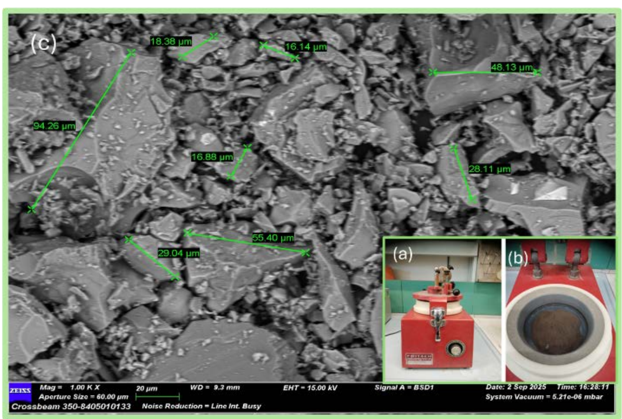

Fig. 2. (a) Mill used for grinding volcanic ash (Pulverisette); (b) Volcanic ash after the milling process; (c) SEM images of ground volcanic ash powder after milling

As a result of the milling process, the volcanic ash powder was reduced to a particle size below 100 µm (Fig. 2c). This approach was adopted to assess the influence of particle size on the material's physicochemical properties, particularly its reactivity and its ability to interact with other components in the mixture.

2.1.2. Epoxy resin

The resin used in this study is a two-component epoxy resin produced by Colorpoint, designed for decorative, technical, and artistic applications on both horizontal and vertical substrates. The product consists of two separate components: Part A (base resin) and Part B (hardener), which must be mixed in a stoichiometric ratio of 100:60 by weight to ensure proper cross-linking and the desired chemical-mechanical properties (Fig 3 a). After mixing, the resin has a fluid, self-leveling consistency, with a working time of approximately 30–40 minutes at room temperature (22 ± 2 °C). Curing occurs gradually, with initial hardening after about 24 hours and full cross-linking completed within 7 days.

The formulation is characterized by:

- High transparency and glossy finish, suitable for artistic casting and protective coatings;
- Excellent adhesion to mineral, metal, and polymeric substrates;
- Chemical resistance to oils, detergents, diluted acids, and atmospheric agents;
- Dimensional stability and high surface hardness once cured;
- Compatibility with pigments and additives, including photoluminescent types, without significantly altering mechanical performance.

The mixture was prepared manually for approximately 3–5 minutes, until a homogeneous compound free of visible air bubbles was obtained. The resulting resin was used for the fabrication of test specimens, poured into pre-defined silicone molds and allowed to cure in a controlled environment (22 ± 2 °C; 50% relative humidity) for a minimum of 72 hours before characterization procedures.

2.1.3. Phtotoluminescent powder

The photoluminescent powder ZYYINI-MYX-RAG-JM04576-03-FBA, produced by Shenzhen Yibai Network Technology Co., Ltd., represents a solution for passive and decorative lighting in various sectors. It is formulated based on strontium aluminate, enriched with trace-level dopant elements, such as europium (Eu) and dysprosium (Dy), which are commonly used to enhance the efficiency and persistence of light emission. This powder can store luminous energy, either from sunlight or artificial sources and gradually release it in the dark, producing a persistent photoluminescent effect that lasts for hours (Fig. 3 b-c). It is non-toxic, non-radioactive, and classified as environmentally friendly, making it suitable for use in public and residential environments.

SEM-EDS analysis (Fig. 4) reveals compositional inhomogeneity across different areas of the sample, with the presence of elements such as Si, Al, Na, Mg, K, Ca, Cu, and notably strontium (Sr) peaks, confirming the strontium aluminate matrix. However, signals attributable to the dopant elements are not clearly visible, likely due to their low concentration and the limited sensitivity of EDS analysis in detecting trace elements, especially those with high atomic numbers or overlapping spectral lines. Nevertheless, the presence of strontium and the material's photoluminescent properties strongly suggest the inclusion of active dopants, such as Eu and Dy, known for their effectiveness in imparting stable and long-lasting luminescent characteristics.

Fig. 3. (a) Epoxy system composed of resin (Part A) and hardener (Part B); (b) Photoluminescent powder; (c) Photoluminescent powder exhibiting visible luminous activity under light exposure

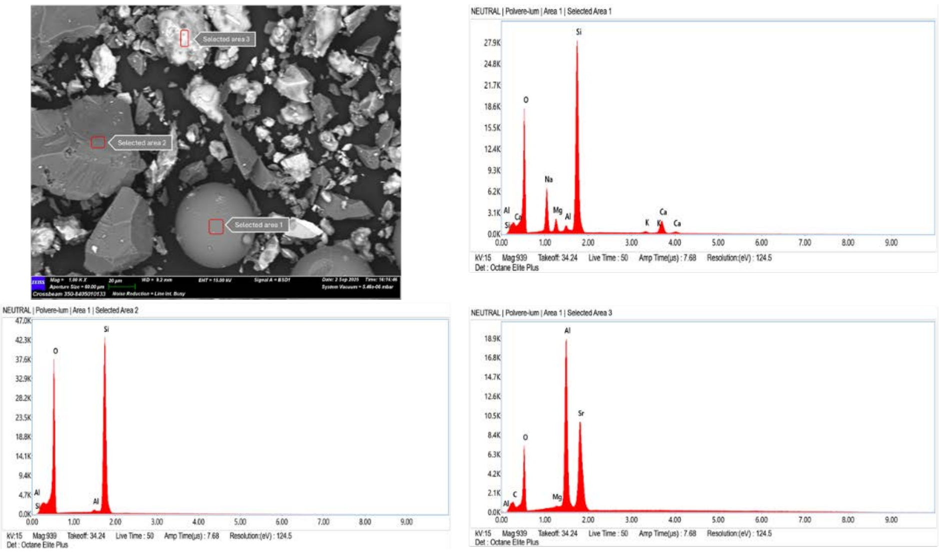

Fig. 4. Morphological and compositional characterization (SEM-EDS) of photoluminescent powder

2.2. Preparation of samples

The samples were prepared by varying the amount of volcanic ash within the polymer matrix. For each sample, predetermined quantities of the epoxy system components, resin (Part A) and hardener (Part B) were combined to obtain the base mixture. Subsequently, the programmed amounts of photoluminescent powders and volcanic ash were added to the blended resin. Two types of volcanic ash were used: untreated ash in its natural form, and ash that had been previously pulverized to reduce particle size. This allowed for the preparation of different sample sets, enabling a comparative evaluation of the influence of ash granulometry on the final composite properties. The mixture was subjected to mechanical stirring for 5 minutes to ensure homogeneous dispersion of the additives. Finally, the system was poured into silicone molds for the curing process (Fig. 5).

Fig. 5. Examples of specimens in silicone molds

Table 1 summarizes the compositions of the six samples developed to investigate the influence of volcanic ash and photoluminescent powders on the behavior of an epoxy-based matrix. In all cases, the epoxy system, consisting of 15 grams of resin (Part A) and 10 grams of hardener (Part B) was kept constant to ensure uniform conditions among the samples. The first sample serves as a control, containing neither volcanic ash nor photoluminescent powder, and provides a reference to observe the changes introduced in the other formulations. The second sample includes only the photoluminescent component, which allows its individual contribution to the material's final properties to be isolated. From sample three to sample six, the amount of volcanic ash increases progressively from 0.25 to 1 gram, while the photoluminescent powder remains constant at 1 gram. This gradual variation enables assessment of both the optical and structural effects of the mineral filler and helps to understand its interaction with the photoluminescent additives, offering insight into the quality of dispersion, processability, and mechanical performance of the cured material.

Table 1. Summary of the compositions of epoxy-based samples with varying amounts of volcanic ash and photoluminescent powder.

Sample	*Epoxy base resin (Part A) [g]*	*Epoxy hardener (Part B) [g]*	*Milled volcanic ash [g]*	*Volcanic Ash as made [g]*	*Photoluminescent powder [g]*
1	15	10	-	-	-
2	15	10	-	-	1.00
3	15	10	0.25	-	1.00
4	15	10	0.50	-	1.00
5	15	10	0.75	-	1.00
6	15	10	1.00	-	1.00
7	15	10	-	10	-
8	15	10	-	5	1.00
9	15	10	-	10	1.00
10	15	10	-	15	1.00
11	15	10	-	10	3.00
12	15	10	-	10	5.00

2.3. Instruments

The materials were characterized by scanning electron microscopy, microanalysis (ESEM Quanta 200 FEG + EDS EDAX GENESIS 2000

3. Results and discussion

The images shown in Fig. 6 illustrate the photoluminescent effect of the samples after direct exposure to sunlight for 15 minutes.

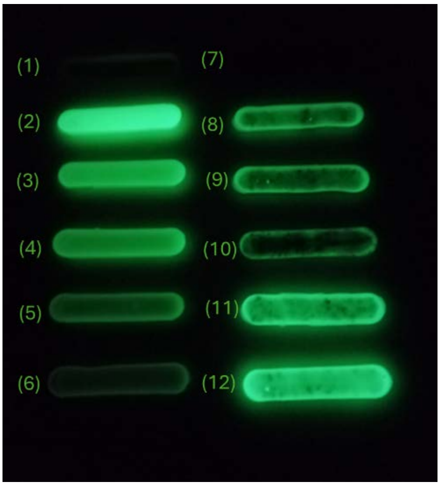

Fig. 6. Samples obtained from the different systems (1–12) after 15 minutes of exposure to sunlight and subsequently placed in darkness to evaluate residual photoluminescent effect.

Substantial differences can be observed among the various samples. Samples 1 and 7, which do not contain photoluminescent materials, show no luminous effect, as expected. However, a significant difference emerges, despite equal amounts of photoluminescent material between the samples containing pulverized volcanic ash (samples 2–6) and those made with untreated ash (samples 8–10). In the former, even small amounts of ground ash (0.25–1 g) progressively reduce the luminous effect. This occurs because the fine dispersion of ash within the polymer matrix blocks light penetration, causing a gradual decrease in luminescence.

Conversely, samples 8–10, made with untreated volcanic ash and therefore with a coarser grain size, demonstrate that much larger quantities of ash (5, 10, and 15 g) can be added without drastically compromising the luminous effect. Although luminescence decreases as the ash content increases, the effect remains visible. This behavior is particularly interesting because it allows for the use of a greater amount of natural material, turning an abundant and often discarded byproduct into a functional resource. In these cases, the ash does not disperse evenly but tends to settle at the bottom of the sample, leaving a surface layer rich in resin and photoluminescent material. This creates a sort of "glazing" effect that enhances light emission without significant shielding (Fig. 7).

The use of volcanic ash has proven advantageous not only from a technical standpoint but also from ecological and practical perspectives. Environmentally, its reuse helps reduce natural waste and promotes a sustainable approach to material design. Practically, incorporating volcanic ash also allows for an increase in the overall mass of the final product while reducing the amount of polymer required for its fabrication. This leads to savings in synthetic resources and greater production efficiency, without altering the photoluminescent properties of the material. Moreover, using a natural and readily available material like volcanic ash helps lower costs and simplifies the manufacturing process.

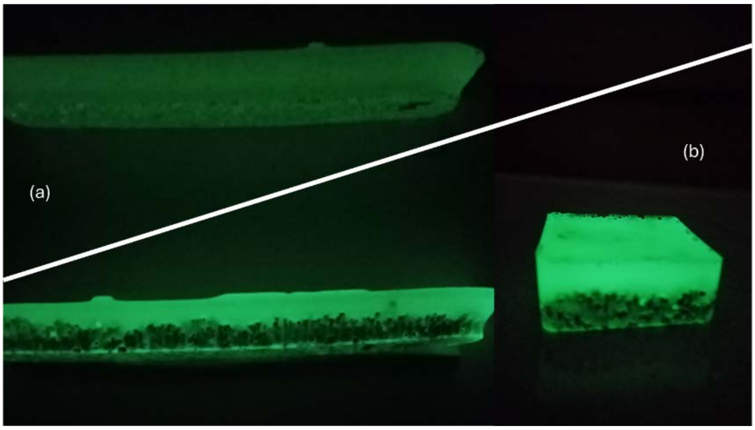

Fig. 7. Cross-section of samples made with (a) ground volcanic powder and (b) untreated volcanic powder, highlighting in the latter a marked sedimentation of the volcanic material at the bottom of the sample and the formation of a photoluminescent surface layer

Finally, samples 11 and 12, containing increasing amounts of photoluminescent powder (3 g and 5 g), show a proportional increase in luminous effect. This demonstrates that, with an optimized formulation, it is possible to balance a high presence of volcanic ash with strong photoluminescent performance, paving the way for smart, sustainable, and high-performing materials. Based on the systems explored, prototype mosaic tiles have been developed as a tangible application within the field of sustainable construction (Fig. 8). These decorative elements were designed not only for their aesthetic and functional qualities, but also to demonstrate how innovative and recycled materials can be integrated into responsible architectural solutions. A key role was played by volcanic ash, used both in its raw and ground form, which allowed for a reduction in the amount of polymer required while adding mass and texture to the material. This approach makes it possible to repurpose a widely available natural byproduct, lowering environmental impact and promoting a circular economy.

The resulting tiles exhibit solid mechanical properties and an appealing visual effect, even without artificial pigments. In some variants, photoluminescent powders were also incorporated, enabling the tiles to store solar energy and release it in low-light conditions, contributing to passive illumination. However, innovation lies not only in luminescence, but in the smart combination of natural resources and low-impact technologies, paving the way for new possibilities in eco-friendly architecture.

These prototypes show how sustainability, design, and functionality can be harmoniously combined, encouraging a construction model that rewards the reuse of local materials and the efficient harnessing of solar energy.

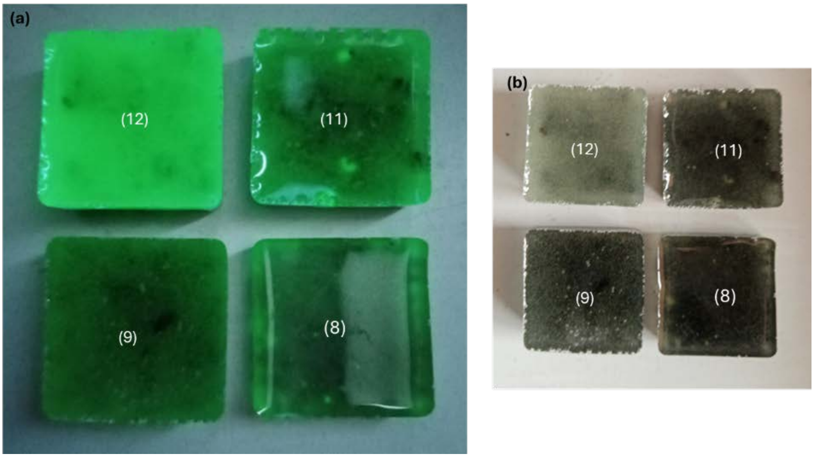

Fig. 8. Examples of prototype mosaic tiles produced using systems 8–12: (a) after exposure to light and subsequent placement in a dark environment, (b) in a non-excited state, with no photoluminescent activity

4. Conclusion

The results demonstrate that untreated volcanic ash, characterized by a coarser grain size than pulverized ash, exhibits superior performance in photoluminescent composites. Its morphology promotes the natural formation of a transparent, glass-like surface layer during sedimentation, which allows the passage of light and preserves the intensity and persistence of the photoluminescent effect. This structural configuration enhances both visual performance and material homogeneity, confirming that particle size plays a decisive role in optical behavior and energy storage capacity.

In addition to the functional advantages, the use of untreated volcanic ash increases the overall mass of the composite and reduces the polymer content, resulting in environmental and economic benefits. This approach minimizes synthetic resin consumption, lowers production costs, and valorizes a locally abundant natural byproduct, aligning with the principles of circular economy and sustainable design. The reuse of volcanic ash also contributes to waste reduction and resource efficiency, integrating environmental responsibility into material innovation.

The ability to modulate the granulometry of volcanic ash and the proportion of photoluminescent powder offers a versatile platform for developing smart, eco-sustainable, and multifunctional composites. These materials combine structural reinforcement, aesthetic value, and passive illumination, with potential applications in construction, urban furnishing, architectural design, and interior decoration. Their capacity to store and re-emit light without energy input supports low-impact solutions for nighttime visibility and decorative purposes.

Future research should focus on the mechanical, durability, and aging behavior of these composites under real environmental conditions, as well as on scaling up their production for industrial applications. Integrating life-cycle and techno-economic analyses would further demonstrate their viability within the framework of sustainable architecture. The synergy between natural raw materials and functional photoluminescent technology thus represents a promising pathway toward the next generation of circular, aesthetically innovative, and energy-conscious building materials.

References

Bernardo E., Cedro R., Fioretti M., (2022), Porous glass-ceramics from volcanic ash and glass waste via low-temperature alkali activation, *Journal of Non-Crystalline Solids*, **589**, 121678–121685.

Buonocore G., De Luca P., (2022), Preparation and characterization of insulating panels from recycled polylaminate (Tetra Pak) materials, *Sustainability*, **14**, 6858–6872.

Cascone S., Fazio F., Saeli M., (2025), Volcanic ash as substrate for extensive green roofs: A Sicilian case study, *Journal of Environmental Management*, **328**, 116993–117004.

DataIntelo Research Team, (2025), *Photoluminescent Products Market Report: Global Forecast 2025–2033*, DataIntelo, 1–250.

Iluyomade T.D., Okwandu A.C., (2024), Innovative materials in sustainable construction: A review, *International Journal of Science and Research Archive*, **12**, 2435–2447.

Loise V., Abe A.A., Porto M., Muzzalupo I., Madeo L., Colella M.F., Oliviero Rossi C., Caputo P., (2024), Plant waste-based bioadditive as an antioxidant agent and rheological modifier of bitumen, *Materials*, **17**, 2303, https://doi.org/10.3390/ma17102303.

López Gómez M., Cultrone G., (2025), Physico-mechanical properties and decay susceptibility of clay bricks after the addition of volcanic ash from La Palma (Canary Islands, Spain), *Sustainability*, **17**, 6545–6563.

Madeo L., Macario A., Candamano S., De Luca P., (2025), Recovery of vegetable fibers from licorice processing waste and a case study for their use in green building products, *Clean Technologies*, **7**, 55. https://doi.org/10.3390/cleantechnol7030055.

Rodionova I., Kolesnikova A., Smirnova N., (2024), Photoluminescent pigments in polymeric building materials: Aging resistance and luminous performance, *Materials*, **17**, 2303–2317.

Saini H., Ledwani L., (2024), A review on application of green materials in different construction systems, their processing, surface modification, testing and certification, *MRS Energy & Sustainability*, **11**, 267–303.

Wu Y., Zhang Y., Li H., (2025), Recycled materials in construction: Trends, status, and future perspectives, *Sustainability*, **17**, 2636–2658.

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ADVANCING CIRCULAR CONSTRUCTION THROUGH INNOVATIVE BIO-BASED MATERIALS AND DIGITAL PRODUCT PASSPORT*

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Abstract

In response to the dual challenge of ecological and digital transition outlined by European strategies, this research explores industrial symbiosis as a systemic lever for innovation, competitiveness, and resource efficiency in the construction sector. The project addresses structural barriers to circularity, such as raw materials consumption, long and fragmented supply chain, lack of product traceability, and limited circular knowledge among stakeholders' value chain, through a combined technological approach: the development of a local, bio-based building block and the implementation of a Digital Product Passport (DPP) platform. The development of an innovative bio-block, composed of lime, hemp, and locally sourced agro-waste, demonstrates how circular practices can be easily implemented from a technical point of view. While adopting a DPP platform for centralizing product lifecycle data and making it accessible through digital interfaces reveals how digital tools can become crucial to enable product traceability, regulatory alignment, and increase stakeholder engagement. By integrating material innovation with life cycle data management infrastructure, this research exemplifies how industrial symbiosis can be promoted and fostered by digital tools. The findings underscore the need for standardized data protocols, cross-sector collaboration, and targeted education to scale these solutions and contribute to a more resilient and climate-neutral industrial ecosystem.

Keywords: bio-based construction, circular economy, digital product passport, innovation, twin transition,

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1. Introduction

The European Union is spearheading a "Twin Transition" aimed at fostering a greener, more circular, and digital economy (European Commission, 2020a). Within this framework, the construction sector has been identified as a strategic domain for implementing this transition, given its considerable economic weight and environmental footprint. Indeed, the construction and building industry is responsible for approximately 50% of all raw material extraction, nearly 40% of total waste generation in the EU (Eurostat, 2023) and contributes between 5% and 12% of national greenhouse gas (GHG) emissions (European Commission, 2020b). In this context, the Circular Economy Action Plan (European Commission, 2020c) strongly promotes the integration of bio-based materials through industrial symbiosis strategies, aiming to reduce the carbon intensity of construction inputs and mitigate the uncontrolled generation of construction and demolition (C&D) waste. Enhancing material efficiency within the construction sector could potentially reduce GHG emissions by up to 80% (European Commission, 2020b).

Moreover, increasing the rate of preparation for reuse and "high-quality" recycling of C&D waste to the current technologically achievable threshold of 83% across the EU would result in annual savings of 33 million tonnes of CO_2 equivalent - surpassing the combined yearly emissions of Estonia, Latvia, and Luxembourg (JRC, 2025). Despite awareness of these benefits, the market penetration of bio-based products in the construction sector remains slow, limited to specific niche markets, and hindered by several barriers. These include a highly fragmented supply chain, unclear legislation, process inefficiencies, non-monetization of environmental impacts, and a low propensity among industry stakeholders to adopt innovative products (Bhavsar et al., 2023; Ghisellini et al., 2024; Mazzoni and Losacker, 2024). Within this landscape, the issue of supply chain traceability emerges as a pivotal enabler for circular value chains, underpinning the certification and quality assurance of materials and supporting the evolution of a new paradigm in sustainable and circular design (Davari et al., 2023; Giovanardi et al., 2023).

To address these challenges, the EU is promoting advanced digital technologies to enhance product and process traceability, thereby supporting more efficient and circular resource management. The Ecodesign for Sustainable Products Regulations (EC, 2024) identifies the Digital Product Passport (DPP) as a pivotal tool to guide the Circular Economy (CE) transition, including within the construction sector. By accessing key life cycle product information, stakeholders - whether manufacturers, builders, managers, or end-users - could easily retrieve data on material composition, supply chain, reuse and repair guidelines, and instructions for disassembly, disposal, recycling, and repurposing.

Building on these premises, the EU-funded project DIGI4BIOMAT explores both opportunities and challenges of the Twin Transition through a real-world case study focused on the development of a new hemp-based bio-block supported by a DPP. This dual approach is designed not only to validate a high-performance bio-based product but also to establish a transparent, data-driven ecosystem that enables a truly circular business model. The DPP is conceived as a dynamic tool capable of collecting and organizing product life cycle data by different companies to actively support the implementation of circularity across all actors involved in the product's value chain. This interpretation of the DPP goes beyond its basic function as a static repository for declarations of conformity and performance of construction products, positioning it as a strategic asset for companies engaging with emerging regulatory frameworks such as the EU Taxonomy, Environmental, Social, and Governance (ESG) reporting, and voluntary sustainability product certification.

This article is organized as follows: after the "Objectives" and "Outline of the work" sections, which outline the general aims of the DIGI4BIOMAT project, the methodology adopted for the development of the research and the case study are presented. The "Results and Discussion" section will focus primarily on the innovative aspects of the proposed combined approach, paving the way in the "Conclusions" for reflections on the theme of CE transition in construction and the next steps to be taken in this direction.

This study aims to achieve a set of objectives designed to drive both technological and circular business innovation within the construction industry, specifically:

- to develop an innovative bio-based building block using 100% natural materials, including locally sourced agro-waste like olive stones and almond shells, as partial replacements for traditional aggregates;
- to clarify the information flows required to characterize a bio-based construction product throughout its entire life cycle;
- to design a DPP platform that centralizes product life cycle data to enhance transparency, traceability, and stakeholder collaboration for bio-based products;
- to pave the way for innovative circular business models by providing data-driven insights for decision-making, sustainability reporting, and supply chain management.

This research is divided in two main parts:

- Part A: case study analysis for the development of a bio-based building block. This section of the project is dedicated to the in-depth examination of a case study concerning the development and production of an innovative bio-based construction block. The objective is to identify and critically assess the key phases of the production process, with particular attention to the technical and operational challenges that may arise. The analysis begins with the systematic characterization of the raw materials - specifically agro-industrial by-products such as olive stones and almond shells - used as natural alternative aggregates. Their physical and mechanical properties were evaluated to determine suitability for integration into the composite matrix. Subsequently, a series of mix-designs was formulated to optimize the combination of these novel aggregates with hemp and lime, aiming to preserve workability while achieving mechanical performance and density comparable to conventional hemp-based blocks. Beyond the technical validation, this phase also includes a replicative effort to map the process workflow, highlighting critical bottlenecks, decision points, and the nature of information exchange required among stakeholders involved in the production chain.
- Part B: design and implement a DPP platform. Building on the findings from Part A, where the life cycle of the bio-based construction block was mapped and key information gaps were identified, this section focused on the creation of a digital infrastructure to enhance product and process traceability. The goal was to implement a DPP platform capable of capturing, managing, and sharing product- related data across the entire value chain. The platform was designed to enable circular data flows, from raw material sourcing through manufacturing, usage, reuse, and end-of-life. It integrates hardware components for automated data collection and software modules for data visualization, traceability, and interoperability with existing systems. This ensures that all stakeholders, from producers to end-users, can access reliable and actionable information. A beta version of the platform was developed and tested with manufacturing companies to validate its technical performance and usability.

2. Materials and methods

The case study focuses on a bio-based materials company located in Apulia, Southern Italy, actively engaged in the development of sustainable construction products. The company's research initiative aims to reduce reliance on conventional mineral aggregates and imported hemp, the latter of which contributes significantly to the overall carbon footprint due to long-distance transportation. In response to these environmental concerns, the project was structured around the development of a bio-based block, designed to meet structural and thermal performance standards while minimizing environmental impact. To achieve this, the company investigated alternative aggregates derived from agro-industrial by-products, such as olive stones and almond shells, which are locally available and offer promising mechanical and ecological characteristics. These materials were selected not only for their potential to replace traditional aggregates but also to reduce the proportion of hemp required in the mix, thereby enhancing the regional sustainability of the product.

The methodological framework adopted for the project was structured around four key phases:

- Materials and mix-design characterization: the bio-based block was developed using a mixture of lime, hemp fibers, olive stones, and almond shells. A comprehensive analysis of the physical, chemical, and mechanical properties of selected agro-waste aggregates was conducted following EN standards. This included granulometric distribution, bulk density, water absorption, and compressive strength, to assess their suitability for use in construction-grade composites.
- Process mapping and stakeholder analysis: a parallel effort was made to document the production workflow and identify critical decision points, information flows, and stakeholder interactions. This analysis was essential for supporting the subsequent development of a DPP and for guiding the design of the innovative circular business model.
- Platform development. The digital DD platform supporting the traceability and circularity of the bio-based block was developed using a user-centered design approach, combined with agile development cycles. The design process was informed by Design Science Research Methodology, which emphasizes iterative prototyping, problem relevance, and artifact evaluation. The platform integrates material data, production workflows, and environmental metrics to enable the creation of a DPP aligned with emerging EU regulatory frameworks.
- Validation with end users. Finally, to ensure the relevance and usability of both the product and the digital platform, a validation phase was conducted involving key stakeholders from the construction and bio-materials sectors. The process followed principles of participatory design and employed methods such as semi-structured interviews, usability testing, and co-creation workshops. Feedback was analyzed using thematic coding and triangulated to refine both the physical product and the digital interface. This approach aligns with established validation frameworks such as the User Acceptance Test (UTA).

2. Results and discussion

The DIGI4BIOMAT project achieved substantial progress in the development of bio- based building block, designed to meet both environmental and performance criteria. The final formulation, which incorporated locally sourced agro-industrial by-products such as olive stones and almond shells, demonstrated a 30% improvement in thermal insulation and a 10% increase in compressive strength compared to conventional hemp-lime blocks. These results were validated through standardized laboratory testing and confirmed during industrial-scale prototyping, indicating the successful scalability of the material and its compatibility with existing production technologies (Fig. 1).

In addition to improved technical performance, the use of regional waste materials contributed to a significant reduction in the environmental footprint of the product. Preliminary estimates suggest the potential to divert up to 500,000 tons of organic waste annually from landfills in the Apulia region, thereby supporting local CE strategies and reducing dependency on imported hemp, which is associated with considerable transport- related emissions. However, the most transformative result of the project lies in the development and role of the DPP platform. The DPP platform enables bio-block manufacturers to consolidate and manage all relevant product-related information in a single, structured, and safety data environment.

Fig. 1. Some images of the bio-block prototype produced and test (courtesy of PEDONE Srl)

This includes information on raw material sourcing, supply chain composition, product declaration and conformity, technical specifications, product and process certification, and guidelines for correct transportation, installation, use, maintenance, and end-of-life treatment. By centralizing this information, the DPP platform facilitates the creation of a complete and verifiable digital identity for each product batch, which can be accessed and updated throughout its life cycle.

To enhance accessibility and usability, the platform incorporates guided data entry modules that assist users in the manual input of information. These modules are designed to reduce errors, improve data consistency, inform users about regulations, and lower the technical barrier for adoption, particularly among small and medium-sized enterprises. Additionally, the platform supports the generation of QR codes linked to individual products, which can be physically applied to each product batch produced. These codes provide public access to selected product data, thereby improving transparency and facilitating communication with designers, contractors, and end-users.

The integration of the DPP platform into the production and commercialization process of bio-based construction materials yielded several strategic benefits, which are discussed below:

- Enhanced traceability and certification readiness. The structured and centralized documentation of product attributes and supply chain data simplifies the certification process and strengthens quality control mechanisms, especially for bio- based products. Furthermore, the availability of detailed lifecycle data facilitates the rapid generation of Life Cycle Assessment (LCA) reports, enabling accurate quantification of environmental impacts and supporting compliance with sustainability standards.
- Operational efficiency and error reduction. The digitization of documentation workflows significantly reduces the time and errors associated with manual data management. This leads to improved operational efficiency, particularly in the handling of regulatory and certification procedures, and reduces administrative burdens for manufacturers and stakeholders.
- Transparent communication of product performance. The platform enables clear and detailed dissemination of product specifications and performance metrics to designers,

architects, and end-users. This transparency supports informed decision- making and promotes the adoption of bio-based materials in construction projects.

- Configurable sustainability through supplier selection. The ability to register and compare suppliers within the platform allows producers to configure their supply chains in a way that minimizes environmental impact. For example, selecting a hemp supplier with lower transport emissions or more sustainable cultivation practices directly influences the overall footprint of the final product. This feature supports the development of adaptive and responsive circular business model.

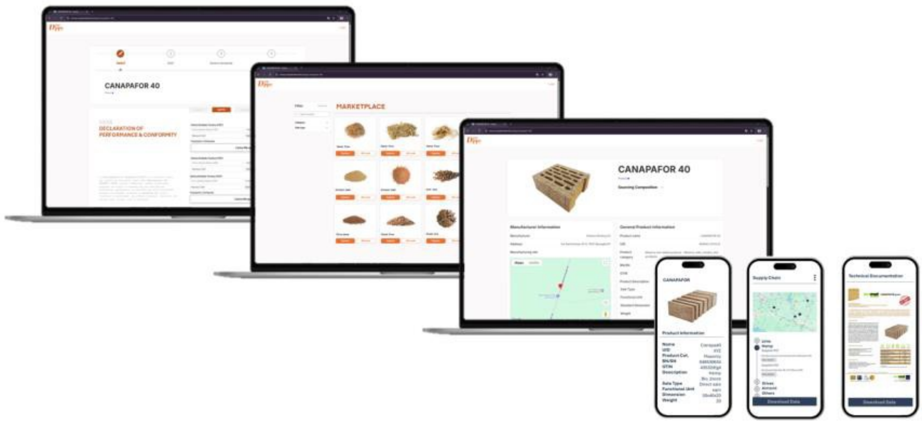

Fig. 2. DPP platform (DeePPy platform developed by Levery)

3. Concluding remarks

The DIGI4BIOMAT project has demonstrated a robust and replicable framework for advancing the Twin Transition - toward both ecological and digital transformation - within the construction sector. Through the successful development of a high-performance bio- based building block derived from locally sourced agricultural residues, the project provides a concrete response to the environmental challenges posed by conventional building materials. The use of regional agro-waste not only enhances material circularity but also contributes to reducing the carbon footprint associated with long-distance transport of imported resources such as hemp.

Crucially, the integration of this material innovation with a web-based DPP platform marks a significant step forward in enabling traceable, transparent, and data-driven circular construction practices. The DPP platform serves as a central repository for product lifecycle information, encompassing supply chain data, technical specifications, certifications, and end-of-life guidelines. It empowers manufacturers to assess and configure their supply chains based on environmental impact, facilitates regulatory compliance, and enhances communication with stakeholders through accessible digital interfaces such as QR codes. This digital infrastructure supports the operationalization of circular business models, particularly those focused on material recovery, reuse, and life extension.

The findings of the project underscore that the convergence of physical product innovation and digital traceability is essential to unlocking the full potential of CE principles in the built environment. However, the research also reveals persistent barriers to widespread adoption. Among these, limited standardization of data protocols and low cultural readiness for systemic change remain critical challenges. Addressing these issues will require coordinated efforts across industry, policy, and research domains.

Awaiting developments in the regulatory framework regarding the mandatory adoption of the DPP for construction products, future replication and scaling of the DIGI4BIOMAT model will depend on sustained collaboration among technology developers, regulatory bodies, and construction stakeholders.

Investments in digital infrastructure, stakeholder education, and harmonization of data standards will be necessary to support the transition toward a more resilient, transparent, and sustainable construction ecosystem. The project thus offers not only a technical proof of concept but also a strategic roadmap for embedding circularity into mainstream construction practices.

Acknowledgements

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References

Bhavsar V., Sridharan S.R., Sudarsan J.S., (2023), Barriers to circular economy practices during construction and demolition waste management in an emerging economy, *Resources, Conservation & Recycling Advances*, **20**, 200198, https://doi.org/10.1016/j.rcradv.2023.200198.

Davari M., Jaberi A., Yousfi E., Poirier E., (2023), A traceability framework to enable circularity in the built environment, *Sustainability*, **15**, 8278, https://doi.org/10.3390/su15108278.

EC, (2020a), *A New Industrial Strategy for Europe*, COM/2020/102, European Commission, Brussels, On line at: https://commission.europa.eu/document/a0dfe54f-f8bb-46f7-8828-d58c1cd8efa8_en

EC, (2020b), *A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*, European Commission, Brussels, On line at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

EC, (2020c), *Circular Economy Action Plan: The European Green Deal*, Publications Office of the European Union, Luxembourg, On line at: https://data.europa.eu/doi/10.2775/458852.

EC, (2024), Regulation (EU) 2024/1781 of the European Parliament and of the Council of 18 July 2024 on ecodesign for sustainable products and repealing Directive 2009/125/EC, *Official Journal of the European Union*. On line at: https://eur-lex.europa.eu/eli/reg/2024/1781/oj/eng

Eurostat, (2023), *Waste Statistics*, January 2023, European Commission, Brussels, On line at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics.

Ghisellini P., Quinto I., Passaro R., Ulgiati S., (2024), Bio-based products for a more sustainable construction sector: Technical, environmental and social performance and impacts, *Procedia Structural Integrity*, **64**, 1689–1695.

Giovanardi M., Konstantinou T., Pollo R., Klein T., (2023), Internet of things for building façade traceability: A theoretical framework to enable circular economy through life-cycle information flows, *Journal of Cleaner Production*, **382**, 135261, https://doi.org/10.1016/j.jclepro.2022.135261.

JRC – European Commission, (2025), *Delivering the EU Green Deal: Progress Towards Targets*, Publications Office of the European Union, Luxembourg, On line at: https://publications.jrc.ec.europa.eu/repository/handle/JRC140372.

Mazzoni F., Losacker S., (2024), What hinders the transition towards a bio-based construction sector? A global innovation system perspective on its value chain, *Progress in Economic Geography*, **2**, 100023, https://doi.org/10.1016/j.peg.2024.100023.

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A DIGITAL TWIN APPROACH TO ENHANCING WATER INFRASTRUCTURE MANAGEMENT: THE CASE OF CONSORZIO DI BONIFICA 3 MEDIO VALDARNO*

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Abstract

The Consorzio di Bonifica 3 Medio Valdarno offers a concrete and significant example of how the Digital Twin paradigm can be effectively adopted and implemented in the management of water infrastructures. Through the development of an advanced integrated remote-control system based on SCADA architecture, the Consortium has created a complete and intelligent digital ecosystem designed to monitor, control, and optimize the performance of its hydraulic assets distributed over a vast territorial area. This system consists of a diversified and synergistic network of pumping stations, each equipped with local automation and remote supervision functions, motorized sluice gates for regulating flood retention basins, hydrometric sensors, and clapet valves connected via IoT. These components, interconnected through secure communication protocols, form a reactive and interactive digital environment that mirrors the physical infrastructure in real time.

The resulting Digital Twin enables on-call technical teams to observe system behavior, detect anomalies, and make quick, data-driven decisions, particularly during critical flood events, when timely interventions are essential to reduce risks. A key strength of the system lies in its modularity and scalability. The Digital Twin is not a static representation, but a continuously evolving model, enriched by the integration of new peripheral devices installed in the field. These devices not only improve the automation and monitoring of specific hydraulic elements, but also contribute to a broader and more integrated understanding of the entire hydraulic network. This ongoing evolution allows for more in-depth analysis of the interactions and interdependencies among assets, thus enhancing both predictive capabilities and coordination of emergency interventions. In addition to real-time monitoring and remote-control functions, the Consortium has also adopted an advanced asset management platform that supports field operations and facilitates the maintenance of hydraulic infrastructure. The platform is designed to ensure that every maintenance activity, preventive or corrective is digitally recorded, uniquely identified, signed, and securely archived. The system improves transparency, traceability, and regulatory compliance, creating a digital archive that can be consulted for audit purposes, planning, and strategic

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decision-making. Overall, the integration of SCADA systems, IoT technologies, and structured asset management tools represents an example of how the Digital Twin approach can transform traditional water infrastructure into a resilient, intelligent, and adaptive system, capable of meeting the growing challenges posed by climate change, extreme weather events, and the increasing complexity of water management.

Keywords: asset management platform, Digital Twin, SCADA, water management

1. Introduction

Water resource management infrastructures today face unprecedented challenges linked to climate change, the increasing frequency of extreme weather events, and the growing complexity of urban and rural water needs. Traditional monitoring and control methods, often based on fragmented data sources and manual interventions, struggle to guarantee the level of responsiveness, precision, and operational efficiency required in this constantly evolving scenario. In this context, the adoption of advanced digital technologies has emerged as a key enabler to increase resilience, efficiency, and adaptability of water systems.

The Digital Twin paradigm, which creates a dynamic virtual replica of physical assets and processes, offers a transformative approach to integrating real-time monitoring, predictive analytics, and decision-support tools into the management of water infrastructure. Decision Support Systems (DSS) are now recognized as a fundamental tool in environmental management and planning (Giusti and Marsili-Libelli, 2014). By bridging the gap between field operations and centralized supervision, this approach fosters data-driven decision-making, optimizes resource allocation, and improves emergency response capabilities. The Consorzio di Bonifica 3 Medio Valdarno represents a concrete and significant case of effective Digital Twin implementation in the water sector, thanks to the use of SCADA-based architectures, IoT-connected devices, and structured asset management tools, with the goal of creating a complete and intelligent operational ecosystem. It can also optimize decision-making and emergency response capabilities through visual management to ensure system stability is quickly restored in the face of unforeseen events (Dui et al., 2025).

2. The Digital Twin paradigm in water management

The concept of a Digital Twin refers to a virtual, dynamic representation of a physical asset, continuously updated with real-time data and capable of simulating various operational scenarios (American Water Works Association, 2021; Ning et al., 2024). In water infrastructure, it goes beyond traditional monitoring, creating an integrated model that accurately mirrors the physical network and supports rapid, informed decision-making (Ghorbani Bam et al., 2025).

By connecting sensors, actuators, and control systems to a centralized platform through secure protocols, the Digital Twin transforms raw data into actionable operational information, combining real-time measurements, historical series, and predictive models (Grieves and Vickers, 2017). The main benefits include enhanced situational awareness, predictive maintenance, energy and hydraulic optimization, resilience to extreme events, and traceability for regulatory purposes (Ghorbani Bam et al., 2025). This transition marks a shift from reactive management to proactive, predictive, and adaptive strategies, essential for ensuring efficiency and sustainability in water infrastructure under growing environmental and social pressures.

3. Overview of the Consorzio di Bonifica 3 Medio Valdarno

The Consorzio di Bonifica 3 Medio Valdarno is a public economic entity with mandatory membership, established under Tuscany Regional Law 79/2012, responsible for hydraulic defense, water regulation, and soil protection in its jurisdiction.

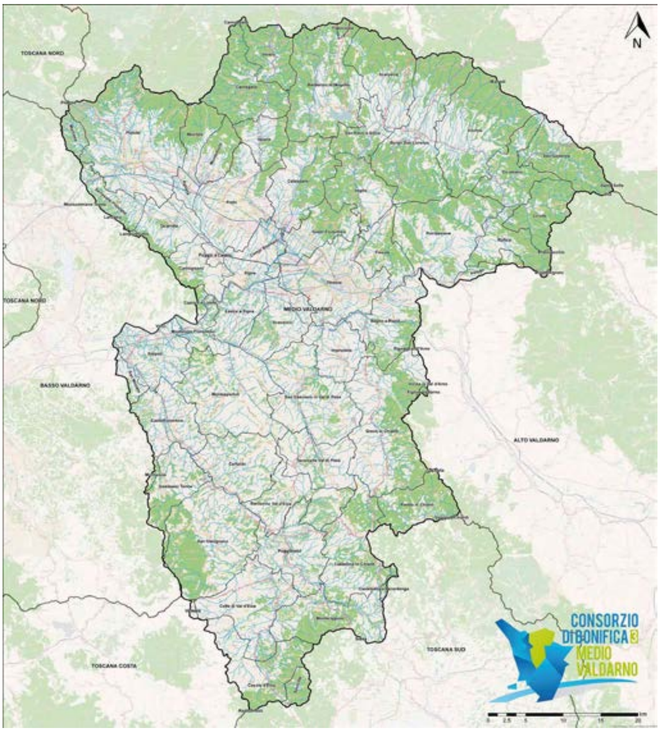

Fig. 1. The area of jurisdiction of the Consorzio di Bonifica 3 Medio Valdarno
https://www.cbmv.it/it/page/il-consorzio-cos-e

The entity is tasked with the ordinary and extraordinary maintenance of the hydraulic network, designing and building new hydraulic works, and managing strategic water infrastructures, operating both with in-house staff and through contracts with external companies. The hydraulic network managed by the Consortium extends for about 5,600 km, including natural and artificial watercourses, flood retention basins, pumping stations, sluice gates, and other hydraulic regulation works. Its jurisdiction includes urban, peri-urban, and rural contexts, aiming to reduce hydraulic and hydrogeological risks and ensure proper surface water flow. Funding comes mainly from the mandatory reclamation contribution paid by property owners within the contributing area, supplemented by regional and national public funds for new works and safety interventions.

In recent years, the increasing frequency of extreme weather events and growing pressure on water infrastructure have pushed the Consortium to adopt an innovative approach to network management, integrating advanced technological solutions. Specifically, the Digital Twin paradigm has been introduced, recognized in technical literature as a strategic tool for improving monitoring, forecasting, and proactive management of water networks (Ghorbani Bam et al., 2025; Ning et al., 2024). The Digital Twin model implemented by the Consortium is based on the combination of a SCADA remote-control system, IoT devices installed along the network, and centralized asset management platforms. This digital ecosystem enables real-time collection, integration, and analysis of field data, providing an updated and interactive virtual representation of the physical network (Grieves and Vickers, 2017). These capabilities allow not only continuous monitoring of operational conditions, but also simulation of future scenarios, maintenance optimization, and timely emergency management.

Thanks to these innovations, the Consorzio di Bonifica 3 Medio Valdarno has strengthened situational awareness, improved operational efficiency, and increased overall system resilience, contributing to a more proactive, predictive, and sustainable water management model.

4. SCADA-Based Integrated Remote Control System

The Digital Twin developed by the Consorzio di Bonifica 3 Medio Valdarno is based on an integrated remote-control system built on a web-based SCADA/HMI architecture, compatible with OPC-UA and MQTT protocols, and equipped with Python scripting capabilities for custom processing (Ghorbani Bam et al., 2025). This platform, comparable to a “central nervous system” for the hydraulic network, enables continuous monitoring, real-time control, and centralized supervision of assets distributed throughout the territory, such as automated pumping stations, motorized sluice gates, hydrometric sensors, and IoT-connected clapet valves. The architecture has been designed for high interoperability and scalability, enabling integration with a wide range of industrial systems and IoT platforms without requiring structural modifications (Fig. 2). It also offers the ability to develop interactive graphic interfaces and synoptics, integrate databases and predictive models, and manage unlimited tags and connections, lowering economic barriers to expansion (Wali and Alshehry, 2024).

These features make the system particularly suited to support the Digital Twin paradigm, as it enables an up-to-date virtual representation of the physical network and feeds advanced analytics and simulation applications. A strategic aspect of implementation was the choice of a cloud architecture instead of traditional on-premise solutions, which allowed for separation of IT and OT domains, significantly improving security, performance, and interoperability. The cloud component ensures data encryption, advanced authentication, firewalls, and intrusion detection systems, enhancing resilience against cyber threats. Furthermore, dynamic scalability allows computational resources to be allocated according to demand, reducing costs and provisioning times, while the remote availability of the SCADA platform as a web service facilitates integration with external systems, such as Civil Protection agencies, for real-time monitoring.

Thanks to this combination of automation, connectivity, centralized intelligence, and architectural flexibility, the Consortium’s remote-control system is a key element in transforming the hydraulic network into a resilient, adaptive, and data-driven infrastructure capable of proactively responding to complex and evolving operational scenarios.

5. Asset management platform

Efficient management of hydraulic facilities is a significant challenge for local water network operators. In this context, an Asset Management platform integrated with the Consortium’s SCADA system is essential for improving operational efficiency, reducing downtime, and supporting predictive maintenance strategies (Di Nardo et al., 2021; Grigg, 2025). The asset management platform, integrated with the SCADA system, collects real-time data from hydraulic actuators and distributed sensors. This integration allows continuous monitoring of asset conditions and early detection of anomalies, preventing potential operational failures (Waltero, 2021).

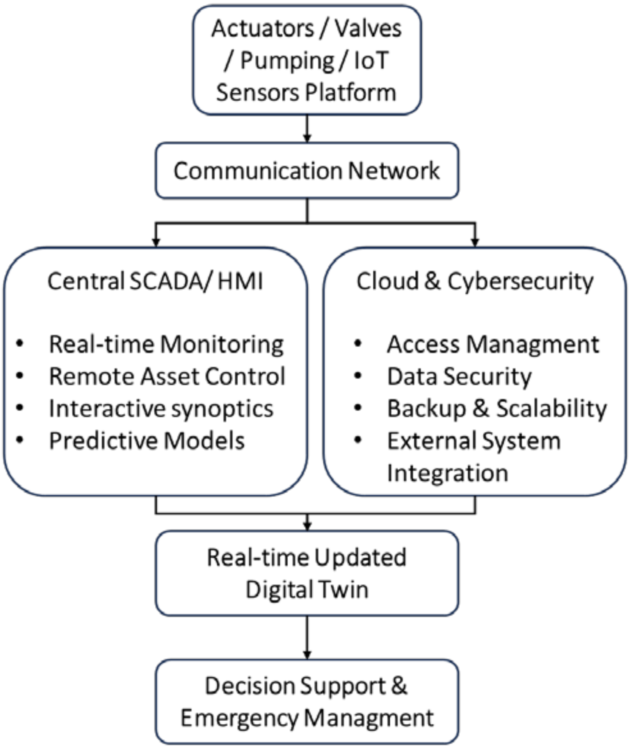

Fig. 2. Architecture of the Digital Twin system for hydraulic infrastructure management, integrating IoT devices, SCADA/HMI, cloud services, and predictive decision support

The collected data is then used to generate predictive models capable of alerting technicians in advance, thereby reducing the risk of unplanned interruptions (Forhad et al., 2024). The platform also centralizes the management of periodic inspections of facilities, a critical process for ensuring the reliability and safety of hydraulic infrastructure. When an inspection is required, the system automatically generates a task assigned to field operators, equipped with smartphones or tablets, and orders requests by priority. This enables targeted interventions on the most critical assets (Fig. 3). During the inspection, the operator collects quantitative data, records qualitative information, uploads photographs, and notes any anomalies. Once completed, the inspection is saved and automatically transmitted to the platform, where the data is processed and analyzed. If a component fails the inspection, the system flags the anomaly, allowing maintenance technicians to plan targeted interventions (Caldera et al., 2021). The maintenance technician is responsible for validating the inspections and digitally signing them, ensuring traceability and operational compliance. All data is automatically archived, creating a continuous and structured database. This dataset not only improves operational management of facilities but also serves as a valuable knowledge base for developing decision-making models and advanced predictive applications (Di Nardo et al., 2021; Forhad et al., 2024).

Integrating fuzzy logic-based predictive models into a Digital Twin of a pumping system enables dynamic and proactive evaluation of the need to intensify routine maintenance operations. The continuously updated digital twin cross-references real-time operational data from the SCADA system (flows, operating hours, power consumption, etc.) with historical and management data from the Asset Management platform (maintenance cycles, past failures, spare parts status). The predictive model, thanks to its ability to handle the uncertainty and variability of real-world contexts, uses membership functions to map complex variables into linguistic values (such as “low,” “medium,” “high” probability of degradation), applies “if... then...” inference rules, and finally produces a crisp output through defuzzification, indicating the urgency level of the intervention.

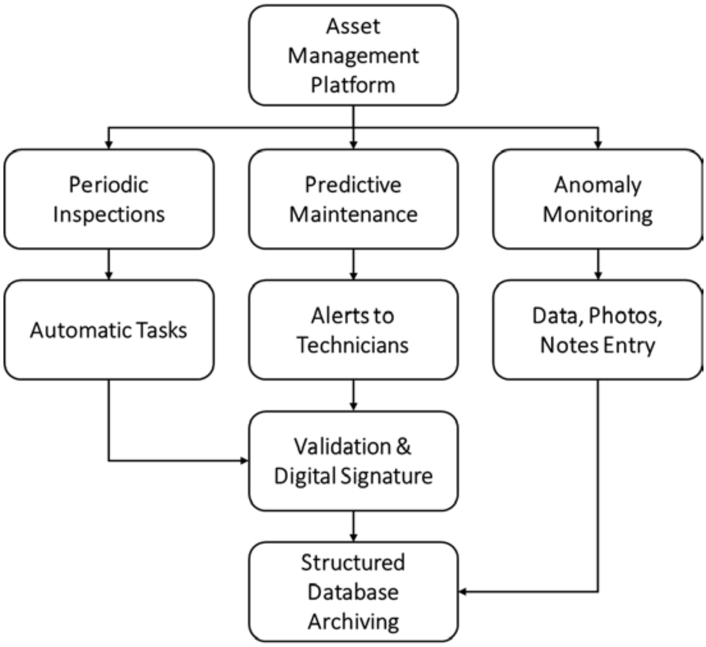

Fig. 3. Workflow of the Asset Management Platform, illustrating processes from inspections and predictive maintenance to anomaly monitoring, validation, and structured data archiving

A relevant methodological reference for similar applications is the study by Giusti and Marsili-Libelli (2015), which developed a Fuzzy Decision Support System for agricultural irrigation, using predictive data on soil moisture content and past irrigation events, applying fuzzy rules to determine the most appropriate irrigation action.

Complete and traceable documentation of inspections is also a key element for regulatory compliance and asset performance monitoring. In summary, the Asset Management platform is a strategic component for the integrated management of water infrastructure, combining real-time monitoring, predictive maintenance, and digitized inspection processes, ensuring reliability, safety, and efficiency (Caldera et al., 2021; Grigg, 2025).

6. Conclusions

The case of the Consorzio di Bonifica 3 Medio Valdarno clearly demonstrates the effectiveness of the Digital Twin approach in advancing the management of complex water infrastructures. The integration of SCADA systems**,** IoT devices, and a centralized Asset Management platform allows continuous and synchronized replication of the physical network’s operational state, enabling real-time supervision and rapid, data-driven decision-making. This dynamic digital environment provides immediate feedback on hydraulic processes, supporting prompt and accurate responses during both ordinary operations and emergency conditions.

The implemented digital model significantly enhances the resilience and adaptability of the hydraulic network by facilitating predictive maintenance and proactive management of critical situations. Through early anomaly detection and the automation of maintenance planning, the system minimizes unplanned interruptions and optimizes the allocation of technical resources, resulting in higher efficiency, safety, and reliability. In addition, the continuous flow of data between interconnected devices and control systems fosters a learning process that strengthens operational intelligence and informs future infrastructural upgrades.

The Asset Management platform plays a strategic role in this ecosystem by ensuring full traceability of interventions, regulatory compliance, and secure digital archiving of all operational activities. Its structured database becomes a repository of historical and real-time data that can be leveraged for predictive analytics, performance assessment, and long-term strategic planning, supporting a continuous improvement cycle in water resource governance.

Overall, the Digital Twin paradigm transforms traditional, static infrastructures into intelligent, adaptive, and interconnected systems, capable of anticipating challenges and responding efficiently to extreme events and climatic variability. It embodies a transition toward predictive, proactive, and sustainable management models, where the integration of digital technologies not only improves immediate operational performance but also contributes to long-term environmental and economic sustainability.

In conclusion, the experience of the Consorzio di Bonifica 3 Medio Valdarno stands as a replicable and scalable model for the modernization of water networks worldwide. By merging automation, connectivity, and data intelligence, it showcases how the Digital Twin can drive the evolution of water management systems toward greater resilience, transparency, and sustainability, aligning technological innovation with the broader goals of resource optimization and environmental protection.

References

American Water Works Association, (2021), *Digital Twins for water utilities: Transforming operational and asset management*, AWWA, Denver, CO, USA. On line at: https://www.awwa.org/resource/digital-twins.

Caldera S., Mostafa S., Desha C., Mohamed S., (2021), Exploring the role of digital infrastructure asset management tools for resilient linear infrastructure outcomes in cities and towns: A systematic literature review, *Sustainability*, **13**, 11965. https://doi.org/10.3390/su132111965

Di Nardo A., Boccelli D.L., Herrera M,, Creaco E., Cominola A., Sitzenfrei R., Taormina R., (2021), Smart urban water networks: Solutions, trends and challenges, *Water*, **13**, 501, https://doi.org/10.3390/w13040501

Dui H., Cao T., Wang F., (2025), Digital twin-based resilience evaluation and intelligent strategies of smart urban water distribution networks for emergency management, *Resilient Cities and Structures*, **4**, 41–52.

Forhad H.M., Uddin M.R., Chakrovorty R.S. et al., (2024), IoT based real-time water quality monitoring system in water treatment plants (WTPs), *Heliyon*, **10**, e40746, https://doi.org/10.1016/j.heliyon.2024.e40746

Ghorbani Bam P., Rezaei N., Roubanis A., Austin D., Austin E., Tarroja B., Takacs I., Villez K., Rosso D., (2025), Digital twin applications in the water sector: A review, *Water*, **17**, 2957, https://doi.org/10.3390/w17202957

Giusti E., Marsili-Libelli S., (2015), A fuzzy decision support system for irrigation and water conservation in agriculture, *Environmental Modelling and Software*, **63**, 73, https://doi.org/10.1016/j.envsoft.2014.09.020.

Grieves M., Vickers J., (2017), *Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems*, Springer, Cham, Switzerland.

Grigg N.S., (2025), Digital transformation in water utilities: Status, challenges, and prospects, smart cities, **8**, 99, https://doi.org/10.3390/smartcities8030099

Ning G., Luo H., Yin W., Zhang Y., (2024), Exploration of the application and practice of digital twin technology in teaching driven by smart city construction, *Sustainability*, **16**, 10312, https://doi.org/10.3390/su162310312

Regione Toscana, (2012), *Legge Regionale 27 Dicembre 2012, n. 79. Nuova disciplina in materia di Consorzi di Bonifica*, *Bollettino Ufficiale della Regione Toscana*, Firenze, Italy.

Waltero, (2021), *Water utility asset management software: Improving monitoring and predictive maintenance*, Available at: https://waltero.com/resources/water-utility-asset-management-software

Wali A., Alshehry F., (2024), A survey of security challenges in cloud-based SCADA systems, *Computers*, **13**, 97, https://doi.org/10.3390/computers13040097

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ENERGY TRANSITION IN SICILY: THE STRATEGIC ROLE OF GREEN HYDROGEN IN TECHNOLOGICAL INNOVATION AND MATERIAL CIRCULARITY*

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Abstract

The ecological transition represents one of the most urgent and complex challenges for Europe's sustainable future and, in particular, for insular regions such as Sicily, which are characterized by significant renewable energy potential but also by considerable infrastructural constraints. Within this framework, green hydrogen is positioned as a strategic instrument for decarbonization and for the revitalization of the regional energy system. This study focuses on the analysis of green hydrogen production alternatives in Sicily, evaluating their potential in relation to the availability of renewable resources, the existing regulatory framework, and the main environmental impacts, with particular attention to water electrolysis technology. Electrolysis enables the production of green hydrogen using only electricity and water, with no CO_2 emissions when powered by renewable sources. As a clean and sustainable process, it is a valuable pathway for the decarbonization of industrial and transport sectors. An additional innovative opportunity examined in this research concerns the reuse of industrial molybdenum waste, which, through cost-effective nanostructuring processes, can be employed as alternative materials for electrodes and catalysts. This approach reduces dependence on critical raw materials and fosters a circular economy within the green hydrogen sector. Finally, the study proposes several recommendations aimed at integrating the green hydrogen value chain into the regional ecological transition strategy, with a specific focus on infrastructure, materials research, and the regulatory framework.

Keywords: critical raw materials, decarbonization, ecological transiction, green hydrogen, membranes

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1. Introduction

The ecological transition represents one of the most complex and necessary processes of our time, particularly for a country such as Italy, where the interconnection between environment, economy, and society is especially pronounced. It is not merely a matter of replacing fossil fuels with renewable energy sources or planting trees to offset emissions: it entails a profound rethinking of our development model, as outlined in the Piano per la Transizione Ecologica (PTE) and in the objectives of the 2030 Agenda for Sustainable Development. It means envisioning cities where mobility is sustainable, industries operate without depleting natural resources, and agriculture works in harmony with biodiversity.

In Italy, the ecological transition holds a particularly urgent meaning due to the fragility of its territory: landslides, floods, droughts, and sea-level rise are tangible manifestations of climate change, which is strongly felt in this context. Moreover, Italy possesses a unique cultural and landscape heritage that risks being compromised unless effective adaptation and mitigation strategies are implemented, as foreseen by the PTE and by the international guidelines of the 2030 Agenda.

Sicily occupies a distinctive position within the national and European energy landscape. Its geographical location, at the center of the Mediterranean, together with the abundance of natural resources (particularly solar and wind), makes it one of the regions with the highest renewable potential in Italy (XXXIII Congresso Geografico Italiano, 2021). However, this favorable condition is intertwined with structural challenges that cannot be overlooked: insufficient electricity transmission capacity, limited integration with the continental grid, and an uneven distribution of energy infrastructures represent concrete barriers to the optimal exploitation of such potential.

In this context, green hydrogen emerges as a strategic lever to support the energy transition and to reduce greenhouse gas emissions. Green hydrogen refers to hydrogen produced through the electrolysis of water powered exclusively by renewable energy. This process separates water molecules into hydrogen and oxygen by means of an electric current, without generating carbon dioxide. Its inherent characteristics, combined with the possibility of storage and use in energy-intensive sectors, make it a technology capable of contributing both to decarbonization and to the management of renewable energy variability.

Electrolysis, indeed, makes it possible to obtain hydrogen without environmentally harmful emissions, and is therefore fundamental for the implementation of a sustainable energy model (Bahman et al., 2024). However, the efficiency and sustainability of electrolysis largely depend on the availability and properties of the materials employed, particularly membranes and catalysts. The latter, often based on critical raw materials such as platinum, iridium, and rare earth elements, present significant challenges in terms of supply and environmental impact. A thorough analysis of membranes highlights the necessity of developing alternative, more abundant, and lower-impact materials to ensure the scalability and accessibility of this technology. Green hydrogen also fosters energy independence by reducing reliance on fossil fuels. Furthermore, the hydrogen produced can be stored and used when required, thereby improving the management of intermittent renewable sources (Ponzio et al., 2021). Although electrolysis is a scientifically consolidated process, it requires specific materials for membranes and catalysts, which today are frequently based on rare and costly elements such as platinum and iridium. This dependency raises issues related to costs, supply security, and the environmental footprint of extractive industries. From this perspective, innovative solutions such as the reuse of industrial molybdenum waste acquire particular relevance. Through low-cost nanostructuring processes, these residues can be transformed into alternative materials for electrodes and catalysts, thereby reducing dependence on critical raw materials and promoting a circular economy approach applied to green hydrogen production (Costanzo et al., 2024).

This publication proposes to investigate the potential of green hydrogen production in Sicily by integrating technological and environmental perspectives. Opportunities deriving from the abundance of renewable resources will be analyzed alongside the critical issues related to infrastructure, materials, and the regulatory framework, with the aim of outlining strategies to incorporate green hydrogen into the regional pathway toward a more resilient, competitive, and sustainable energy system.

2. Materials and methods

Sicily is a region that, due to its natural conditions, geographical location, and availability of resources, exhibits extraordinary potential to produce energy from renewable sources. Within this framework, green hydrogen emerges as a strategic energy carrier capable of absorbing excess renewable energy that cannot be immediately utilized, converting it into a molecule that is easily storable and deployable in hard-to-electrify sectors such as heavy industry, long-distance mobility, and maritime transport. Renewable-powered electrolysis, if integrated into a well-balanced system of production and consumption, may represent the missing link to ensure flexibility and security in the Sicilian energy system. In this context, technological innovation plays a decisive role: the reuse of industrial molybdenum waste to produce catalysts and electrodes can reduce dependence on critical raw materials and foster a circular economy, thereby strengthening the overall sustainability of the value chain.

The production of green hydrogen through electrolysis can be carried out using different technologies, which differ primarily in the type of electrolyzer employed, the materials used, the operating conditions, and the level of industrial maturity. At the core of all variants lies the same physico-chemical principle: electricity from renewable sources is used to split water into its two elemental components, hydrogen and oxygen, thereby avoiding the emission of CO_2 and other climate-altering substances (Matarazzo, 2024). The main differences concern efficiency, costs, durability, operational flexibility, and scalability.

The most historically established method is that of alkaline electrolyzers (AEL, Alkaline Electrolysis), which employ a potassium hydroxide or sodium hydroxide solution as a liquid electrolyte. This technology is characterized by simplicity, reliability, and relatively low costs, and can operate at moderate temperatures, generally between 60 and 80 °C. Their operational longevity is high; however, their energy efficiency does not reach the levels of more recent technologies, and their response to rapid load fluctuations is less immediate, an important limitation when operating with variable renewable sources such as wind and solar.

Proton Exchange Membrane electrolyzers (PEM) employ a solid polymer membrane that conducts protons while physically separating hydrogen from oxygen. This technology offers high current density, rapid start-up, and greater compatibility with intermittent renewable energy. However, the catalysts used in the electrodes often require noble metals such as platinum and iridium, which are both costly and scarce, and the membrane itself entails significant production costs. Current research is increasingly oriented toward the use of alternative materials, including the recovery of industrial waste, such as molybdenum residues, which, when properly processed, can partially or fully replace traditional catalysts, thereby reducing both economic and environmental impacts.

A third category is represented by Solid Oxide Electrolysis Cells (SOEC), which operate at high temperatures, generally between 650 and 850 °C, and use a solid ceramic electrolyte that conducts oxygen ions. Heat can be supplied by industrial processes, geothermal plants, or concentrated solar power, thereby reducing the electricity demand for water splitting (Flis, 2023). High conversion efficiency is one of the strengths of this technology; however, the elevated operating temperatures require resistant materials and careful management of thermal stresses, factors that still limit large-scale deployment.

In recent years, hybrid and innovative solutions have also begun to emerge. Anion Exchange Membrane electrolyzers (AEM), for example, combine features of both alkaline and PEM systems, employing a solid membrane that conducts OH^- anions instead of protons. This configuration makes it possible to avoid the extensive use of noble metals, thereby reducing costs, while offering a faster and more flexible response compared to traditional AEL, though the technology has not yet reached the same level of maturity. Experimental approaches have also been proposed, such as direct seawater electrolysis, which is still at the research stage but could potentially integrate desalination processes to produce hydrogen in coastal areas with abundant renewable energy yet limited freshwater availability.

3. Case study

When considering the relationship between costs and environmental impact, the three main electrolysis technologies (alkaline, AEL; proton exchange membrane, PEM; and solid oxide, SOEC) present different advantages and limitations, and the optimal choice strongly depends on the application context. Alkaline electrolyzers are the most mature and widespread solution: they involve relatively low investment costs, employ common materials such as nickel and steel, and ensure good operational durability. From an environmental perspective, their limited reliance on critical raw materials reduces risks associated with extraction and supply, and the overall balance is favorable when powered by stable renewable sources. Their efficiency is good, though not the highest, and their response to rapid load fluctuations is slower, an important consideration when electricity comes from variable sources such as solar or wind (McKenzie et al., 2024). PEM technology offers excellent operational performance in terms of flexibility: it can start up and shut down rapidly, easily following the intermittent output of renewables. However, it requires catalysts based on platinum and iridium, rare and expensive metals whose extraction and refining cycles have significant environmental impacts. This makes the environmental profile of PEM less advantageous when considering the full life cycle, and production costs are also higher due to the material component.

SOECs operate at high temperatures and can achieve higher efficiencies than the other technologies, especially when the required heat is available at low cost from industrial processes, geothermal sources, or concentrated solar power. In such cases, the environmental impact can be very low, as renewable electricity consumption per unit of hydrogen produced is reduced. The main limitation is that SOECs are less mature, with higher costs and shorter operational lifetimes compared to AELs, mainly due to thermal stresses on ceramic materials.

If the immediate objective is to minimize costs and implement a robust system sustainable in terms of materials, alkaline electrolyzers currently represent the most balanced choice. If, instead, the priority is to track real-time variable renewable generation, PEMs are unsurpassed from an operational standpoint, though with higher economic and environmental costs due to their reliance on critical raw materials. In the long term, with improved durability and cost reductions, SOECs may offer the best environmental and economic compromise, particularly in contexts where renewable heat is readily available. For a region such as Sicily, a combination of AELs for continuous production and SOECs where high-temperature heat can be exploited appears to be the most promising strategy. The conditions established by DL 144/2022 for accessing renewable energy consumption incentives require that electrolyzers be powered exclusively by clean sources and that temporal correspondence between renewable electricity production and its consumption for electrolysis be guaranteed. This requirement favors technologies capable of rapidly modulating their operation according to intermittent solar and wind availability. In this regard, PEM electrolyzers are advantaged: their rapid start-up and operational flexibility allow even short renewable production windows to be exploited, maximizing the use of "certified" energy and reducing the risk of resorting to non-renewable grid electricity. While AELs offer lower costs and use less critical materials, their slower load response makes optimal compliance with temporal correspondence more challenging, unless constant renewable power or electricity storage systems are available. SOECs, owing to their high efficiency, could achieve significant environmental benefits when powered by renewable heat and clean electricity, but their current limited capability for rapid start-up/shutdown cycles makes them less suitable for variable generation without a stable energy profile.

Reform 3.2 of MASE (2025), on the other hand, through capital grants, contracts for difference, and streamlined permitting, lowers the entry barrier for all technologies but can shift preferences depending on medium- to long-term strategies. In industrial projects aiming for continuous operation with dedicated renewable sources (for example, photovoltaic and wind plants combined with storage), AELs become particularly competitive due to their low CAPEX and long lifetime. In contexts where high-temperature renewable heat is available (concentrated solar power, geothermal energy, or industrial waste heat recovery), SOECs can exploit their higher efficiency to reduce both electricity consumption and the levelized cost of hydrogen, while still benefiting from MASE (2025) incentives for infrastructure. In cases where hydrogen production is tightly coupled with variable renewable availability and large storage systems are not in place, PEMs remain the ideal candidates, despite higher costs and the use of noble metals, precisely because of their ability to maximize hydrogen production while meeting the requirements of DL 144/2022.

Ultimately, the regulations do not favor a single technology outright but instead create conditions that reward different approaches depending on context: the stringent traceability and temporal matching requirements of DL 144/2022 favor the flexibility of PEMs; the investment strategy and simplifications of Reform 3.2 allow AELs to fully express their cost-effectiveness in constant-operation plants; and SOECs to become the highest-yield choice where renewable heat is available. For a region such as Sicily, endowed with abundant solar and wind resources as well as opportunities to exploit geothermal and concentrated solar heat, a calibrated combination of the three technologies, selected on a site-specific basis, could maximize access to incentives and fully leverage the national and European support framework.

4. Results and discussion

The geographical location and natural characteristics of Sicily confer upon it a potential leading role within the Mediterranean energy landscape. The combination of abundant renewable resources, both solar and wind, and proximity to major maritime trade routes provides an opportunity to transform the island into a true hub for green hydrogen (NextEU, 2025). In this perspective, the energy produced locally could not only meet a significant share of domestic demand but also be exported to other European and North African countries, creating an energy corridor based on a fuel free from direct emissions. The connection with strategic ports, already equipped with industrial and logistical infrastructures, represents an additional competitive advantage that could support the development of an efficient and integrated distribution network. On the technological front, the adoption of innovative solutions in hydrogen production is a decisive factor for the competitiveness of the value chain. In particular, the use of electrodes and catalysts obtained from the recycling of industrial molybdenum waste, suitably processed through nanostructuring techniques, appears to be a promising pathway to reduce both costs and dependence on critical raw materials (U.S.

Geological Survey, 2024). This approach not only lowers the environmental impact associated with the extraction and processing of rare metals such as iridium and platinum, but also establishes a direct link with circular economy strategies, enhancing resources already available locally while stimulating new industrial supply chains in the region.

When comparing the different electrolysis technologies, it is not sufficient to assess only efficiency or operational costs: a crucial aspect is the reliance on critical raw materials such as platinum, iridium, and rare earth elements, whose limited availability and high costs represent a barrier to the large-scale diffusion of advanced electrolyzer technologies. To quantify this dimension, the Critical Raw Material Substitution Index (CRM-SI) has been introduced, a synthetic indicator that measures the capacity of a technology to reduce or replace the use of critical raw materials with more abundant, cost-effective, or recycled alternatives (Table 1). The index ranges from 0 (total dependence on critical raw materials) to 1 (complete substitution or total absence of CRM).

Table 1. Comparison of main water electrolysis technologies for green hydrogen production, highlighting key materials, involvement of critical raw materials, and the Critical Raw Material Substitution Index (CRM-SI)

Electrolysis technology	***Key materials***	***Critical raw materials involved***	***Crm – si (0-1)***
AEL (Alkaline Electrolysis)	Nickel, steel	Low dependence on CRMs	0.8
PEM (Proton Exchange Membrane)	Pt, Ir, Polymer Membrane	Platinum and Iridium (highly critical)	0.1
PEM with recycled Mo-based catalysts	Recycled Mo + reduced share of Pt/Ir	Partial substitution of noble metals	0.6
SOEX (Solid Oxide Electrolysis Cells)	Rare earth elements, advanced ceramics	Rare earth elements (moderate criticality)	0.4

Applying this indicator to the three main electrolysis technologies:

- Alkaline electrolyzers (AEL) use abundant materials such as nickel and steel and show minimal dependence on critical raw materials, resulting in a high CRM-SI value.

- PEM electrolyzers, while offering optimal performance in terms of flexibility and compatibility with intermittent renewable sources, are heavily dependent on platinum and iridium. Their CRM-SI value is therefore very low. However, with the introduction of catalysts derived from industrial molybdenum waste, the index increases significantly, thereby reducing the overall criticality of the value chain.

- Solid oxide electrolyzers (SOEC), although highly efficient, require advanced ceramic materials and rare earth elements, yielding an intermediate CRM-SI value.

This approach provides a clear and comparable representation of the contribution of different technological solutions not only to the energy transition but also to the development of a genuinely circular and sustainable value chain.

The molybdenum market in 2024 is experiencing a phase of growth, albeit with some tensions linked to global supply and demand dynamics. Global production increased by about 6% compared to the previous year, signaling a consolidation of supply, mainly driven by China, followed by Chile, Peru, the United States, and Mexico. These five countries account for over 90% of global production, confirming the strong geographical concentration of this metal.

During 2024, prices in Europe remained high, ranging between €21,000 and €30,000 per ton depending on the product type (raw ore, oxides, ferromolybdenum, or chemical compounds). This relatively elevated level reflects the strategic importance of the metal and the growing attention toward critical raw materials required for energy and industrial transitions. The year 2024 has thus been marked by a strengthening of global molybdenum supply, relatively high European market prices, and sustained demand from the energy sector. Although Italy is not a producer, it remains a relevant actor as an importer and processor, thereby confirming its dependence on international dynamics in this strategic market.

Environmental aspects related to green hydrogen production play a significant role in the overall assessment of the project. The sustainability of this technology does not depend solely on the renewable origin of the electricity used for electrolysis but also on material management, plant life-cycle considerations, and the ability to integrate the process into a circular economic system. The adoption of technical solutions that reduce the use of critical raw materials, the reuse of industrial by-products, and the optimization of energy efficiency are all elements that contribute to minimizing the overall ecological footprint, making the supply chain more resilient and less exposed to commodity market fluctuations.

From an economic perspective, Sicily presents conditions that could attract substantial investments in the green hydrogen sector. The competitive cost of local renewable resources, combined with the availability of suitable areas for production and storage facilities, creates a favorable context for the development of large-scale projects. Integration with existing industrial clusters, particularly those with high energy consumption and significant emissions, offers the opportunity to initiate targeted decarbonization processes, thereby reducing dependence on fossil fuels and improving the competitiveness of products on international markets. In addition, the presence of incentives and support measures, such as those provided by DL 144/2022 and MASE Reform 3.2, can accelerate the implementation of investments, supporting both the initial installation phase and long-term operations (MASE, 2025).

In this vision, Sicily would not only be able to meet a growing share of its own energy demand through sustainable sources but could also export hydrogen and related technologies, consolidating its strategic role within the European and Mediterranean energy landscape.

The analysis shows that no single solution is universally valid: the different electrolysis technologies (alkaline, proton exchange membrane, and solid oxide) each find their own area of excellence, and in Sicily, a carefully tailored combination of approaches adapted to site-specific characteristics can deliver the best results. Integration with renewable heat, the use of recycled materials such as molybdenum waste, and the adoption of circular economy principles further strengthen the sustainability of the entire value chain, reducing both costs and dependence on critical raw materials.

5. Conclusions

Sicily occupies a unique and rare position within the European energy landscape: a territory capable of generating a significant amount of renewable energy and transforming it into an economic and environmental opportunity of strategic importance. Green hydrogen does not emerge as a mere technological option, but rather as the connecting element between natural resources, industrial innovation, and decarbonization policies.

The island's geographical location, abundance of solar and wind resources, and proximity to major Mediterranean energy routes position it as a potential hub for the production, storage, and distribution of green hydrogen. By integrating renewable energy generation with advanced electrolysis technologies, Sicily can play a decisive role in the creation of a circular and sustainable hydrogen economy. Moreover, the valorization of local industrial by-products, such as molybdenum residues reused for catalyst production, strengthens the link between clean energy and material circularity, reducing dependence on critical raw materials while fostering new industrial value chains.

To fully realize this potential, coordinated action between research, industry, and public institutions is essential. Stable regulatory frameworks, infrastructure modernization, and targeted financial support can enable large-scale deployment of electrolyzers powered exclusively by renewables. In parallel, investment in research and innovation will be crucial for improving the efficiency, durability, and environmental performance of emerging electrolysis technologies.

If supported by stable policies, adequate infrastructure, and targeted investments, green hydrogen production on the island can evolve from a local initiative into a project of international relevance, capable of powering industrial processes, decarbonizing transport and manufacturing sectors, and enabling exports to other Mediterranean markets. In this way, Sicily could become a cornerstone of the European hydrogen strategy, a model of how insular regions, through technological innovation and resource optimization, can lead the transition toward a resilient, low-carbon, and circular energy system.

References

Bahman A.H., Ozcan H., (2024), Green hydrogen production by water electrolysis: Current status and challenges, *Green and Sustainable Chemistry*, **5**, 100–115.

Cormos C., (2024), Decarbonized green hydrogen production by sorption-enhanced biomass gasification: An integrated techno-economic and environmental evaluation, *International Journal of Hydrogen Energy*, **95**, 592–603.

Costanzo V., Nocera F., Detommaso M., Evola G., (2024), Decarbonizing cities through electrification: A strategic study for densely built residential districts in Southern Italy, *Sustainable Cities and Society*, **113**, 105995.

Decreto Legge n. 144, (2022), *Condizioni per l'accesso alle agevolazioni sul consumo di energia rinnovabile in impianti di elettrolisi per la produzione di idrogeno verde, Gazzetta Ufficiale della Repubblica Italiana*, n. 223, 23 September 2022.

Flis G., (2023), *Solid oxide electrolysis: A technology status assessment*, Clean Air Task Force (CATF) Report, On line at: https://cdn.catf.us/wp-content/uploads/2023/11/15092028/solid-oxide-electrolysis-report.pdf.

Frey M., (2021), Le imprese nella transizione ecologica, *Impresa Progetto – Electronic Journal of Management*, **2**, 1–7.

IEAGHG, (2024), *Comparative analysis of electrolytic hydrogen production technologies with low-carbon (CCS-abated) hydrogen pathways*, IEAGHG Technical Report, On line at: https://publications.ieaghg.org/technicalreports/2024-08%20Analysis%20of%20electrolytic%20hydrogen.pdf.

Martinelli M., Visconti C.G., Lietti L., Forzatti P., Deiana P., Bassano C., (2014), Sintesi, caratterizzazione e prova di catalizzatori di tipo strutturato in forma di monolita per la produzione di Synthetic Natural Gas da carbone, *Report ENEA*, 10–14, On line at: https://www.ricercasistemaelettrico.enea.it/archivio-documenti.html?task=download.send&id=4586:sintesi-caratterizzazione-e-prova-di-catalizzatori-di-tipo-strutturato-in-forma-di-monolita-per-la-produzione-di-synthetic-natural-gas-da-carbone&catid=440

MASE, (2025), *Riforma 3.2: Misure per promuovere la competitività dell'idrogeno*, Ministero dell'Ambiente e della Sicurezza Energetica, On line at: https://www.mase.gov.it/portale/-/riforma-3.2-misure-per-promuovere-la-competitivita-dell-039-idrogeno

Matarazzo A., (2024), *Towards Sustainable Hydrogen Production: Innovations in Nanostructured Catalyst Synthesis and Life Cycle Assessment*, In: Proceedings of the 2nd World Recycling Convention, 28–30 October 2024, Rome, Italy.

McKenzie H., Esposito A.M., Peterson D., Miller D., Stanford J., (2024), *Hydrogen Shot: Water Electrolysis Technology Assessment*, U.S. Department of Energy, Energy Earthshot Initiative, On line at: https://www.energy.gov/sites/default/files/2024-12/hydrogen-shot-water-electrolysis-technology-assessment.pdf.

NextEU, (2025), Sicilia a idrogeno: La nuova valle green che trasformerà l'Italia, On line at: https://www.nexteu.it/sicilia-a-idrogeno-la-nuova-valle-green-che-trasformera-litalia.

Ponzio A., Galli S., (2021), Il ruolo dell'idrogeno da elettrolisi nella sovrapproduzione di energia da fonti rinnovabili. Parte I, *La Chimica e l'Industria – Rivista della Società Chimica Italiana*, **103**, 60–66.

Redazione, (2025), Sicilia, nel 2024 parere ambientale positivo a 10.8 GW rinnovabili, *Rinnovabili – Inform, Act, Share*, **13**, 1–3.

Restifo I.C., (2025), La Sicilia protagonista della svolta green: Investimenti e opportunità, *Canale Energia*, On line at: https://www.canaleenergia.com/rubriche/transizione-ecologica/la-sicilia-protagonista-della-svolta-green-investimenti-e-opportunita/.

U.S. Geological Survey, (2024), *Mineral Commodity Summaries 2024,* U.S. Department of the Interior, Washington, D.C.

XXXIII Congresso Geografico Italiano, (2021), *Geografie in movimento*, Università di Padova, Padova, Italy.

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MICROBIAL DETECTION IN INDUSTRIAL PROCESSES*

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Abstract

Microbial slime growth in the production processes of industrial forest and biocirculation industries may cause increases in flow resistance, blockages, and the formation of persistent biofilms. All these require costly interruptions in production, equipment downtime during cleaning, reduced product quality, and even rejection of damaged products. Microbes are removed and their further growth is prevented by adding chemicals, which creates challenges both from an environmental and occupational safety standpoint. On the other hand, tightening environmental regulations are increasing the pressure to use fewer and fewer chemicals. The same problems are relevant also for other industries where microorganisms are involved, such as mining, fuel production, and wastewater purification. The key needs and continuous challenges of these energy-intensive processes include energy and raw material efficiency, improving product quality, and increasing the processing value. This can be achieved by optimising the operation of microbial cultures. In practice, an industrial process can be managed and adjusted better when the number of microbes in the process is constantly known and tightly controlled. Microorganism detection and cell count monitoring can be accomplished by several different methods, such as the bioluminescent analysis of adenosine triphosphate (ATP), which is more reliable and suitable for industrial applications. Over the last few decades, ATP analysis has been developed and optimised for a wide range of different applications. In this paper we present current research results on how ATP-based microbial population monitoring technology can be applied in various fields: biomining, pulp and paper mills, and wastewater treatment plants. These results are based on current knowledge of the biochemical reaction theory underlying ATP analysis and are obtained using modern measuring equipment required to detect bioluminescence. Particular attention is paid to a wide range of industries specific factors inhibiting bioluminescent-based ATP analysis. Various examples of the correct interpretation of ATP measurement results for different types of applications were also given. As far as impact is concerned, the overall impact of suboptimal microbial growth is complex to assess, as the impacts are also highly sector-specific. For example, in water treatment plants, the financial costs incurred by failed cleaning may be small compared to the costs of health impacts, if they can even be assessed in financial terms. In industry, production downtime due to process cleaning is, to a certain

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extent, part of normal operations. On the other hand, long-term production shutdowns due to equipment failures caused by, for example, microbial activity, combined with the effects of certain gases, are very expensive and, in the worst cases, result in significant environmental and health impacts.

Keywords: ATP analysis, ATP method, bioluminescence, industrial applications, microbial monitoring technology

1. Introduction

Monitoring the microbiological quality of water and other solutions during various technological processes allows us to confirm the success of treatment measures and optimise technologies in order to reduce the harmful impact of human activities on the environment. Bacterial cell counts can be estimated by direct methods such as plate count, direct microscopic count, flow cytometry and dry weight/biomass, as well as indirect methods such as optical density (OD), electrical impedance, calorimetry, real-time PCR, metabolite monitoring, ATP bioluminescence, oxidation-reduction potential (ORP), etc. Each of these methods has its own advantages and disadvantages, depending on the environmental or production conditions. The traditional method for assessing bacterial numbers is colony forming unit (CFU) counting (Bhuyan et al., 2023). This method is better suited for culturing bacteria only for certain species, takes several days or weeks and can be done in a laboratory setting by trained staff. The direct counting of bacterial cells by microscopy using counting chambers is still a method suitable for laboratory research conditions and is not used for industrial purposes (Daims et al., 2007).

The two most widely used methods for assessing bacterial cell counts of both cultured and uncultured bacteria are flow cytometry (FCM) and bioluminescent ATP assay. FCM is a rapid, reproducible and economical technique for quantifying total bacterial numbers and biomass concentrations (Brown et al., 2019) requires special equipment and highly qualified personnel to perform. A bioluminescent ATP assay can rapidly measure all active microorganisms in the sample (Lomakina et al., 2015). The process takes less than an hour and makes it possible to monitor the level of microorganisms in real time. ATP is the main universal source of energy for different biochemical processes occurring in all living cells, making it a parameter that can be used as an independent, complimentary method for viability assessment. In most cases, samples must be pre-treated before using ATP measurement (Lundin, 2014). When an increase in sensitivity is needed, pre-treatment involves the concentration of samples. In order to keep the assay in a linear range, pre-treatment involves the dilution of samples. The pH level and other inhibitory factors can also be controlled by the pre-treatment procedure.

The main areas of ATP assay applications in industry are hygiene monitoring, the quality control of purified water, pulp and paper industry, the microbial analysis in the food industry, maintenance of pharmaceuticals and estimation of medicine quality, and the monitoring of various technological processes, such as biomining (Efremenko et al., 2022).

This article summarizes current knowledge of the theoretical principles of ATP bioluminescent analysis and practical issues concerning the measuring equipment for detecting luminescence in the enzymatic reaction of a firefly luciferin-luciferase system, the content and operating principles of ATP bioluminescent assay reagent kits. The description of the factors inhibiting an ATP bioluminescent assay is accompanied by the experiments investigating the influence of pH and divalent ions on luminescence intensity and the amount of ATP. The main advantages and disadvantages of the ATP bioluminescence method are also discussed.

2. Theory and practice of ATP measurement

2.1. Theory

Bioluminescent ATP analysis is the most sensitive, rapid and selective of various methods for determining ATP concentration, such as enzymatic methods with spectrophotometric detection, radioactive, chromatographic methods etc. (Lomakina et al., 2015). The importance of ATP as a component in the reaction catalysed by the firefly luciferase enzyme was first discovered by McElroy (McElroy, 1947).

Luciferase enzymes belong to the class of oxidoreductase enzymes and function as oxidative enzyme. The accepted name of the P.pyralis luciferase enzyme is Photinus-luciferin 4-monooxygenase (decarboxylating, ATP-hydrolysing), but it is commonly referred to as firefly luciferase or simply luciferase (Luc). The substrate firefly luciferin (LH_2) is (S)-2-(60-hydroxy-20-benzothiazolyl)-2-thiazoline-4-carboxylic acid, which functions in the bioluminescent reaction only in the form of the D optical isomer (Marques and Esteves da Silva, 2009). The overall bioluminescent chemical reaction in the firefly luciferin-luciferase system is represented by Eq. (1).

$$D\text{-}LH_2 + ATP + O_2 \xrightarrow{Luc,\ Mg^{2+}} AMP + PPi + CO_2 + \text{oxyluciferin} + \text{light quantum (560nm)} \quad (1)$$

Here $D\text{-}LH_2$ is D optical isomer of firefly luciferin, ATP is adenosine triphosphate, O_2 is oxygen, AMP is adenosine monophosphate, PPi is pyrophosphate, CO_2 is carbon dioxide, Luc is luciferase and Mg^{2+} is divalent cation of magnesium.

2.2. Practice of ATP measurement

Over the past two decades, many variants of ATP bioluminescent assay reagent kits have been developed and commercialised. The main component of the kit is the ATP reagent, which consists of a lyophilised mixture of luciferase, luciferin, magnesium salt, buffer component and stabilisers. (Lundin, 2000). The ATP source is either taken from the sample or an ATP standard, which is usually supplied in the kit. ATP in a cell sample exists inside the cells and is called intracellular ATP. Any living cell contains ATP. Dead or dying cells are the source of extracellular ATP, which is also known as dissolved ATP. Extracellular ATP serves as an indicator of cellular stress or lysis. Total ATP reflects all ATP in a sample, including ATP from both living and dead cells and extracellular ATP. The ratio of extracellular ATP to total ATP in a sample is called the Biomass Stress Index (BSI). A high BSI score reflects a high proportion of cell death, indicating stress factors affecting the microbial community. BSI is a parameter used to assess the level of stress on microorganism populations in wastewater treatment processes. This ratio helps treatment facilities to evaluate the balance and stability of microbial communities that play a crucial role in breaking down waste materials.

To quantify total ATP, cells are lysed with extraction buffer to release intracellular ATP into a solution containing extracellular ATP, then ATP reagent is added, and the luminescence intensity is measured (Fig.1A). To exclude extracellular ATP from these measurements, some kits suggest pretreating the sample with eliminating reagent, which contains a milder lysis buffer than the extraction buffer to deactivate extracellular ATP (Fig.1B). If only extracellular ATP is needed, then both types of measurements must be performed, followed by subtraction of the intracellular ATP from the total ATP (Fig. 1C).

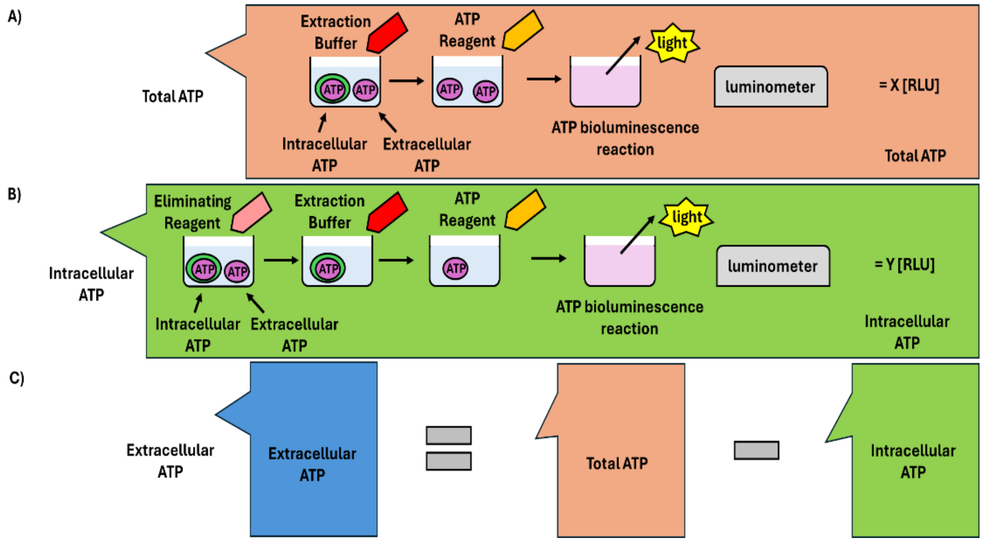


Fig. 1. A) Total ATP combines two types of ATP: intracellular ATP and extracellular ATP. Both types of ATP can be measured when intracellular ATP is released from the cell by the action of an extraction buffer. B**)** Intracellular ATP can only be measured when extracellular ATP is destroyed by an eliminating reagent prior to addition of the extraction buffer. C) Extracellular ATP can be calculated by subtracting intracellular ATP from total ATP. In this case, both types of measurements should be performed: total ATP and intracellular ATP

The ATP concentration in the analysed sample can be calculated by comparison with the standard. To quantitatively determine viable cells, it is necessary to construct a graduation dependence between the concentration of intracellular ATP and the concentration of cells in the sample. There is linear correlation between the number of viable cells [CFU/mL], that is determined using the standard method, and the ATP content in 1 mL of the sample that is determined using the bioluminescence method.

The characteristics of the extraction buffer and lysis buffer affect the efficiency of ATP extraction. These characteristics are important to consider depending on the type of microorganisms present in the sample. Gram-negative bacteria, gram-positive bacteria, yeasts and most eukaryotic microorganisms have very different cell walls, and therefore the choice of extractant and lysis buffer may vary depending on the sample content. Different types of extraction and lysis buffers, their characteristics and ability to not act as an inhibitor of the luciferase bioluminescence reaction are described in the works of Romanova et al. (1997), Lundin (2000), Lomakina et al. (2015).

The light output from the bioluminescence luciferin-luciferase reaction can be measured using sensitive photo detectors of light meters in an instrument called a luminometer. Modern luminometers use a photon counter in combination with a highly efficient photomultiplier to detect the bioluminescence signal. The signal of the luminometer is presented in relative luminescence units (RLU). The amount of light produced by the firefly luciferase bioluminescence reaction is proportional to the concentration of ATP in the linear range of 10 fM to 1 μM, where M = mol/L. One bacterial cell contains about 1 femtogram of ATP (Gerba and Pepper, 2019; Yaginuma et al., 2014). To determine the number of microbes in each sample, it is assumed that 1 picogram of ATP is equal to 1,000 bacterial cells.

A tube luminometer is a specialized device for measuring luminescence in tubes of various types. It is highly sensitive and versatile: it supports a variety of luminescence technologies, including flash-type, glow-type, bioluminescence, and chemiluminescence. The handheld luminometer is a portable and convenient instrument for field testing and on-site applications. The key features of plate-reading luminometers include high throughput screening due to multiple simultaneous samples and high sensitivity (they provide high sensitivity to detect low levels of light, ensuring accurate measurements).

3. Materials and methods

The total ATP was determined using an ATP Biomass Kit HS (266-311, BioThema AB, Handen, Sweden) according to the manufacturer's instructions. Bioluminescence intensity was measured as relative luminescence units (RLU) using a Varioskan LUX multimode microplate reader (ThermoFisher Scientific). The ATP assay mixture contained an ATP standard in aqueous solution with different concentrations of HCl (Sigma-Aldrich), NaOH (Sigma-Aldrich), and MgSO4 (Sigma-Aldrich), as well as the following kit components: luciferase and luciferin, buffer, ATP extractant, and additional ATP standard. The ATP measurements were done in triplicates.

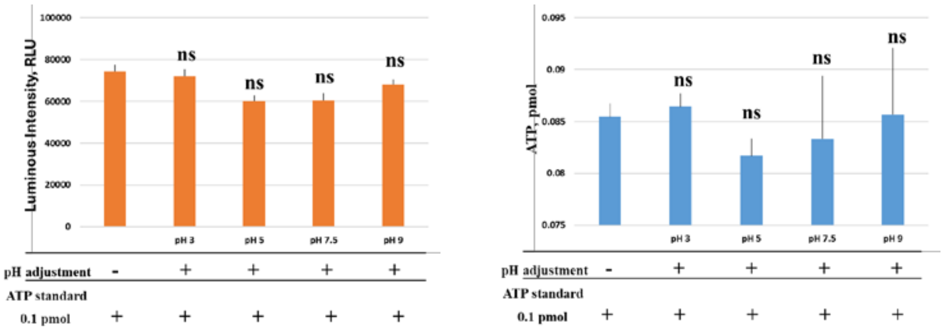
Statistical analyses for comparisons between two groups were performed using Student's two-tailed t-test and denoted as $^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$ and 'ns' (not significant) in all experiments.

4. Results

Various factors can inhibit the bioluminescence luciferin-luciferase reaction at different stages of the assay. Extraction and lysis buffers can be very effective in their main function of lysing the cell wall, but at the same time they can be harmful to the luciferase enzyme and, as a result, will inhibit the bioluminescence reaction. The sample matrix can inhibit the bioluminescence reaction and make the assay impossible or give a false negative result. It has been shown that an increase in the concentration of heavy metal salts of Pb, Zn, Cu and Fe lead to inhibition of the ATP luminescence reaction (Efremenko et al., 2022). All commercially available ATP kits are designed to measure ATP in fresh water. One of the most common salts with inhibitory action in many types of water samples is sodium chloride NaCl. Mutant forms of luciferase resistant to NaCl inhibition were specifically generated and can be used for these types of samples (Yawata et al., 2021). NaCl and other seawater salts interfere with the luciferin-luciferase reaction, which limit the use of ATP analysis for assessing the quality of salt water. The most important problem is the use of ATP analysis in desalination plants: this has influenced the development of special ATP reagents (Abushaban et al., 2017).

This is why it is necessary to investigate the sample composition, optimise the pre-treatment procedure, and test the ATP assay kit to ensure reliable results with each new sample type. There are many good reviews that discuss various classes of substances as inhibitors of the bioluminescence reaction (Efremenko et al., 2022). In this paper, the influence of pH and divalent ions on the luminescence intensity and the amount of ATP was investigated.

The bioluminescence luciferin-luciferase reaction is very sensitive to pH changes. The optimal enzyme activity pH range is typically between pH 7.5 - 7.8 (Lundin, 2000; Lundin, 2014). Deviations from this range can reduce enzyme activity, leading to decreased luminescence. Extreme pH levels can cause ATP to hydrolyse into ADP and phosphate, which disrupts the luminescent reaction. Maintaining the correct pH is crucial for accurate and reliable luminescent assays involving ATP. These requirements dictate the need to develop a pre-treatment protocol for samples with pH outside the specified ranges. This applies to most environmental and industrial samples.



a) b)

Fig. 2. Comparison of the effect of pH of the sample on a) the intensity of luminescence and b) the amount of ATP. Bioluminescence intensity was measured and ATP amount were calculated.

Commercially available ATP assay kits already contain a certain proportion of buffers in ATP reagents and ATP extraction solutions to stabilise the pH of the working solution. The effect of the pH in the samples with the ATP standard on the luminescence intensity and calculated amount of ATP was determined. In other words, the efficiency of the buffer capacity of the ATP reagent for regulating the pH of the sample was determined. The ATP analysis of 0.1 pmol ATP standard with pH 3.0, 5.0, 7.5, 9.0 (adjusted by HCl or NaOH) showed no difference in the luminescence intensity and the amount of ATP compared to the control (Fig. 2). These results showed that the buffer in the ATP reagent is able to maintain an optimal pH over a wide range of samples. ATP assay kits from different manufacturers should be tested for buffering capacity individually. Analysis of the various acids and bases used to adjust pH should determine their effect on luminescence intensity to reveal chemical specificity rather than a general tendency to provide a particular pH. Further studies are needed to investigate the possibility of ATP extraction from samples with different pH.

Mg^{2+} is a catalyst for the ATP luminescence reaction. The additional presence of these ions in the sample can affect the yield of the reaction and influence the final result. The presence of other divalent ions can also influence the course of the reaction. It has been shown that an increase in the concentration of Mn^{2+}, Ca^{2+} and Mg^{2+} ions does not affect the quantum yield and colour of the radiation, whilst the presence of Zn^{2+}, Cd^{2+}, Fe^{2+}, Ni^{2+}, Co^{2+} and especially Hg^{2+} can reduce luminescence (Efremenko et al., 2022).

Magnesium sulfate ($MgSO_4$ $7H_2O$) solutions are commonly used in the pulp and paper industry, agriculture and other industries where ATP analysis is widely used to monitor microbiological status. The recommended concentration range of 1.4–5.8 % by weight for magnesium sulfate heptahydrate ($MgSO_4$ x $7H_2O$) in industrial solutions corresponds to a molarity of 0.057- 0.24 mol/L. This is the reason why many types of industrial samples for ATP analysis contain relatively high concentrations of magnesium sulfate.

The ATP reagent already contains Mg^{2+} as an essential component that catalyses the luciferin-luciferase reaction. The manner in which magnesium sulfate would affect the luminescence intensity and, in turn, the calculated amount of ATP in industrial samples was determined. It was found that the luminescence intensity decreased significantly when 0.1 pmol ATP standard containing 0.5 M and 0.25 M magnesium sulfate was analysed by an ATP assay (Fig. 3). Therefore, high concentrations of magnesium sulfate may interfere with the luciferin-luciferase reaction in the ATP assay and result in false positive or false negative ATP determinations (Fig. 3). The ATP analysis of 0.1 pmol ATP standard containing 0.125 M magnesium sulfate showed no difference in the luminescence intensity and the amount of ATP compared to the control (Fig. 3).

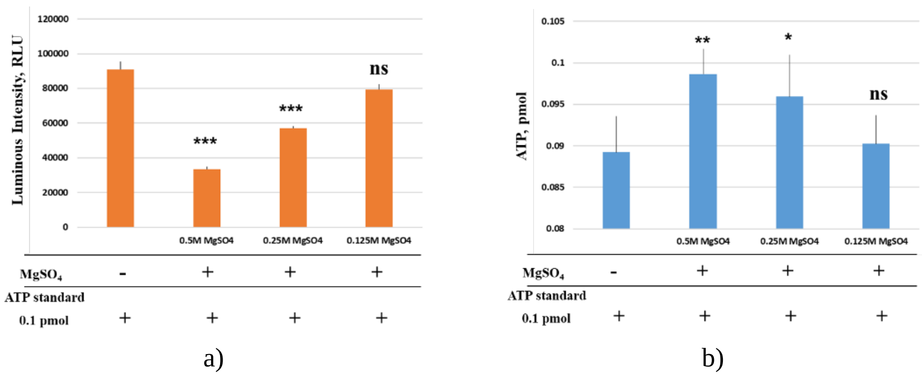


Fig. 3. Comparison of the effect of magnesium sulfate on a) the intensity of luminescence and b) the amount of ATP. Bioluminescence intensity was measured, and ATP amount was calculated.

The upper limit of the recommended concentration range of 0.057–0.24 mol/L for magnesium sulfate heptahydrate ($MgSO_4.7H_2O$) in industrial solutions is very close to the 0.25 M solution tested, and samples with this concentration should be excluded from ATP analysis or subjected to a pre-treatment procedure that reduces the magnesium sulfate concentration. Different ATP assay kits from different manufacturers should be tested individually for sensitivity to magnesium sulfate concentration. A more precise correlation between the luminescence intensity and the amount of ATP at intermediate concentrations of magnesium sulfate from 0.25 M to 0.125 M needs to be determined further. The analysis of various magnesium salts should determine the influence of Mg^{2+} on the luminescence intensity and exclude the influence of various anions.

5. Discussion

Bioluminescent ATP analysis is already actively used to monitor the microbiological status of various stages of industrial processes in wastewater treatment, the pulp and paper industry and biomining industry, but it can be used even more effectively by optimising the protocols for pre-treatment of industrial samples. ATP assay is one of the main cultivation-free methods to quantify viability of natural microbial communities in aquatic environments (Hammes et al., 2010).

Recent specific applications of ATP analysis in aquatic environments include the analysis of drinking water, bottled water, river and lake water, sea water, wastewater effluent, groundwater, biofilters in water treatment plants, and bacteria in biofilms from distribution networks. In freshwater aquatic environments, ATP has been used to monitor water quality across treatment trains in drinking water plants (Siebel et al., 2008), measuring active biomass on granular activated carbon, sand and anthracite grains (Magic-Knezev and van der Kooij, 2004), measuring the biostability of drinking water and biofilm formation in distribution systems (Prest et al., 2016a) and determining ATP in ground water (Eydal and Pedersen, 2007). An ATP assay together with flow cytometry was used as a main method for monitoring long term bacterial dynamics in a full-scale drinking water distribution system (Prest et al., 2016b).

Different technological approaches for enhanced wastewater treatment to eliminate various organic micropollutants are evaluated by ATP assay (Lee at al., 2016). In water reuse technology, a method has been developed for determining assimilable organic carbon in purified water based on ATP luminescence (Li et al., 2017). The application of ATP in seawater is limited due to the interference of salts in the luciferase-luciferin reaction. A direct method for measuring ATP in seawater was developed, in which commercial reagents are added directly to the seawater (Abushaban et al., 2017).

ATP analysis is one of the methods for detecting and monitoring extremophilic bacteria in industrial biomining and biohydrometallurgical processes (Slowik et al., 2024). The metabolic activity of acidophilic bacteria used in these processes can be assessed by the number of these specific bacterial cells, thus becoming a very important characteristic of the industrial process. The extremely low pH (pH2) and the presence of salts and heavy metals in the samples make the sample pretreatment protocol a subject for optimisation (Pakostova et al., 2013a; Pakostova et al., 2013b). More recent studies have used various modifications of the ATP measurement protocols to assess intracellular ATP as an important characteristic of samples containing acidophilic bacteria (Johnson and Pakostova, 2021; Chen et al., 2022; Izquierdo-Fiallo et al., 2025).

As early as the end of the 20th century, ATP analysis was considered one of the most promising methods for monitoring bacterial growth in the paper industry (Mentu et al., 1997). Rapid ATP analysis has been successfully applied in papermaking to optimise biocidal treatment strategies for fine paper machines (Kiuru et al., 2010). At that stage of ATP analysis development, a list of the disadvantages of this method was noted (Lund et al., 2012). The most significant disadvantages were: 1. The ATP assay is unable to differentiate between ATP produced by one type of microorganism versus another; 2. The ATP assay does not detect organisms that are viable but inhibited; 3. Chemical additives and detection limits lead to false positive or false negative results; 4. If bacteria are found in a defect, it is impossible to tell which organism is responsible for the defect and what part of the process it originated in. The first drawback was eliminated using PCR methods in combination with ATP analysis (Rice and Lund, 2013). Both of these methods, in combination with fluorescence in situ hybridization, made it possible to determine the diversity of microbial populations in paper production (Flemming et al., 2013).

Like any other method, the ATP bioluminescence method has several advantages and disadvantages that must be considered when choosing its application. Among the main advantages, it should be noted that there is a wide variety of luminometers with very high sensitivity for measuring bioluminescence: the method is fast, cost-effective and easy to calculate, the result can be obtained by in situ detection and can be applied to a wide range of microorganisms. One of the important advantages of ATP-bioluminescence analysis is that it can be applied to different ranges of microorganism concentrations: it can become a valuable tool for determining the effectiveness of environmental or industrial cleanliness procedures even at very low microorganism counts. Moreover, bioluminescent methods often have several advantages over fluorometric methods, mainly because the bioluminescent method allows one to distinguish between living and dead cells and to quantify both intracellular ATP and released ATP.

The ATP bioluminescence reaction is very sensitive to a large list of inhibitors. This increases the need for sample pretreatment, and the pretreatment protocol is different for each sample type and must be developed and optimized separately. In the current paper the design of experiment with proper controls can exclude the possibility of false negative results (Ali et al., 2020). Another disadvantage of bacterial bioluminescent assays is incomplete lysis of gram-negative bacteria, which in some cases can lead to an incorrect or false negative result.

One possible way to increase the efficiency of lysis is to use additional methods of bacterial wall destruction, such as ultrasound treatment in combination with a lysis solution (Lomakina et al., 2015). A protocol for the lysis of samples containing different proportions of gram-positive and gram-negative bacteria of different species should be developed separately for different sample types and tested by other methods of comparable sensitivity, such as PCR.

6. Conclusion

Luminescence-based ATP analysis is one of the most useful cultivation-free methods for quantitatively assessing the viability of microbial communities in a wide range of industrial samples. The method is rapid, and in case of an optimised sample pre-treatment protocol, the procedure can be performed without laboratory conditions. Optimisation of the sample pre-treatment protocol is the most resource-intensive step towards widespread implementation of ATP analysis in various industrial applications.

The present study highlights that accurate ATP quantification strongly depends on controlling inhibitory factors such as pH and divalent ion concentration, which can significantly alter luminescence intensity and lead to false interpretations. The findings demonstrate that the buffering capacity of commercial ATP assay kits ensures stable performance across a wide pH range, while excessive magnesium sulfate concentrations in industrial matrices can inhibit the luciferin–luciferase reaction. Therefore, a precise adjustment of these parameters is critical to obtaining reliable and reproducible results.

Overall, ATP bioluminescence analysis represents an efficient and environmentally compatible tool for real-time microbial monitoring in diverse industrial processes, including wastewater treatment, pulp and paper manufacturing, and biomining. Its further development will depend on the continued refinement of sample-specific pre-treatment procedures and the adaptation of reagents to challenging industrial matrices. The integration of ATP-based monitoring with complementary analytical and digital process-control methods may also facilitate improved microbial management, reduced chemical usage, and enhanced process sustainability across multiple sectors.

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References

Abushaban A., Mangal M., Salinas-Rodriguez S., Nnebuo C., Mondal S., Goueli S., Schippers J., Kennedy M., (2017), Direct measurement of ATP in seawater and application of ATP to monitor bacterial growth potential in SWRO pre-treatment systems, *Desalination and Water Treatment*, **99**, 91–101.

Ali A., Altemimi A., Alhelfi N., Ibrahim S., (2020), Application of biosensors for detection of pathogenic food bacteria: A review, *Biosensors (Basel)*, **10**, 58, https://doi.org/10.3390/bios10060058.

Bhuyan S., Yadav M., Giri S., Begum S., Das S., Phukan A., Priyadarshani P., Sarkar S., Jayswal A., Kabyashree K., Kumar A., Mandal M., Ray S., (2023), Microliter spotting and micro-colony observation: A rapid and simple approach for counting bacterial colony forming units, *Journal of Microbiological Methods*, **207**, 106707, https://doi.org/10.1016/j.mimet.2023.106707.

Brown M., Hands C., Coello-Garcia T., Sani B., Ott A., Smith S., Davenport R., (2019), A flow cytometry method for bacterial quantification and biomass estimates in activated sludge, *Journal of Microbiological Methods*, **160**, 73–83.

Chen G., Shi H., Ding H., Zhang X., Gu T., Zhu M., Tan W., (2022), Multi-scale analysis of nickel ion tolerance mechanism for thermophilic *Sulfobacillus thermosulfidooxidans* in bioleaching, *Journal of Hazardous Materials*, **443**, 130245, https://doi.org/10.1016/j.jhazmat.2022.130245.

Daims H., Wagner M., (2007), Quantification of uncultured microorganisms by fluorescence microscopy and digital image analysis, *Applied Microbiology and Biotechnology*, **75**, 237–248.

Efremenko E., Senko O., Stepanov N., Maslova O., Lomakina G., Ugarova N., (2022), Luminescent analysis of ATP: Modern objects and processes for sensing, *Chemosensors*, **10**, 493, https://doi.org/10.3390/chemosensors10110493.

Eydal H., Pedersen K., (2007), Use of an ATP assay to determine viable microbial biomass in Fennoscandian Shield groundwater from depths of 3–1000 m, *Journal of Microbiological Methods*, **70**, 363–373.

Flemming H., Meier M., Schild T., (2013), Microbial problems in paper production, *Biofouling*, **29**, 683–696.

Gerba C., Pepper I., (2019), *Environmental and Pollution Science*, 3rd ed., Academic Press, London.

Hammes F., Goldschmidt F., Vital M., Wang Y., Egli T., (2010), Measurement and interpretation of microbial adenosine tri-phosphate (ATP) in aquatic environments, *Water Research*, **44**, 3915–3923.

Izquierdo-Fiallo K., Muñoz-Villagrán C., Schimpf C., Mardonez M., Rafaja D., Schlömann M., Tello M., Orellana O., Levicán G., (2025), Adaptive response of the holdase chaperone network of *Acidithiobacillus ferrooxidans* ATCC 23270 to stresses and energy sources, *World Journal of Microbiology and Biotechnology*, **41**, 121, https://doi.org/10.1007/s11274-025-04325-7.

Johnson D., Pakostova E., (2021), Dissolution of manganese (IV) oxide mediated by acidophilic bacteria, and demonstration that manganese (IV) can act as both a direct and indirect electron acceptor for iron-reducing *Acidithiobacillus* spp., *Geomicrobiology Journal*, **38**, 570–576.

Kiuru J., Tsitko I., Sievänen J., Wathen R., (2010), Biocide strategies for fine paper, *BioResources*, **5**, 514–524.

Lee Y., Imminger S., Czekalski N., von Gunten U., Hammes F., (2016), Inactivation efficiency of *Escherichia coli* and autochthonous bacteria during ozonation of municipal wastewater effluents quantified with flow cytometry and adenosine tri-phosphate analyses, *Water Research*, **101**, 617–627.

Li G., Yu T., Wu Q., Lu Y., Hu H., (2017), Development of an ATP luminescence-based method for assimilable organic carbon determination in reclaimed water, *Water Research*, **123**, 345–352.

Lomakina G., Modestova Y., Ugarova N., (2015), Bioluminescence assay for cell viability, *Biochemistry (Moscow)*, **80**, 600–612.

Lund L., Rice L., Luth E., Sirois D., (2012), The use of on-line monitoring tools and advanced analytical techniques to optimize bio-control treatment strategies for papermaking systems, *PaperCon 2012 Proceedings*, New Orleans, USA. http://doi.org/10.13140/2.1.5021.9523.

Lundin A., (2000), Use of firefly luciferase in ATP-related assays of biomass, enzymes, and metabolites, *Methods in Enzymology*, **305**, 346–370.

Lundin A., (2014), Optimization of the firefly luciferase reaction for analytical purposes, *Advances in Biochemical Engineering and Biotechnology*, **145**, 31–62.

Magic-Knezev A., van der Kooij D., (2004), Optimisation and significance of ATP analysis for measuring active biomass in granular activated carbon filters used in water treatment, *Water Research*, **38**, 3971–3979.

Marques S., Esteves da Silva J., (2009), Firefly bioluminescence: A mechanistic approach of luciferase catalyzed reactions, *IUBMB Life*, **61**, 6–17.

McElroy W., (1947), The energy source for bioluminescence in an isolated system, *Proceedings of the National Academy of Sciences USA*, **33**, 342–345.

Mentu J., Pirttijärvi T., Lindell H., Salkinoja-Salonen M., (1997), Microbiological control of pigments and fillers in paper industry, in *The Fundamentals of Papermaking Materials*, Trans. of the XIth Fund. Res. Symp. Cambridge (C.F. Baker, ed.), FRC, Manchester, 955–993.

Pakostova E., Mandl M., Omesova Pokorna B., Diviskova E., Lojek A., (2013a), Cellular ATP changes in *Acidithiobacillus ferrooxidans* cultures oxidizing ferrous iron and elemental sulfur, *Geomicrobiology Journal*, **30**, 1–7.

Pakostova E., Mandl M., Tuovinen O., (2013b), Cellular ATP and biomass of attached and planktonic sulfur-oxidizing *Acidithiobacillus ferrooxidans*, *Process Biochemistry*, **48**, 1785–1788.

Prest E., Hammes F., van Loosdrecht M., Vrouwenvelder J., (2016), Biological stability of drinking water: Controlling factors, methods, and challenges, *Frontiers in Microbiology*, **7**, 45, https://doi.org/10.3389/fmicb.2016.00045

Prest E., Weissbrodt D., Hammes F., van Loosdrecht M., Vrouwenvelder J., (2016), Long-term bacterial dynamics in a full-scale drinking water distribution system, *PLoS One*, **11**, e0164445, https://doi.org/10.1371/journal.pone.0164445.

Rice L., Lund L., (2013), Detection and quantification of nucleic acid to assess microbial biomass in paper defects and machine felts, *United States Patent* No. *US 8,613,837 B2*.

Romanova N., Brovko L., Ugarova N., (1997), Comparative assessment of methods of intracellular ATP extraction from different types of microorganisms for bioluminescent determination of microbial cells, *Applied Biochemistry and Microbiology*, **33**, 306–311.

Siebel E., Wang Y., Egli T., Hammes F., (2008), Correlations between total cell concentration, total adenosine tri-phosphate concentration and heterotrophic plate counts during microbial monitoring of drinking water, *Drinking Water Engineering and Science Discussions*, **1**, 1–6.

Slowik G., Richer R., Stryjska A., Dabrowski P., (2024), Bacteria *Acidithiobacillus ferrooxidans*, terrestrial analogue of extraterrestrial microorganisms?, *International Journal of Astrobiology*, **23**, e22, https://doi.org/10.1017/S1473550424000181.

Yaginuma H., Kawai S., Tabata K., Tomiyama K., Kakizuka A., Komatsuzaki T., Noji H., Imamura H., (2014), Diversity in ATP concentrations in a single bacterial cell population revealed by quantitative single-cell imaging, *Scientific Reports*, **4**, 6522, https://doi.org/10.1038/srep06522.

Yawata S., Noda K., Shimomura A., (2021), Mutant firefly luciferase enzymes resistant to inhibition by sodium chloride, *Biotechnology Letters*, **43**, 1585–1594.

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TOWARDS MICROPLASTIC-FREE RECYCLED WOOD FIBRE*

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Abstract

The relation between wood-based recycled fibre and plastics, particularly microplastics, in recycled laminated cardboard has been investigated. From an environmental sustainability perspective, energy and material consumption as well as the environmental impact of consumers and industrial products need to be minimised. At the same time, efforts should be made to extend the life-cycle and reusability of products while supporting the transition to a circular economy. The transition to a circular economy also requires solutions to recycle raw materials used in packaging more efficiently and to make take-back and reuse concepts more widespread.

When the package is no longer viable or can no longer be used in its original form and for its original purpose, it should be recycled as material for new products. Producing recycled material in large quantities requires industrial processes with industrial quality standards – presumably microplastics-free with a competitive price in the future. The overall need for process engineering is therefore to obtain timely measurements for better process control, optimisation and validation.

In this paper, a wood-based recycled fibre manufacturing process was studied from the measurement perspective. European and American industry guidelines are reviewed, the type and source of microplastics are investigated, and suitable measurement techniques are discussed. In addition, the practical application of measurement as part of the recycling process is assessed. It was discovered, for instance, that the role of logistics in the recycled fibre mill process was surprisingly significant. This study clarified the requirements of an online measurement concept needed to ensure and validate the manufacturing process of microplastic-free recycled fibre to meet the needs of the mill operator, customer and potential upcoming environmental regulations.

In terms of impact, the European Union is currently discussing tightening the regulation of microplastics in various industrial sectors. The forest industry is one potential target for microplastic restrictions, with recycled pulp made from recycled laminated cardboard products being discussed. There are two challenges: the total amount of microplastics and monitoring the amount of microplastics. A complete ban on microplastics in recycled pulp could significantly reduce the amount of laminated cardboard being

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put into circulation, which in turn could affect recycling operations. In the worst case, laminated cardboard would end up more often in energy use. In both cases, the impact would be enormous. On the other hand, the lack of sufficient online measurement methods, measuring devices, as well as the measurement results that would meet the needs of pulp mill operators, end users, and authorities, complicates the discussion on setting appropriate limit values for microplastics.

Keywords: measurement, microplastics, pulp, recycled fibre

1. Introduction

From an environmental sustainability perspective, the amount of energy and materials needed to manufacture consumer and industrial products must be minimised. At the same time, efforts must be made to extend the life-cycle and recyclability of products and support the transition to a circular economy. Ensuring that products reach customers undamaged requires packaging solutions that protect against shock, abrasion, moisture, and liquid exposure. The transition to a circular economy also requires more efficient recycling of packaging solutions and raw materials used in packaging, as well as the widespread adoption of take-back and reuse concepts. This, in turn, requires involving customers in the development of new packaging concepts. When packaging is no longer worthwhile or can no longer be used in its original form or for its original purpose, the packaging should be recycled as material for new products. Producing recycled material in large quantities requires industrial processes with industrial quality requirements – not to mention a competitive price.

Energy-intensive process industries consume significant amounts of raw materials and process chemicals. The chemicals used are challenging for both the environment and workers, which requires reducing chemical loads. All of this needs to be optimised. In the process industry, the timely adjustment of process parameters is key to end-product quality management, energy efficiency, and safety (Seppälä et al., 2005). Industrial processes are controlled by measurement systems (Bentley, 2005), (Vijaya, 2018). To optimise control, there is a need to research and develop intelligent measurement principles, processes, hardware, and software. Such developments enable industrial operators to innovate and to meet growing competitive and regulatory demands (Hayes et al, 2005). This paper discusses the boundary conditions of the concept of an online measuring device for microplastics, which are needed to validate the amount of microplastics in the manufacturing process of recycled pulp.

Several drivers aim to reduce the harm caused using plastics. Common drivers include political programmes, the need to increase environmental resilience, and the development of processes and efficiency. At a concrete level, political programmes aim to improve the state of the environment and support the circular economy through regulation. Effective recycling generates cross-sector synergies and promotes the efficient use of virgin raw materials and energy resources. Better control of processes can improve product quality and reduce maintenance costs for production equipment. Figure 1 presents these drivers.

Recyclable cardboard, paperboard, paper, etc. contain plastics from many different sources. The paperboard may be coated with plastic to make it suitable for liquid packaging (Stora-Enso, 2024). The cardboard may also contain plastic packaging tapes, glued plastic pockets for delivery forms, plastic labels, coatings etc. (CEN, 2020). When cardboard, paperboard, etc. collected for recycling are finally processed in a mill, portion of the plastics is removed from the recycled pulp. However, some of the plastic remains in the recycled pulp, since plastics have broken down into smaller particles.

Public authorities, customers of recycled pulp products, and mills are interested in the microplastics contained in recycled pulp. If the regulation limits the microplastic content of recycled pulp, the authorities will require compliance, which will lead to mills bearing responsibility for their own monitoring. This regulation also imposes quality requirements on recycled pulp products. This affects the price of the product and is thus also of great interest to the customers. However, the mill is the only actor that can influence the microplastic content in the final product through its choices, by adjusting the manufacturing process and the raw materials used.

Fig. 1. Many drivers can affect the amount of microplastics in recycled pulp

2. Industry guidelines

The purpose of industry guidelines is to create market value for recyclable paper, cardboard, paperboard, etc. based on the quality of this material. European standard EN 643 describes the components of recyclable raw materials that are prohibited and should not be present (EN, 2014). The list of prohibited substances includes materials that pose a risk to health, safety and the environment, such as pharmaceutical waste, contaminated personal hygiene products, hazardous waste, organic waste including food, bitumen, toxic powders and equivalent. All foreign substances and objects that are not part of the cardboard or paperboard product, and that can be separated by dry sorting, such as metal, plastic, glass, textiles, wood, sand, construction materials, synthetic materials, must also be removed. The remaining recyclable raw material is graded into five quality classes according to the total amount of non-paper components and unwanted materials included in the raw material. Table 1 shows the quality classes according to standard EN 643.

Table 1. Quality classes of recyclable cardboard and paperboard according to EN 643

Group		***Non-paper components (% weight)***	***Non-wanted material total (% weight)***
1	Ordinary grades	0.5–1.5	1–3
2	Medium grades	0.25–1	1–2
3	High grades	0.25–0.5	0.5–1
4	Kraft grades	0.25–1	0.5–2.5
5	Special grades	0.25–3	1–3

North America has its own guidelines outlining the trade of recyclable raw material batches. The recycling guidelines published by the Institute of Scrap Recycling Industries Inc. cover non-ferromagnetic and ferromagnetic metals, glass, paper, plastic, electronics, and tire material batches (ISRI, 2022). This guideline is also followed widely worldwide. The term "zero tolerance" as used in this guideline includes any material containing any amount of medical, organic, food waste, hazardous, toxic, radioactive or poisonous waste, and other harmful substances or liquids.

In this guideline, "prohibited material" includes: a) any mate rial in excess of the permitted amount that renders the raw material unacceptable and unusable for the specified category; and b) any material that may damage the equipment. Due to the broad scope of the ISRI guidelines, there are dozens of quality classes. Standard classes related to paper, cardboard, and paperboard recycling include, for example: (4) boxboard cuttings, (5) mill wrappers, (9) over-issue news (OI or OIN), (10) magazines (OMG), (58) sorted clean newspapers (SCN). Special classes include, for example: (1-S) white waxed cup cuttings, (2-S) printed waxed cup offcuts, (3-S) poly coated cups, (37-S) silicone release liner.

The commercial value of a batch of recyclable raw materials is based on its quality and mass. These material bales are usually transported in uncovered trucks and trailers, so they get wet in the rain. They are also stored uncovered in the yard. Therefore, the moisture content of the bales is determined so that rainwater will not be included in the weight. According to the instructions, all papers and boards must be packed dry with a maximum moisture content of 12%. In addition, the buyer and seller agree in advance on the moisture percentage and the determination method used. The above EN 643 standard or ISRI guidelines, sorting processes or measurement methods do not consider the type of plastic.

3. Microplastics and measurement point in process

Fibre-based products collected for recycling are a heterogeneous assortment, even if they have been pre-sorted. The assortment can easily include coated, uncoated, corrugated, uncorrugated cardboard and paperboard, etc. The paperboard product has a layered structure including barriers and other structures, improving the product's properties, e.g. to control liquid, moisture, grease and stiffness (Stora-Enso, 2024). Barrier structures very commonly include plastic layers. These plastic layers can be bioplastics or traditional plastics made from fossil raw materials. The plastic layers can also be specifically biodegradable plastics. On the other hand, there are many types of plastics, and their number only increases when the origin of the raw material of the plastics and other distinguishing properties are included in the list. In this context, it is practical to only use the term plastics for all types.

Typically, in the recycling pulp mill, the collected bales are crushed into smaller pieces, mixed with water and filtered through screens of different sizes. In this pulper process, the recycled fibres and plastics are partially separated from each other, creating different material fragments. However, it is not entirely clear to what extent pure plastics or recycled fibre fragments are created and to what extent impure fragments occur. This is due to some of the fibres being permanently attached to the plastic during the thermoplastic bonding process of the barrier film. With regard to the measurement of microplastics, the measurement target can therefore be pure plastic, fibre attached to plastic, plastic attached to fibre, or pure fibre fragment.

Plastic particles ranging in size from 1 to 5 mm are defined as macroplastics and plastic particles ranging in size from 1 to 1000 µm are defined as microplastics (CEN, 2020). There is also a size class for smaller plastic particles - nanoplastics. The thickness of the barrier films used is typically 10–100 µm. Before processing, the amount of plastic in some recycled fibre products can be even 5–20% by weight. Typically, the smallest screen aperture size in a pulper is 0.15–0.2 mm, through which portion of microplastics can pass along with the fibres. In addition to plastics (PE, PET, PP, PA, PMMA, etc., their compounds and modifications) and fibres (conifer, birch, eucalyptus, bamboo, etc.), cardboard and paperboard may contain metals (Al, Ag etc.), colorants (pigments, water-soluble), fillers (clay etc.) and coatings (waxes, silicones etc.).

The pulp contains microplastic particles and, for example, adhesives from book spines. Under the pressure and heat (90–95 °C) of the mill process, these particles become soft and sticky that partially adhere to the fibres, even possibly ending up in the final product. These particles are called stickies, which are typical impurities in recycled fibre pulps. There are several methods for measuring stickies in the final product (INGEDE, 2013), (ISO, 2015), (Ossard et al., 2016). The stickiness classes are [mm²/kg]: >5.00, 1.00–5.00, 0.40–1.00, 0.15–0.40, 0.04–0.15, and 0.018–0.04. These methods cannot be used proactively to control the process or to influence the quality of the product.

There is an automated testing system that determines the classification of the incoming bales by measuring its moisture content, lignin, ash, and plastic content at the mill gate (Valmet, 2025). Regarding microplastic validation, the measurement of dry bales at the mill gate does not directly indicate the properties of the recycled pulp. On the other hand, the measurement of stickiness does indicate the quality properties of the recycled pulp, and to some extent also the amount of microplastics contained therein. However, corrective measures can no longer be taken at this stage. Only measures taken during the wet process of recycled pulp manufacturing can affect the final product. The microplastics validation point should be located in the wet process after all pulp components are mixed. For these reasons, the concept of a microplastics measurement device should be studied with regard to the mill's wet process. This would benefit the mill, the end customer, and authorities. Figure 2 shows the recycling value creation chain from the perspective of the logistics field and internal production process of the mill.

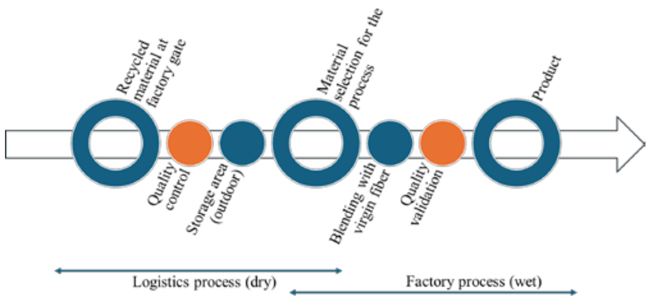

Fig. 2. The recycled pulp value generation chain includes the logistics process with raw material quality classifications, pulp processing validation, and final product quality specifications.

4. Measurement technology

When developing future technology solutions, predictions are made about their potential compared to current technologies. The future solution can be found in the domain of probable, plausible, or possible technology. The desired future solution is typically found in the probable range, but alternative solutions and completely new wild card solutions can also be found in the plausible and possible ranges. Figure 3 shows possible projections of future technologies.

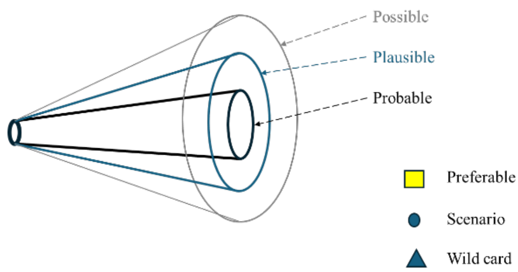

Fig. 3. A projection of a future technological solution from the current state of technology

Today microplastics have been studied by collecting samples (campaign) and sending them to laboratories specialising in microplastics. However, the time from sampling to analysis can take weeks. Methods and measurement technology used in laboratory analyses vary from laboratory to laboratory. These methods are protected by IPR (i.e. not public). Spectroscopic technologies used in laboratories include, for example, FT-IR, NIR, Raman, and hyperspectral cameras. The characteristics of microplastic particles can be found by applying data analysis tools on the spectra produced by these devices. These laboratory devices are very expensive and are not directly suitable for use on the factory floor.

The FT-IT spectrometer is the best of the technologies used, and as an expensive piece of equipment, it is worth utilising it as reference equipment during the research phase. Similarly, the Raman spectrometer produces reference-level measurement data. The drawback to using Raman equipment is its relatively slow measurement speed. Hyperspectral cameras are used in industrial material sorting in recycling plants, where a wide variety of dry materials are moved on belt conveyors. Near-infrared (NIR) and mid-infrared (MIR) spectrometers are likely technologies when applied to a more limited material flows. In addition, NIR spectrometers are more cost-effective compared to hyperspectral cameras, Raman and FT-IR spectrometers.

A NIR spectrometer is used for testing dry paper, cardboard and paperboard bales (Valmet, 2025). Tests with the NIR spectrometer technology have been conducted to measure plastic fragments in recycled paper (Alieva, 2023). Measuring microplastic particles in water has also been studied using a NIR spectrometer (Hietanen et al., 2023). From the technology projection perspective, validating the amount of microplastics in the recycled fibre manufacturing process – including the wet process – could be approached using NIR spectrometer technology.

An automatic online measuring device must be suitable for very challenging conditions. The device must be durable, reliable, and easy to maintain. In addition, it must measure correctly, quickly enough, and from a suitable location. All these requirements may even be contradictory. The accuracy of an online measuring device is typically not the same as that of a reference device in a laboratory. On the other hand, the response time of an online measuring device may be very short compared to circulating the sample through a reference laboratory. The process conditions may be so difficult that an online measuring device cannot be placed in the most optimal location. With all its compromises, an online measuring device must provide sufficiently good, real-time information to control the process. Figure 4 shows that an online measurement device is a compromise between different requirements.

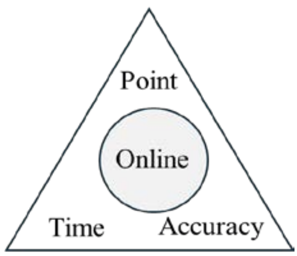

Fig. 4. An online measuring device is a compromise between measuring time, point, and accuracy

5. Measuring microplastics in wet pulp

In the wet process of a recycled fibre mill, all cardboard, paperboard, etc. bales are crushed and mixed with water. The individual layers of these materials are also broken into fragments. After being run through screening processes, the pulp is assumed to be uniform. To obtain first-hand information about plastic fragments, the barrier films of paperboard samples were experimentally separated by soaking them in water. After the sample was soaked through, the film was carefully torn off from the fibre layer. Ice cream packaging, wrapping paper from a meat/fish counter, and a pastry box were used in this experiment.

The mechanical strength of the layers obtained varied greatly. For example, wood fibres could be easily removed mechanically from wrapping paper, resulting in a transparent, uniform, and stable plastic film that stretched without tearing. The structural layers of the ice cream package paperboard (inner layer, intermediate paperboard layer, outer printed layer) were separated from each other by tearing. The printed surface layer of the ice cream package tended to degrade relatively easily, while the inner surface remained in one piece. However, the inner surface layer of the pastry package was difficult to detach, regardless of the degree to which the paperboard was wetted. Overall, the success of separating these fragments was significantly affected by the degree of the paperboard wetting. The durability of the detached plastic films varied considerably. This can be explained by the different coating techniques used on the boards. A separate plastic film can be thermally bonded to cardboard using roll-to-roll technology. The plastic can also be applied to the surface in various suspensions or pastes, which create loose bonds between the plastic particles. These fragments show wood fibres stuck to the film.

The spectra of the above-mentioned fragments were preliminarily measured dry and wet, using reflection and scattering measurement techniques to identify plastics and fibres. The spectra of wet samples are so complex that visual interpretation of the spectra is not sufficient for reliable differentiation of different plastics, not to mention quantitative analysis. However, the principal component analysis (PCA) provides clearly specific differences between sample types, i.e., the amount and type of plastics with sharp spectral bands, depending on whether the measured sample contains plastic or not. The residue remaining after the first principal component explains how the spectra differ between sample types more effectively than visual interpretation.

In addition, samples were taken from the fractioning process. Fragment samples having different plastic concentrations were measured using a self-built combination spectrometer apparatus. The sample was microplastics mixed with pulp, which had a solids content of approximately 2%. The sample was injected into a glass cuvette. The measurement was taken through the glass wall of the cuvette. The PCA was used to interpret the spectral information. In Figure 5, the wet pulp samples are clearly distinguishable from each other based on the amount of microplastics. In Fig. 5, the samples are marked with colours according to the assumed plastics concentration on the score plot. The red dots are plastics fragments. The blue dots are screened fibre fractions. In the classification analysis, it is possible to distinguish sample types using a linear decision boundary (e.g. SVM-C). When the classification model is further developed to regression model then the content of plastics in the sample can be predicted.

6. Conclusions

Industrial production control and quality assurance should be performed with online measuring devices, as the process sample can alter between sampling and laboratory measurement. Online measuring devices also facilitate energy-, material-, and chemical -efficient production processes. Combined with the expected tightening of microplastic regulations for recycled fibre pulp, this creates new measurement and validation needs. Environmental authorities and, in turn, both the mill producing recycled fibre pulp and its customers are interested in the microplastic content.

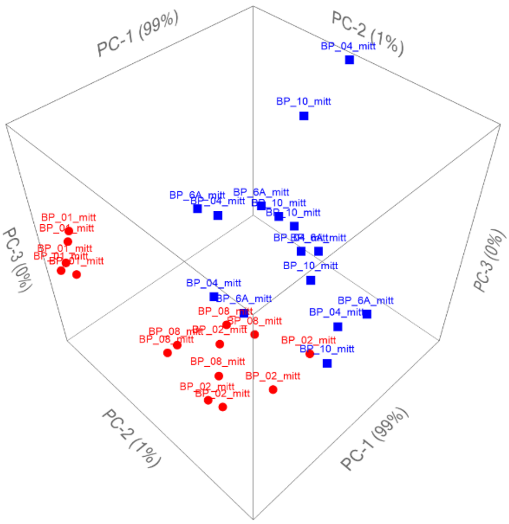

Fig. 5. PCA image of wet samples measured with a combined spectrum instrument. The samples are marked with colours according to the assumed plastics concentration in the score plot

The trade in paper, cardboard, paperboard, etc. collected for recycling is regulated by standard EN 643 and ISRI guidelines. These guidelines do not address the plastics type of the collected materials. In addition to raw material selection, the amount of microplastics in the recycled fibre pulp process should be monitored and validated. Plastic particles can be measured from wet pulp samples. From both a process and environmental perspective, the most effective monitoring of microplastics can be carried out in a wet process using online measurement. In terms of technical implementation, optical spectroscopy combined with appropriate data analysis can determine the amount of plastic in recycled fibre pulp. These tools can also identify different types of plastics.

Although measuring microplastics in the wet process of a recycled fibre mill will be possible in the future, caution should be exercised in setting potential limit values, at least until sufficient practical experience has been gained with the applicable online measurement technology.

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References

Alieva F., (2023), *Prediction of plastic fragments in recycled paper using near-infrared spectroscopy*, MSc Thesis, Karlstads University, Sweden.

Bentley J.P., (2005), *Principles of Measurement Systems*, 2nd ed., Pearson Prentice Hall, London.

CEN, (2020), *Plastics — Environmental aspects — State of knowledge and methodologies, CEN ISO/TR 21960:2020,* European Committee for Standardization, Brussels, Belgium.

EN, (2024), *Paper and board: European list of standard grades of paper and board for recycling, EN 643:2014 E,* European Committee for Standardization, Brussels, Belgium.

Hayes R., Pisano G., Upton D., Wheelwright S., (2005), *Operations, Strategy, and Technology – Pursuing the Competitive Edge*, Wiley, Hoboken, USA.

Hietanen J., Karttunen K., Huttunen H., Karjalainen P., Sutinen V., Leinonen I., (2023), Device concept to detect microplastics in water, *Procedia Environmental Science, Engineering and Management*, **10**, 289–294.

INGEDE, (2013), *Method No. 4: Analysis of Macro Stickies in Deinked Pulp (DIP)*, International Association of the Deinking Industry, Darmstadt, Germany.

ISO, (2015), *Recycled pulps: Estimation of Stickies and Plastics, Part 2 – Image analysis method, ISO 15360-2:2015*, International Organization for Standardization, Geneva, Switzerland.

ISRI, (2022), *Guidelines for Nonferrous Scrap, Ferrous Scrap, Glass Cullet, Paper Stock, Plastic Scrap, Electronics Scrap, Tire Scrap*, Institute of Scrap Recycling Industries, Washington DC, USA, On line at: https://www.bmluk.gv.at/dam/jcr:6769d086-18c6-44ab-8556-7c3e840ddd52/National-Guidance-Plastic_20210115.pdf

Ossard S., Huber P., Borel P., Soysouvanh D., Delagoutte T., Rech D., (2016), 3D-Stick latest developments, *Technologiekring Paper & Board Industry*, On line at: https://www.gzs.si/LinkClick.aspx?fileticket=uQpk3ZlcOYc%3D&portalid=183

Seppälä M.J., Klementti U., Kortelainen V.-A., Lyytikäinen J., Siitonen H., Sironen R., (2005), *Kemiallinen metsäteollisuus 1 – Paperimassan valmistus*, 2nd ed., Opetushallitus, Helsinki, Finland.

Stora-Enso, (2024), *Data Sheets: Natura Life-en.pdf, NaturaDUO-en.pdf, Nature-RFA-CLC-F-en.pdf, Nature-Barr-en.pdf, NaturaBoard-en.pdf, PromeBoard-en.pdf.*

Valmet, (2025), *How does Valmet Bale Tester work?*, On line at: https://www.valmet.com/board-and-paper/recycled-fiber/occ-lines/bale-handing-and-pulping/bale-tester/how-does-valmet-bale-tester-work/.

Vijaya N.H., (2018), *Rheological Study of Polymeric Materials Based on the Extrusion On-Line Measurements*, MSc Thesis, Warsaw University of Technology, Poland.

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CHALLENGES OF TRANSFERRING THE ISO 5351 LABORATORY METHOD TO THE FACTORY FLOOR*

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Abstract

The cellulose fibres needed in paper production are obtained from wood pulp, which is produced by removing the lignin and hemicellulose from wood. The longer and less damaged the fibres are after pulping, the stronger and therefore more valuable the paper can be made. One challenge is that if the pulp is not sufficiently processed, too much lignin and hemicellulose will remain, thus reducing the quality of the paper produced. On the other hand, if the pulp is over-processed, the polymer chains of the fibres will begin to break, also reducing the quality of the paper. Pulp production has a large environmental footprint, because its processing consumes a lot of wood, energy, and chemicals. The chemicals used are challenging for both the environment and employees, which means that measures to reduce chemical loads are needed for environmental and occupational safety. All of these are being optimised. Therefore, the timely adjustment of process parameters is key to product quality control, energy and material efficiency, safety, and the environmental footprint. A key quality parameter in paper manufacturing is the tear strength of the paper web and paper. In addition to fibre length, the degree of polymerisation affects the strength properties. The degree of polymerisation can be further described by the viscosity value of the pulp. The viscosity value of pulp is determined using a hazardous cupri-ethylenediamine (CED) solution. The viscosity determination of the manufacturing process is carried out on a sample basis in the laboratory using the ISO 5351 standard. The method is primarily suitable for CED-soluble samples of bleached chemical pulp. The method can also be applied to any pulp that dissolves completely in the CED solution. The results can be used to estimate the degree of cellulose degradation caused by pulping and bleaching. Here the focus is on the transferability of viscosity measurement from the laboratory to the factory floor. The requirement for real-time and continuous measurement results, along with the stages and bottlenecks of the transfer process, are also described. Furthermore, alternative measurement methods have been discussed here in order to avoid using a hazardous CED solution altogether. Although this is primarily a measurement issue, environmental, management, and business considerations also play a significant role.

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The shift from factory laboratories to fast, chemical-free measurements on the factory floor is clearly driven by the increasingly stringent environmental requirements placed on industry. Although the amount of chemicals used in a single measurement is small, the overall impact on chemical savings potential is significant on a global basis.

Keywords: CED solution, pulp, standardization, technology transfer, viscosity

1. Introduction

In the process industry, the timely adjustment of process parameters is key to end-product quality control, energy efficiency and safety (Seppälä et al., 2005). Energy-intensive process industries consume significant amounts of energy, raw materials and process chemicals. Chemicals are a challenge for both the environment and employees, thus requiring that measures be taken to reduce chemical loads in order to ensure environmental and occupational safety. All of these are optimised in terms of both cost structure and environmental impact. Industrial processes are controlled by measurement systems (Bentley, 2005). Some of the measurements are conventional direct measurements, such as the temperature of a process step, while others are indirect measurements tailored to monitor the process or product. Some of the measurement parameters must be carried out on a sample basis in the laboratory due to the unsuitability of the measurement devices for factory conditions. In some situations, the sample is even chemically modified before measurement. The reason may be a regulatory standard, a state of the art, or even the excessively high development costs of the measurement device.

From a cost structure perspective, laboratory measurements involve significant costs in terms of labour, equipment, and the maintenance of expertise. On the other hand, the long response time of laboratory analyses may result in an under - or over-processing that degrades the quality of the final product and unnecessarily consumes energy. Another problem is the large amounts of chemicals used in repeated laboratory measurements. To optimise cost efficiency, there is a need to research and develop intelligent measurement principles and processes, hardware and software. These enable industrial operators to innovate and respond to ever-increasing competition. A key need in the process industry is to shorten the measurement response time and automate it, thus improving the representativeness, timeliness, and cost-effectiveness of data. Typically, an automated system also produces straightforward and cost-effective maintenance procedures. From an occupational safety perspective, there is also a need to reduce chemicals that may cause harm or even pose potential danger to workers and/or the environment. It should be emphasised that the use of chemicals in general is tightly regulated and restricted. This study maps out, at a thematic level, principled solution options for the situation described above from the perspective of measurement methods (Hayes, 2005; Mintzberg, 2003; Roussel et al., 1991).

This paper discusses the transfer of the ISO 5351 pulp viscosity measurement method from the laboratory to the factory floor (ISO, 2004). The aim is to provide know-how in developing laboratory measurements towards more direct, faster and online measurements. In addition, the aim is to identify bottlenecks related to measurement transfers and to develop alternative operating models. Pulp (wood pulp i.e., paper pulp) itself is a composite consisting of cellulose, hemicellulose and partially removed lignin, i.e., the binding agent of wood fibres. Cellulose is a chemical structural component of wood, which is a hydrophilic and water-insoluble crystalline and strong polymer. Hemicellulose is amorphous and branched. When lignin is being removed by cooking wood pulp in a chemical solution, as a side effect of the process, the cellulose polymer chains also inevitably start to break (Seppälä et al., 2005). The term degree of polymerisation refers to and describes the average number of monomers in the polymer chains of a mixture, i.e., the average length of these chains. From the perspective of monitoring and controlling the progress of the process, the average degree of polymerisation of cellulose is a desired quantity that current technology cannot provide with sufficient and timely sampling intervals. The ISO 5351 standard describes in detail the laboratory measurement method used to determine the viscosity value of pulp (ISO, 2004). The method determines an estimate of the intrinsic viscosity of pulp in a dilute solution of cupri-ethylenediamine (CED). The method is based on measuring the flow times of the diluted solvent and the pulp solution through a capillary tube viscometer at 25 °C and is primarily suitable for bleached pulp samples.

These results can be used to estimate the extent of cellulose degradation caused by cooking or bleaching. Furthermore, the viscosity of the pulp in the CED solution provides an indication of the average degree of polymerisation (DP) of the cellulose. This measurement therefore provides a relative indication of the degree of cellulose degradation (reduction in cellulose molecular weight) resulting from the pulping and/or bleaching process, once the pulp has been cooked. Excessive breaking of the cellulose polymer chains in turn reduces the quality of the pulp.

2. Theory

The physical and chemical properties of a material determine its suitability for industrial processes, technical solutions and products. The material can be solid, liquid or gaseous. Both liquids and gases are called fluids. Isaac Newton defined the concept of the viscosity of an ideal fluid (Rayleigh, 1893). The concept is based on the flow of a fluid between two plates. The flow is created by a moving upper plate, which has a constant speed. The internal processes of the fluid resist the movement of the upper plate. The fluid can be divided into infinitely thin layers, each of which has a laminar flow.

Viscosity is a function of several parameters. The physicochemical nature of a liquid (such as oil or water), temperature, and pressure determines viscosity. Time can also be an important parameter when several substances are mixed. Newtonian fluids are ideal in the sense that the ratio of their parameters τ (the force acting on a moving surface in the fluid) and D (the shear force, i.e., the vertical velocity of the fluid divided by the thickness of the layer) is constant. However, this is not always the case, and these non-ideal fluids are called non-Newtonian fluids. Non-Newtonian fluids can be further grouped into pseudo-plastic fluids, dilutive fluids, and plastic fluids. Plastic fluids are pseudo-plastic fluids that have a yield point.

The viscosity of non-Newtonian pseudo-plastic fluids decreases as the shear rate increases. In other words, as the driving pressure increases, the fluid flow increases more than linearly. The reason for this behaviour may be the orientation of the particles within the fluid in the direction of the flow, the stretching of the molecules, the deformation of the materials, or the fragmentation of the particles. Fluids may have two "linear" viscosity regions and a transition region between them. The behaviour of non-Newtonian dilutive fluids is the opposite of that of pseudo-plastic fluids. The viscosity of dilutive fluids decreases as the volume fraction increases. This may be because the free internal space of the fluid decreases with increasing pressure, causing the particles to interact with each other.

For non-Newtonian plastic fluids, a large initial force is required before the fluid starts to move. Once this initial force is overcome, the viscosity decreases as the velocity of the section increases. The initial force is needed to break the internal clusters of the fluid. When a non-Newtonian fluid is measured in the τ - D range from zero to a certain value, it returns to zero via a different path. This hysteresis may be due to a weak three-dimensional network structure that easily ruptures during the transition. All in all, viscosity is a rather complex phenomenon.

Viscosity can only be solved mathematically in analytical form for Newtonian fluids under strictly limited binding conditions. This highlights the test and measurement arrangements. The flow must be laminar. The flow must be uniform. The boundary interaction must be constant without slippage. The sample must be homogeneous and the internal constituents of the sample, air bubbles, etc. must be smaller than the boundary layer and must be evenly distributed. The sample must be physically and chemically stable and immutable. The flexible sample should not be pressed outwards against the wall of the test cup, nor absorbed into the axis of rotation. Viscosity must be measured over a certain period without rapid movements. In the notation made in accordance with ISO 5351:2004, the viscosity or dynamic viscosity of a fluid, η, is defined by Newton's equation (Eq. 1).

$$\tau = \eta \gamma \qquad (1)$$

where: τ is shear stress, η is viscosity, and γ is the velocity gradient dv/dz (v is the relative velocity difference of the plate and z is the distance between the plates). Furthermore, according to ISO 5351, the shear rate G is the velocity gradient of the liquid layer parallel to the flow direction at the edge of the capillary, which is defined by Eq. (2).

$$G = 4 V / (\pi r^3 t_f) \qquad (2)$$

where: V is the volume (mL) between arbitrary calibration marks of the viscometer, r is the radius (cm) of the capillary tube, and t_f is the liquid outflow time (s).

Viscosity ratio (relative viscosity) η_{ratio} is the ratio of the viscosity η of a polymer solution with a given concentration to the viscosity η_0 of the solvent at the same temperature, (Eq. 3).

$$\eta_{ratio} = \eta / \eta 0 \qquad (3)$$

The viscosity relative increment is given by Eq. (4).

$$(\eta / \eta_0) -1 = (\eta - \eta_0) / \eta_0 \qquad (4)$$

Viscosity number ratio (VN) of the relative increase in viscosity to the polymer concentration c of the solution, expressed in grams per millilitre (Eq. 5).

$$VN = (\eta - \eta_0) / (\eta_0 c) \qquad (5)$$

The limit viscosity number [η] is the limit value of viscosity at infinite dilution (Eq. 6).

$$[\eta] = \lim_{c \to 0} [(\eta - \eta_0) / (\eta_0 c)] \qquad (6)$$

In the case of a non-Newtonian high molecular weight polymer solution (cellulose), the relationship between shear stress and velocity gradient varies with shear stress. The information needed to estimate the intrinsic viscosity number is obtained with a capillary tube viscometer. The shear rate has a significant effect on the measurement results.

3. Current reference method

In the forest industry, the value of the viscosity of pulp is determined using a dilute cupri-ethylenediamine (CED) solution with the method described in detail in the standard ISO 5351 (ISO, 2004). The viscosity determination must be carried out on a sample basis in the laboratory. The method is primarily suitable for CED-soluble samples of bleached chemical pulp. The method can also be applied to any pulp that is completely soluble in CED solution. The results can be used to estimate the degree of cellulose degradation caused by cooking or bleaching.

The method is based on measuring the flow times of a diluted solvent and a stock solution through a capillary tube viscometer at a temperature of 25 °C. The intrinsic viscosity number is calculated from these measurements and the known concentration of the solution. The concentration c is chosen so that when multiplied by the intrinsic viscosity [η], the result is $[\eta]\ c = 3.0 \pm 0.4$, which corresponds to a viscosity ratio $\eta/\eta_0 = 6–10$. The determination is made at a reproducible shear rate G $(200 \pm 30)\ s^{-1}$; using two viscometers, one of which is used for calibration and the other for measuring pulp viscosity.

The results obtained from samples containing significant amounts of non-cellulose should be interpreted with caution. Viscosity measurement methods can only be applied in the strictest sense to the polysaccharide fraction of the sample. Nevertheless, viscosity measurement can generally be used to obtain results from unbleached pulp with a lignin content of up to 4%, since most of these pulps can be successfully dissolved in CED. On the other hand, the mere fact that an unbleached pulp can be dissolved in CED does not mean that the results are valid. In summary, viscosity results from pulp containing more than 0.5% lignin cannot be accepted for specification.

Furthermore, the viscosity of the pulp in the CED solution provides an indication of the average degree of polymerisation (DP) of the cellulose. Such a measurement therefore provides a relative indication of the degree of cellulose degradation (reduction in the molecular weight of the cellulose) resulting from the pulping and/or bleaching process. Conclusions regarding the strength properties of the pulp should not be made solely based on viscosity measurements, unless a relationship has been observed in previous studies. No direct relationship has been observed between pulp strength and viscosity. It should also be noted that cleaning a capillary tube viscometer must be done very carefully. This requires strong solvents, such as acetone and sulfuric acid, which might be allowed to work overnight. Overall, this method is relatively labour-intensive and requires well-trained laboratory staff as well as the necessary laboratory equipment and maintenance. Skin contacts with used CED and ethylenediamine solutions should be avoided. Ethylenediamine is volatile and repeated exposure may lead to severe respiratory allergic reactions and sensitisation. CED solution is also harmful to the environment and must be disposed of properly.

PSL-Rheotek has introduced the RPV-1 AutoPulpIVA laboratory equipment, which is compatible with the ISO 5351 standard (PSL-Rheotek, 2023). This viscometer system fully automates the viscosity measurement of cellulose and paper pulp. The equipment takes care of, among other things, sampling, preparation, mixing, nitrogen purging, and the simultaneous measurement of two samples with viscometer tubes. The equipment produces the measurement results of relative viscosity, intrinsic viscosity (intrinsic viscosity number), degree of polymerisation (DP), K-value, kinematic viscosity (mm^2/s) and dynamic viscosity (mPa·s).

The equipment can analyse 4-6 samples per hour. The preheating of the equipment takes 30 minutes. The solution concentrations suitable for the equipment can be 0.2–0.5% and the measurement temperature used is 25 °C. The accuracy of the device is stated to be better than 1%. Although the equipment itself is automatic in terms of measurement, an operator must feed the sample into the test bottle and transfer it to the sampler after dilution standardisation. Consequently, the equipment cannot be directly transferred to a factory hall environment. From a cost structure perspective, use of the equipment involves significant labour, laboratory and competence maintenance costs.

4. Benchmarking transfer processes

Transferring laboratory measurements to a factory floor environment thematic is a complex issue. From a thematic perspective, one must consider techniques, technology, products, chemicals, regulations, guidelines, operating methods, personnel, costs, etc. There is no ready-made guideline for this, so this thematic can be compared with business literature (Hayes et al., 2005; Kim and Mauborgne, 2005; Mintzberg et al., 2003; Roussel et al., 1991). Production transfer means transferring the implementation of a product or service to a new production location. The transfer is closely linked to the company's strategy. Practical measures are taken regarding the organisation, logistics flows, facilities, products, personnel, working methods, operational processes, and customer interface.

Technology transfer means transferring technological expertise and the necessary development methods to a new organisation. Management of technology is typically transferred as a result of a corporate acquisition or licensing. Here, strategy-oriented know-how is integrated to create a new product. Practical measures are taken in intellectual property rights (IPR), personnel skills, development methods and tools, and the implementation and integration of production equipment together with strategic partners. Technology development means the development of technology unknown to the organisation for its own use. Technology development leads to a genuinely new production, product or service capability. The technology is initially developed based on a vision and later evolves into strategic expertise. Practical measures are taken in the areas of IPR, personnel skills, development methods and tools, and ultimately also together with strategic customers to ensure the usability of the technology.

Overall, the goal of these operating models is to: achieve profitable growth in the short and long term through synergies; reduce the organisational footprint; renew the organisation's technological base; enable the profitable adoption of technology; and facilitate a unique technological competitive advantage. The time frame of the change processes is assumed to be a few years. After this, further development takes place as part of normal development activities. Ultimately, the organisation is capable of manufacturing, maintaining, and operating the new technology and product profitably, thus achieving a lasting competitive advantage.

The operating models discussed above can be utilised in transferring a laboratory measuring device to a factory floor. In summary, the transfer process includes not only the transfer of production and production documentation, but also other functions. For example, manufacturing inventory, maintenance statistics and technical cause analysis are essential. Technology cannot be transferred without knowledge of the reasons behind the design principles, tolerances and limitations. The transfer process is also not complete until the new product has been designed and achieved success on the market. To ensure a good end result, all the information is needed, down to the smallest detail.

5. Transfer to the factory floor

Product or technology transfer is a comprehensive process. It includes initial idea validation, the development of know-how, operational assurance, design work, testing, and the implementation of operational capabilities. In connection with validating the transfer idea, a preliminary technical validation of the idea is carried out by conducting, for example, a pre-study or feasibility study. In the simplest form of a transfer, the device to be transferred is purchased and its operation is tested in the desired environment. The technical functionality should be examined from the perspective of customer requirements and intended use cases. Also, business case should be clarified.

Know-how is key to product and technology transfer. If in-depth knowledge of the details of the technology does not exist, it must be acquired. Furthermore, know-how in managing measurement capabilities, possible technical change needs, component availability, and customer requirements must be developed. To ensure commercial success, consideration must be given to how the updated device will be accepted in the new installation location with respect to the customer and potential standards. Progressing from this point requires alignment with the company's strategy, a commitment of substantial R&D resources, and the acquisition of intellectual property rights.

It is very difficult and risky to transfer a product or technology if there is no access to the technology's design history, technical details or user experiences, not to mention all the tacit knowledge associated with them. Therefore, before starting the process, one should secure access to intellectual property rights (IPR) and enter into a strategic agreement with the IPR owner. If existing IPR cannot be accessed and utilised as such, a corresponding feature must be developed without infringing upon existing rights. However, it is worth noting that IPR are a much broader concept than just patent protection. Sufficient time and resources must be allocated to developing the necessary technology. The actual technical implementation includes design, prototypes, consideration of implementation constraints and tolerance chains, customer demonstrations as well as the implementation of alternative concepts and plans to solve selected problem areas.

To ensure successful marketing and customer satisfaction, it must be possible to demonstrate that the designed product and its accessories meet the internal, customer, and regulatory requirements set for it. In accordance with the normal product development process, the product is documented, the planned R&D testing is conducted, and the necessary regulatory approvals and certificates of conformity are obtained. Finally, production, service, marketing and sales capabilities are implemented using a variety of methods. At this stage, small product changes are still possible, but their implementation is typically very expensive. Figure 1 shows the steps needed for technology and production transfers.

6. Discussions

Viscosity measurement was chosen as the subject of the study because response time and chemical load in laboratory measurements are common challenges faced in the process industry. In the quality control of industrial production processes, efforts should be made to perform the necessary measurements on the production line, as the process sample may change between sampling and laboratory measurement. On the other hand, laboratory equipment can rarely be transferred directly to the production line. Therefore, special equipment suitable for the factory floor is needed. When developing a measuring device, its usability in different operating environments must be taken carefully into account. In addition, the relationship between the material being processed and the measurement that describes it must be understood very precisely. If this relationship is not satisfactorily understood, it is easy to draw incorrect conclusions.

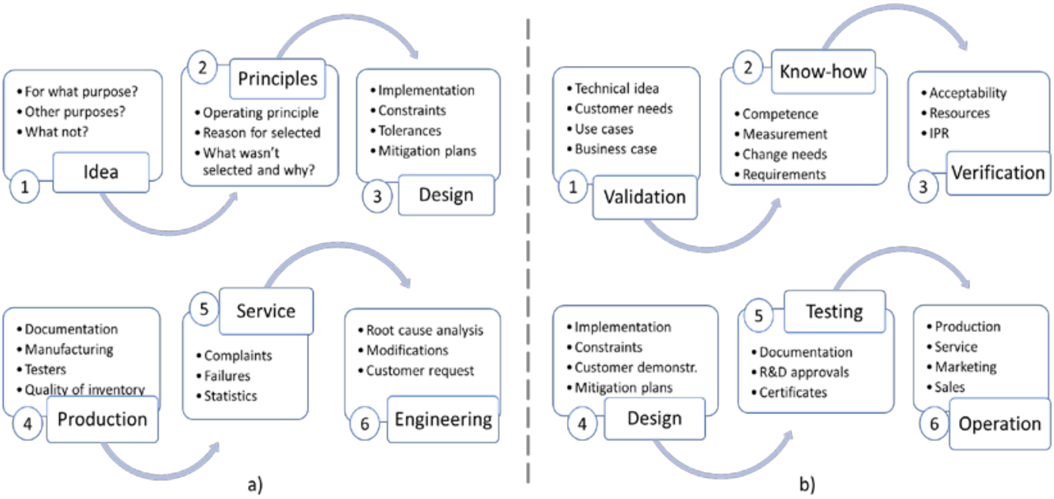

Fig. 1. Process details: a) production transfer and b) technology development

For example, one must be familiar with:

- The physical properties of the material being processed and the cross-correlation (cross-effects, matrix-effect) of other phenomena.
- The interactions between a given process step and its environmental properties, such as temperature, pressure, material movement and sample homogeneity.
- Traditional laboratory measurement principles and their suitability for online measurement - development of the measuring device or its interface.
- Measurement uncertainty, repeatability and the role of the operator performing the measurement.
- The maintainability, life cycle, cost structure of the measuring device and its operation.
- Occupational safety and other standards related to the measuring device.

A key tool in the development of measuring instruments is requirements management. Requirements management should not be underestimated, as it links the desired features to the real needs of customers. Requirements management consists of three steps:

1. Collect requirements describing the target market.

2. Develop methods to verify the requirements so that the product being developed meets them.

3. Validate the correctness of the requirements with customers.

In development projects, the available resources and time, as well as the scope and level of the development goals, are essential factors. In addition to these bottlenecks, in thematic development, IPR form a difficult entity that must be resolved during development. A straightforward concept – although difficult to implement – is just construct alternative device suitable for the factory floor. However, this approach does not make the chemicals used more environmentally-friendly or reduce their quantity. From this perspective, the use and utilisation of the upgraded device only improves cost efficiency. On the other hand, the ISO 5351 standard states in many ways that there are several limitations in interpreting the results. Simply transferring equipment to the factory floor as a development project will not solve this problem. It is important to study customer needs so that the target level of the development project can be set to match the related operational objectives. It is also necessary to develop alternative measurement methods and solutions that are suitable for the industry to reduce chemical loads.

6. Conclusions

The transition from laboratory-based analyses to industrial-scale applications represents a fundamental step toward improving process efficiency, sustainability, and safety in modern manufacturing environments. With regard to the transition from laboratory to factory floor, the key aspects are: strengthening the functionality of the idea; the know-how for developing and maintaining the necessary measurement capabilities; and ensuring the usability of IPR. Coordination of the development project's objective, risk and business levels as well as customer approval must be invested in, as this would involve operating with a known standardised technology/method on new markets, albeit in connection with existing markets. In order to fully exploit the potential of reducing chemical loads, there is a need to investigate alternative chemical-free measurement methods.

Furthermore, the successful transfer of laboratory methods to industrial environments requires a holistic approach that integrates technical innovation, process optimisation, and sustainability objectives. Continuous monitoring systems and advanced sensor technologies can significantly enhance the responsiveness and accuracy of factory floor operations while minimising reliance on hazardous substances.

Collaboration between research institutions, equipment manufacturers, and industrial operators is essential to ensure that newly developed technologies meet both performance and environmental standards. In this context, lifecycle assessment and cost–benefit analysis become vital tools for evaluating the long-term feasibility and ecological advantages of chemical-free measurement solutions. Ultimately, the transition represents not only a technological challenge but also an opportunity to promote safer workplaces, reduce environmental impact, and enhance overall industrial efficiency.

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References

Bentley J.P., (2005), *Principles of Measurement Systems*, 2nd ed., Pearson Prentice Hall, London.

Hayes R., Pisano G., Upton D., Wheelwright S., (2005), *Operations, Strategy, and Technology – Pursuing the Competitive Edge*, Wiley, Hoboken, USA.

ISO, (2004), *Pulps: Determination of Limiting Viscosity Number in Cupri-ethylenediamine (CED) Solution*, *ISO 5351:2004(E)*, International Organization for Standardization, Geneva, Switzerland.

Kim W.C., Mauborgne R., (2005), *Blue Ocean Strategy*, Harvard Business School Press, Boston, USA.

Mintzberg H., Lampel J., Quinn J.B., Ghoshal S., (2003), *The Strategy Process*, Prentice Hall, Harlow, UK.

PSL-Rheotek, (2023), *RPV-1 AutoPulpIVA – Fully Automatic Pulp Cellulose Viscometer*, On line at: https://www.psl-rheotek.com/rpv-1-autopulpiva-fully-automatic-pulp-cellulose-viscometer.html

Rayleigh Lord Sec. R.S., (1893), On the flow of viscous liquids, especially in two dimensions, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, **36**, 354–372.

Roussel P.A., Saad K.N., Erickson T.J., (1991), *Third Generation R&D*, Little, Brown and Company, Boston, USA.

Seppälä M.J., Klementti U., Kortelainen V.-A., Lyytikäinen J., Siitonen H., Sironen R., (2005), *Kemiallinen metsäteollisuus 1 – Paperimassan valmistus*, 2nd ed., Opetushallitus, Helsinki, Finland.

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IMPACT OF WEED CONTROL ON URBAN HYGIENE MANAGEMENT IN MUNICIPALITIES*

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Abstract

Weed control, in the context of urban hygiene, refers to the elimination of weeds from public areas such as streets, sidewalks, parks, and gardens. This practice contributes to urban cleanliness and decorum, facilitating waste collection and improving the usability of spaces.
Weed control in urban areas is a common practice aimed at maintaining the aesthetic order and functionality of public and private spaces. However, the methodologies used and their frequency can have significant implications for the urban environment, biodiversity, human health, and the economy. This scientific article explores the multidisciplinary impact of weed control in cities, analyzing the ecological, health, social, and economic effects of different weed management strategies. The consequences of the use of chemical herbicides, mechanical techniques, and integrated management practices are examined, highlighting the need for sustainable approaches that balance urban needs with environmental and public health protection.

Keywords: environmental impact, LCA, recovery, special waste

1. Introduction

Cities are complex ecosystems where the interaction between human infrastructure and natural elements creates unique challenges in managing urban greenery. Weeding, or the removal of unwanted vegetation, is a widespread practice in urban settings, applied to sidewalks, streets, parks, private gardens, and industrial areas (Booth et al., 2010). The motivations behind weeding are varied and include aesthetics, safety (preventing tripping, improving visibility), infrastructure maintenance (preventing root damage), and health (controlling allergens or disease vectors). Roadside weeding is a major source of protest and a perceived neglect. It's a calling card for a region and an activity that often lacks the financial resources to carry it out, and depending on the climate, it leads to an increase in annual

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interventions. A challenging period for this sector is the period of increasingly frequent seasonal changes. This activity was conducted to understand the feasibility of implementing low-impact preventative and follow-up actions to ensure resource savings while simultaneously achieving economic and environmental improvements (Bajwa et al., 2026).
From the data analysis conducted in several locations in central Italy, obtaining detailed data was nearly impossible, as the waste managed was either collected from street sweepings or collected through green waste collection. Starting from this assumption, we analyzed the hours spent per kilometer managed. The monthly peaks are always recorded in the months of April/May/June and then September/October (Fig. 1). The values analyzed in the first phase included mechanical weeding without any type of herbicide.

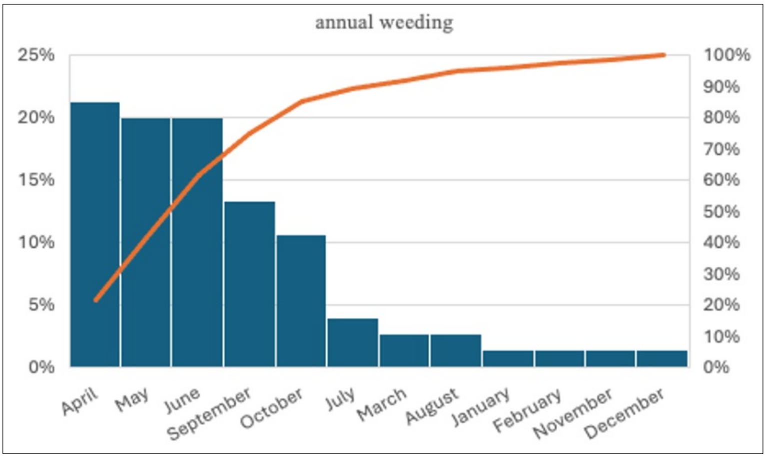

Fig. 1. Comparative regrowth of weeds following mechanical weeding and treatment with natural herbicide mixtures of salt and vinegar at different concentrations

We then proceeded to use natural herbicides in order to verify, with the same interventions, their possible improvement action. First of all, we found what the bibliography reported on herbicides. She highlighted that among the most common natural herbicides there are (Chalker-Scott, 2013):

- Vinegar: The acetic acid present in vinegar (especially the white one with a higher concentration) can dehydrate the leaves of weeds, leading to their death. Spray the vinegar directly on the weeds, avoiding the desired plants. Effectiveness is greater on sunny days.
- Salt: Salt (sodium chloride) can dehydrate plants. Dissolve some salt in water (about 200g per litre) and spray the solution on the weeds. Be careful because salt can make the soil sterile in the long term and damage nearby plants.
- Baking soda: Sprinkling baking soda on weeds, especially those growing between cracks in floors, can help them dry out.
- Marseille Soap: Dissolving some Marseille soap in water and spraying it on weeds can help other natural weeding solutions adhere better to the leaves and may have a slight drying effect.
- Essential oils: Some essential oils such as lemon, clove or citrus may have herbicidal properties. Dilute them in water with a little Marseille soap as an emulsifier and spray on the weeds.

Based on the above, some of the components were mixed and a herbicide composed of salt and vinegar in various concentrations was prepared.

4. Materials and methods

In urban areas, various weed control systems are used, each with its own characteristics, advantages and disadvantages (Rask and Kristoffersen, 2007). The most common systems are presented in Table 1 (Rask and Kristoffersen, 2007; Kristoffersen et al., 2008).

Table 1. Estimated frequency and duration of weeding activities in urban areas based on monthly variations in maintenance intensity

Type of method	***Descriere***
Chemical herbicides	They represent one of the most common methods due to their effectiveness and relative speed of action. They are divided into different categories depending on the mechanism of action (e.g. systemic, contact, pre-emergence, post-emergency) and selectivity. However, their use raises concerns about environmental impact (soil and water contamination, effects on non-target organisms) and human health (direct and indirect exposure). Common examples include glyphosate, dicamba, and 2,4-D.
Mechanical weeding	Includes a variety of physical techniques for removing weeds. o Mowing: Use of brush cutters, lawn mowers or mowers to cut the aerial part of weeds. It is effective at controlling growth and spread, but often requires repeated interventions. o Manual weeding: Manual removal of weeds, particularly suitable for small areas or for selective interventions. It is an environmentally friendly but labor intensive method. Mechanical Weeding: Use of specific equipment (e.g. mechanical hoes, weeders) to remove weeds from the soil. It can be more efficient than manual weeding for larger areas. o Aeration and Scarifying: Techniques used mainly for turf management, they help reduce thatch and improve the penetration of air and water, making the environment less favorable to some weeds.
Heat treatments	Use heat to destroy weeds. o Water Vapor: The application of high temperature steam causes the denaturation of plant proteins, leading to the death of the plant. It is an ecological method but may require specific equipment and high energy consumption. o Hot Water: Similar to steam, hot water applied directly to weeds can be effective, especially for young plants.
Mulching	Consists of covering the soil with organic materials (e.g. bark, straw, compost) or inorganic materials (e.g. plastic sheets, gravel). Mulching prevents weed seeds from germinating, reduces growth and maintains soil moisture.
Biological management	Using living organisms to control weeds. This approach is less common in urban settings than in agriculture, but may include the introduction of phytophagous insects or pathogenic fungi specific to certain weed species.

Based on the above, our focus was based on natural herbicide. Some of the components were mixed and an herbicide composed of salt and vinegar in various concentrations was prepared (Table 2). The regrowth times were therefore analyzed under equal conditions between a mechanical cut and a cut with a natural herbicide at different concentrations (Table 3) and we analyze the regrowth of the three different mixed component (Fig. 2). Once the above has been analyzed, we went into detail by comparing the mechanical weeding method with natural herbicides.

Table 2. Composition of natural herbicide mixtures prepared with varying concentrations of vinegar, salt, and water

Solution	***Vinegar***	***Salt***	***Water***
n. 1	1 lt	1/4	1 lt
n. 2	1 lt	1/4	2 lt
n. 3	1 lt	1/4	4 lt

Table 3. Comparison of weed regrowth times following mechanical weeding and treatments with different natural herbicide mixtures.

Solution	***Time (Week)***	***Normal***	***Regrowth (Days)***	***Day/Year***
n. 1	1	1 week	14	55
n. 2	1	1 week	10	30
n. 3	1	1 week	10	30

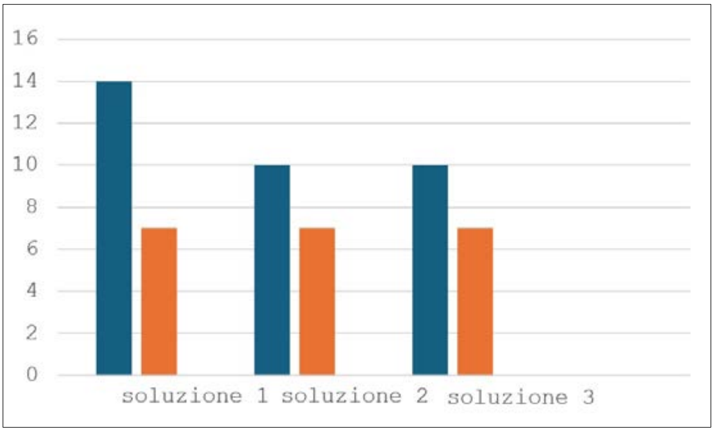

Fig. 2. Comparison of weed regrowth rates for different natural herbicide mixtures based on vinegar and salt concentrations

5. Results and discussion

The impact of weeding extends not only to decoration but also to the social and economic sphere because it develops the following themes (Benvenuti, 2004; Shaner and Beckie, 2014; Travlos et al., 2018):

- Economic costs: Weed management in cities involves significant costs for governments and individuals, including the purchase of herbicides, maintenance of mechanical equipment, labor and disposal of plant waste.
- Urban aesthetics and public perception: Weeding is often perceived as necessary to maintain urban order and decorum. However, excessive control of spontaneous vegetation can lead to sterile urban landscapes lacking in naturalness, with a negative impact on the psychological well-being of citizens and the use of green spaces.
- Ecological value and ecosystem services: Weed removal can result in the loss of important ecosystem services provided by urban vegetation, such as absorption of air

pollutants, urban heat island mitigation, stormwater drainage, and support of biodiversity. These services have an intrinsic economic value that is often not considered in weed control management decisions.

A more sustainable approach to weed management in cities is based on the principles of Integrated Management which should aim to minimize environmental and health risks through a combination of preventive, biological and mechanical strategies. Some key elements of integrated management in urban contexts include (Pimentel, 2005; Travlos et al., 2018):

- Prevention: Adoption of urban green design and maintenance practices that reduce the proliferation of weeds, such as the choice of plant species suitable for the local context, correct soil and irrigation management, and the use of mulch.
- Monitoring: Regular assessment of the presence and abundance of weeds to determine the need and timing of interventions.
- Mechanical and physical control: Use of techniques such as mowing, manual or mechanical weeding, the use of hot water or steam to eliminate weeds.
- Chemical control (last resort): Selective use of low environmental impact herbicides, only when other strategies are not sufficient and applied in a targeted manner to minimize exposure and dispersion.
- Education and awareness: Inform citizens and urban greenery operators on the importance of sustainable management practices and the risks associated with the indiscriminate use of herbicides.
- Natural Herbicide that is what we analyze and this application shows that using a natural herbicide can improve green management.

6. Concluding remarks

Weeding in the cities is a complex practice with implications that go beyond the simple removal of unwanted vegetation. The ecological, health, social and economic impacts of weed management strategies require multidisciplinary evaluation and the adoption of more sustainable approaches. The excessive use of chemical herbicides poses significant risks to biodiversity, human health and the quality of the urban environment.

Integrated Weed Management offers a conceptual framework for developing more balanced and effective management strategies, which prioritize prevention, biological and mechanical control, and reserve the use of chemical herbicides for specific and well-defined situations. Public administrations, urban green professionals and citizens have a crucial role in promoting and adopting sustainable weeding practices, in order to protect the urban environment, public health and the quality of life in our cities.

Further research is needed to evaluate the effectiveness and costs of different strategies in specific urban contexts and to develop evidence-based guidelines for more responsible urban green management.

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References

Bajwa A.A., Sadia S., Ali H.H., Jabran K., Peerzada A.M., Chauhan B.S., (2016), Biology and management of two important *Conyza* weeds: A global review, *Environmental Science and Pollution Research*, **23**, 24694–24710.

Benvenuti S., (2004), Weed dynamics in the Mediterranean urban ecosystem: Ecology, management and sustainability, *Weed Research*, **44**, 341–354.

Booth B.D., Murphy S.D., Swanton C.J., (2010), *Weed Ecology in Natural and Agricultural Systems*, 2nd ed., CABI, Wallingford, UK.

Chalker-Scott, L. (2013). Organic Weed Control, Fact Sheet FS223E, Washington State University Extension, Pullman, USA.

Kristoffersen P., Rask A.M., Grundy A.C., Franzén I., Kempenaaar C., Raisio J., Schröder H., Spijker J., Verschwele A., Zarina L., (2008), Review of pesticide / herbicide policy and regulation for urban amenity areas in seven European countries, *Weed Research*, **48**, 201-214

Pimentel D., (2005), Environmental, energetic, and economic comparisons of organic and conventional farming systems, *BioScience*, **55**, 573-582.

Rask A.M., Kristoffersen P., (2007), A review of non-chemical weed control on hard surfaces, *Weed Research*, **47**, 370–380.

Shaner D.L., Beckie H.J., (2014), The future for weed control and technology, *Pest Management Science*, **70**, 1329–1339.

Travlos I.S., Bilalis D.J., Katsenios N., de Prado R., (2018), *Sustainable Weed Control in Vineyards*, In: *Weed Control*, Korres N.E., Burgos N.R. (Eds.), CRC Press, Boca Raton, pp. 526–542.

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THE LEAK DETECTION AND REPAIR (LDAR) PROGRAM AS AN EFFECTIVE STRATEGY FOR THE MITIGATION OF ODOR EMISSIONS IN INDUSTRIAL PLANTS*

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Abstract

Implementing a Leak Detection and Repair (LDAR) program is a critical strategy for the Volatile Organic Compounds (VOCs) fugitive emissions management, which constitute a large portion of diffuse emissions from industrial equipment, pipelines, and storage systems. The primary objective of LDAR campaigns is to identify, quantify, and ultimately mitigate emission sources that exceed the threshold values defined as "leaks" in the Integrated Environmental Authorization (IEA) applicable to each industrial plant, with direct reference to U.S. EPA Method 21. Once emission sources are identified, corrective actions are undertaken through targeted maintenance and repair, in strict compliance with the Equipment Leak Emissions Estimation Protocol (EPA-453/R-95-017). In addition to reducing VOC loads, LDAR programs also contribute to reducing odor nuisance, as several compounds have low odor thresholds and therefore play an important role in safeguarding environmental quality and public well-being. This methodology is recognized as best practice under the IPPC Directive and is based on visual inspection of process components combined with instrumental measurements.

The present study is based on an extensive dataset obtained from several annual LDAR monitoring campaigns carried out at three large chemical plants. Special emphasis was placed on pollutants of high environmental relevance that have a strong odorous impact, including SO_2, HCl, NH_3, and BTEX compounds. Emission levels before and after maintenance were compared to evaluate the program effectiveness. In addition, the influence of meteorological conditions, temperature, wind speed and humidity was investigated, since these factors affect both the pollutants dispersion and the measurements' reliability. Overall, longitudinal analysis of the dataset revealed a consistent reduction in odor-related emissions, while also enabling the identification of key process components responsible for the large part of fugitive releases.

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Keywords: fugitive emissions, IPPC directive, *LDAR*, odor emissions

1. Introduction

Leak Detection and Repair (LDAR) programs are critical in addressing the environmental and health risks associated with fugitive emissions, unintentional releases of gases or vapors from industrial equipment, pipes, and systems, as well as from landfills. These emissions, which often go undetected in routine monitoring, can have significant environmental and public health impacts, contributing to air pollution and posing risks to workers and surrounding communities. Fugitive emissions are typical in industries such as petrochemicals, natural gas processing, and waste management (Kashyap et al., 2016), where they can involve volatile organic compounds (VOC) and hazardous air pollutant substances (HAP) like sulfur dioxide (SO_2), ammonia (NH_3), hydrochloric acid (HCl), and BTEX (benzene, toluene, ethylbenzene, and xylene). These compounds are not only toxic but also exhibit strong and often pungent odors, further amplifying the need for effective detection and repair systems.

Sulfur dioxide, with its characteristic pungent, irritating odor, is detectable at low concentrations (WHO, 2005) and is a significant air pollutant. Ammonia, known for its sharp, acrid smell, presents substantial risks to human health, especially in industrial environments (Jiang et al., 2024). Hydrochloric acid, though less odorous, can be highly corrosive and poses serious respiratory hazards (ATSDR, 2010). BTEX compounds, with their sweet, gasoline-like odor, are volatile and carcinogenic, necessitating their careful monitoring and swift intervention to prevent long-term health effects (Durmusoglu et al., 2010).

Effective LDAR systems enable the early detection and mitigation of these dangerous emissions, utilizing a variety of advanced monitoring technologies, including infrared cameras and gas analyzers. By identifying leaks in a timely manner, and after maintenance, these systems reduce emissions, protect workers and local communities, and support compliance with environmental regulations. In this context, LDAR programs play a key role within the framework of the Industrial Emissions Directive (IED) 2.0, which emphasizes the need for comprehensive emissions monitoring, management, and reduction across various industries.

The Intergovernmental Panel on Climate Change (IPCC, 1996) define fugitive emissions as “emissions (of greenhouse gases) that are not produced intentionally by a stack or vent” and stipulates that they may “include leaks from industrial plants and pipelines” (IPCC, 2006). This definition was detailed, considering the potential sources as “they may be caused by the production, processing, transmission, storage and use of fuels and include combustion emissions only if they do not meet production needs (e.g. natural gas flaring at gas and oil production facilities) “(IPCC, 1996). IED 2.0 aims to strengthen the industrial emissions control across the European Union by considering stricter emission limits, improved monitoring, and more rigorous enforcement of best available techniques (BAT). LDAR programs are explicitly recognized as an important component under the updated directive, which requires operators to implement measures that minimize fugitive emissions VOCs and HAPs, including SO_2, ammonia, HCl, and BTEX. According to IED 2.0, industries must ensure that their facilities are equipped with effective leak detection and repair technologies as part of their compliance with BAT-associated emission limits. This directive also encourages the use of innovative technologies to reduce emissions and improve air quality, supporting the transition toward more sustainable and environmentally responsible industrial practices (European Commission, 2022). Including LDAR program into the broader regulatory framework of IED 2.0 not only ensures that industries reduce harmful emissions but also helps mitigate public health risks and environmental damage, aligning with broader EU objectives of reducing air pollution and minimizing industrial impact on ecosystems.

The objective of this study is to analyze fugitive emissions from components that transfer streams of substances that may have an odorous impact on the environment. Specifically, ammonia (NH_3), sulfur dioxide (SO_2), hydrochloric acid (HCl), and BTEX (Benzene, Toluene, Ethylbenzene, Xylenes) were considered, which have a strong odor component and are characteristic of the chemical plants considered (PL1, PL2, PL3) described in the following chapters. The assessment of fugitive emissions follows internationally recognized procedures, established by the United States Environmental Protection Agency and subsequently incorporated into the European standard UNI EN 15446 (2008), which currently represents the reference guideline for these activities. Furthermore, following the identification of the leaking components, the estimated emission flows after the maintenance performed were analyzed.

This work is divided into three main parts:

- selection of case studies: data collection regarding the LDAR monitoring surveys conducted in three Italian chemical plants named as PL1, PL2 and, PL3, subjected to the Integrated Environmental Authorization (IEA) under the European Directive on Industrial Emissions (IED) 2010/75/EU, that are characterized by using volatile compounds that have a strong odorous component:
- evaluation of emission flows for each component considered,
- analysis of results, drawing conclusion and evidence that the correct implementation of an LDAR program can lead to the reduction of volatile compounds fugitive emissions and that such a program can be a very useful tool for the odor emissions reduction.

2. Materials and methods

2.1. Plants description

The case study chosen for the present work, are three Italian chemical plants named as PL1, PL2 and, PL3, subjected to the Integrated Environmental Authorization (IEA) under the European Directive on Industrial Emissions (IED) 2010/75/EU.

- The PL1 chemical plant's activities are aimed at nitric acid production, ammonium nitrate-based fertilizers, and complex fertilizers.
- The PL2 chemical plant mainly produces sulfuric acid, hydrochloric acid, phosphorus, sodium, and potassium fertilizers.
- The PL3 chemical plant is designed to produce styrene and styrene-based polymers.

2.2. Meteorological data

Meteorological conditions are a critical parameter in the fugitive emissions assessment, as they can influence both the atmospheric gas dispersion and the monitoring instruments performances. To account for this influence, the emission fluxes in this study were evaluated in relation to key meteorological parameters such as temperature, wind speed, humidity, and precipitation. Temperature variations influence the emission plumes buoyancy and, their dispersion patterns, also influencing the chemical stability of some compounds. Humidity can modify instrument sensitivity by modifying the gas density and interfering with sensor response, particularly in optical and spectroscopic techniques. Precipitation can reduce atmospheric concentration by retaining pollutants.

Wind speed has a prominent influence on measurements; high wind speed enhances atmospheric turbulence and accelerate gas dilution increasing unstable measurement conditions. According to UNI EN 15446 (2008), for the OGI measurements and, for wind speeds exceeding 1.8 km/h, special attention should be used during monitoring to minimize uncertainties associated with turbulent airflow. Neglecting these effects may lead to emission rates underestimation or overestimation, compromising the reliability and comparability of monitoring surveys. Careful integration of meteorological data into the fugitive emissions evaluation is essential to ensure robust quantification and meaningful interpretation of monitoring results. In Table 1 the meteorological parameters values measured during the surveys are reported.

Table 1. Meteorological data

	PL1			***PL2***			***PL3***		
Parameter	***2022***	***2023***	***2024***	***2022***	***2023***	***2024***	***2022***	***2023***	***2024***
Temperature [°C]	7-10	5-7	17-20	10-25	9-12	16-17	5-29	22-29	7-18
Humidity [%]	77-91	88-91	74-89	58-81	87-88	78-91	45-88	46-74	71-99
Wind speed, [km/h]	8-13	4-5	12-13.5	10-20	4-4.5	2-4	9-52	6-16	0-1

The meteorological conditions measured during the 2022 and 2023 surveys conducted in the PL1 plant were optimal for the fugitive emissions evaluation. For instance, UNI EN 15446 (2008) recommends not to carry out measurements in the presence of wind speeds in the range 20-28 km/h. For plant PL3, that includes the monitor of fugitive emissions from non-accessible sources using the OGI technique, the wind condition during the 2024 campaign, with a wind speed lower than 1.8 km/h, was the optimal according to UNI EN 17628 (2022).

2.3. LDAR protocol description

The Leak Detection and Repair (LDAR) program is implemented in strict accordance with USEPA Protocol 453/95 (USEPA, 1995). An initial component inventory is established, including classification by type, fluid phase, and fluid category, spatial allocation within the process line, and assignment of a unique TAG ID. Each monitoring campaign generates data for a generic component *i*, allowing direct comparison with previous measurements. Components are aggregated into groups based on spatial proximity or technical similarity, which serve as the basis for defining monitoring paths. Each path includes all relevant components and defines a mandatory monitoring sequence to ensure systematic data acquisition. This approach minimizes operator discretion, reduces errors associated with manual data handling, and ensures consistency across campaigns. Rigorous data management and processing are essential to guarantee the reliability and accuracy of emission estimates.

Subsequently, emissions from the inventory were calculated according to EN 15446 (2008) procedures, considering both monitored and unmonitored components. The monitored components were previously inventoried and grouped into the following categories: agitators (AGT), compressors, and pumps (PMP), valves (VLV), safety valves (PSV), flanges (FLG), and line ends (END). Each category was further divided into gas or light liquid (LL) subgroups depending on the stream phase, following the classification criteria of EPA Protocol 453/95 (USEPA, 1995). The flange category includes line flanges (piping), equipment flanges (heat exchangers), and valve bonnet flanges.

Each identified source is then monitored using different techniques according to the stream considered. After measurements, the sources are classified according to their leakage. A leak is defined as the identification of an emission with a concentration, expressed in ppmv of methane, higher than the threshold value and determined using EPA method 21. A source that has shown an emission visible to the optical system used (OGI) is defined also as a leak. To complete the definition, any emission that is visible and/or audible and/or odorous during inspection (visible vapors, liquid leaks, etc.), regardless of the concentration, is considered a leak. The components with a leakage higher than the threshold defined in the IEA decree, that depends on the stream considered and, on the components, are considered divergent (leaking source). The divergent components are subjected to maintenance and subsequently to re-monitoring to check if the maintenance has fixed the leakage.

The leakage threshold for this study is 10,000 ppmv for PL1 and PL2 since the stream considered (NH_3, SO_2 and, HCl) are not classified as H350 substance (“May cause cancer” - carcinogenicity category 1A or 1B) according to the CLP Regulation. For PL3 the threshold is 500 ppmv for the Benzene because it is classified as H350 while for Toluene, Ethylbenzene, and Xylenes that are not classified as H350 is 1.000 ppmv.

2.4. Monitoring techniques

Usually, the LDAR program is implemented to measure the fugitive emissions of Volatile Organic Compounds (VOC), including BTEX, according to the EPA METHOD 21 using instruments to detect leaks. The photoelectric ionization detector (PID) and the flame detector (FID) are widely used to monitor the VOC leakage. In addition to VOCs, fugitive emissions include a wide range of volatile inorganic compounds (VICs), which are chemicals that contain other elements than carbon and can evaporate or vaporize at low temperatures, becoming gases or vapors. Portable Inorganic Gas Analyzers are designed to detect and measure the concentration of specific volatile inorganic compounds, such as ammonia (NH_3), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and use specific sensors to detect each compound of interest. Fugitive SO_2 and HCl emissions can be quantified using both direct (in situ) instruments and indirect techniques. For SO_2, portable ultraviolet fluorescence (UVF) analyzers exploiting gas-specific fluorescence are commonly employed for spot monitoring. Infrared-based instruments, including nondispersive infrared (NDIR) and portable Fourier-transform infrared (FTIR) analyzers, are suitable for both gases and applicable to spot measurements as well as portable CEMS. Tunable Diode Laser Absorption Spectroscopy (TDLAS), widely used in industrial applications, provides selective, real-time detection of HCl with high sensitivity.

Indirect and laboratory-based techniques are also employed. Passive diffusive samplers offer cost-effective, time-integrated measurements of both gases, although they lack temporal resolution and are mainly used for indicative assessments. Active sampling with colorimetric detector tubes, according to the UNI EN 1231, (1999), enables rapid, low-cost process measurements for HCl and other gases (e.g. NH_3, SO_2, H_2S, CH_2O), with immediate on-site readings obtained directly from the vial scale. Impingers, in which air is bubbled through absorbent solutions and subsequently analyzed by titration or ion chromatography, provide accurate quantification of HCl in laboratory settings. The non-accessible sources using the US EPA Method 21, can be monitored using an Optical Gas Imaging instrument (OGI) that uses an infrared thermal imaging camera, equipped with an optical filter, sensitive to the absorption of infrared radiation by some VOCs according to the UNI EN 17628 (2022); this method was used in PL3 to monitor the non-accessible sources.

In this study:

- NH_3 streams were measured using a portable flame ionization analyzer (FID) with a measurement range of 0.00–100,000 ppmv;
- SO_2 streams were measured using a portable FTIR combustion analyzer with a measurement range of 0–500 ppmv;
- HCl streams were measured with a portable analyzer operating over a range of 0–200 ppmv;
- BTEX streams were monitored with a portable FID detector operating over a range of 1.0-10,000 ppmv.

2.5. Emission flow calculations

To estimate the emission flux, the correlation equations in Annex C of EN 15446:2008, Table C1 – US EPA Chemical Industries correlation parameters and factors EPA 453/R-95-017, and the emission factors provided by the US EPA SOCMI Correlation method were used. The EPA 453 method allows the estimation of emission fluxes using correlation equations (Lotrecchiano et al., 2025; USEPA, 1995).

3. Results and discussion

This paper presents an important study regarding the use of the LDAR program as a tool for the reduction and mitigation of odorous emissions from an industrial plant. Starting with the inventory and analysis of the components that may cause leaks, we move on to the subsequent monitoring and emission estimate calculation. Following the measures and maintenance of the components considered leaky, the emission flow is reduced, resulting in a reduction in odorous impact. In Table 2 the results of the sources census for PL1 and PL2 in the period considered (2022-2024) are reported, highlighting the number of monitored and unmonitored sources with reference to the number and the percentage of leaking components, considering only the components conveying NH_3, SO_2 and HCl. The percentage of divergent components was calculated as the ratio between the number of divergent components and the monitored sources. For the PL3 plant, the results of the LDAR campaigns were analyzed on all VOC-conveying components and, results are reported in Table 3 where the monitored sources have been divided into accessible and non-accessible.

Considering the source census, for the components handling NH_3, the number of monitorable sources has changed over the years and only in the 2022 survey revealed a divergence compared to the Leak Definition of 10,000 ppmv, equal to 0.06% (3 divergences detected out of 5,384 monitorable sources). In PL2, the number of monitorable sources remained constant over the years, and no components handling SO_2 or HCl were found to be divergent. The PL3 plant, as described in paragraph 4.1.4, monitored both accessible and non-accessible sources VOC-conveying. As shown in Table 3, accessible components represent the largest percentage of the censed components, reaching approximately 71%, while non-accessible monitored components account for approximately 20%. Between 2022 and 2023, the number of surveyed components remained unchanged, decreasing in 2024 due to the temporary shutdown of part of the PL3 plant during the year. None of the non-accessible sources were divergent over the year. Among the accessible sources, the divergence was of 0.07% in 2022, 0.05% in 2023 and 0.04% in 2024, highlighting that the maintenance done during after the previous LDAR survey was effective. No leaky components were detected in any measurement surveys carried out on PL3 inaccessible sources inspected using OGI.

Table 2. PL1 and PL2 sources distribution

Stream	***PL1***			***PL2***					
	NH_3			***SO_2***			***HCl***		
	2022	***2023***	***2024***	***2022***	***2023***	***2024***	***2022***	***2023***	***2024***
n. censed sources	5,852	5,855	5,835	1,263	1,263	1,263	1,921	1,921	1,921
n. monitorable sources	5,834	5,385	5,365	1,166	1,166	1,166	1,851	1,851	1,851
n. unmonitored sources	468	470	470	97	97	97	70	70	70
percentage of monitored sources	92.0	91.97	91.94	92.3	92.3	92.3	96.4	96.4	96.4
divergent components	3	0	0	0	0	0	0	0	0
percentage of divergent components	0.06	0	0	0	0	0	0	0	0

Table 3. PL3 sources distribution

		PL3		
		2022	***2023***	***2024***
Measurement method	n. of censed sources	95,721	95,721	92,290
EPA Method 21 (FID/TCD)	n. of accessible monitorable sources	71,610	71,461	66,304
	percentage of accessible monitorable sources, %	74.8	74.7	71.8
	n. of divergent components	49	33	28
	percentage of divergent components, %	0.07	0.05	0.04
OGI	n. of non-accessible monitorable sources	19,146	19,140	18,472
	percentage non accessible monitorable sources, %	20	20	20
	n. of divergent components	0	0	0
	percentage of divergent components, %	0	0	0
	total monitorable sources	90,756	90,601	84,776
	n. of unmonitored sources	4,965	5,120	7,514

As described above, the components censed were divided into categories. As it is possible to see in Fig.1, the large part of monitorable components is represents by flanges (FLG) that represents the 59-81% of the monitorable sources while the valves (VLV) cover the 12-30%. Figure 1 shows the number of monitorable components for 2022; this choice derives from the analysis of the data reported in Tables 2 and 3, from which for PL2 this number has not changed during years, while for PL1 and PL3 it represents the year in which there is the greatest number of monitorable components. The LDAR protocol provides for maintenance on components found to be divergent during the measurement survey. After the maintenance on PL3 divergent VOC-conveying components reported in Table 3, percentage of divergence decreased sensitively as reported in Table 4.

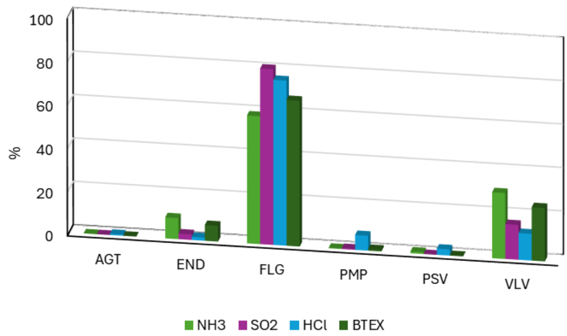


Fig. 1. Percentage distribution of monitorable components handling NH3, SO2, HCl and BTEX in 2022. Agitators (AGT), compressors, and pumps (PMP), valves (VLV), safety valves (PSV), flanges (FLG), and line ends (END)

Table 4. PL3 divergent components pre- and post-maintenance.

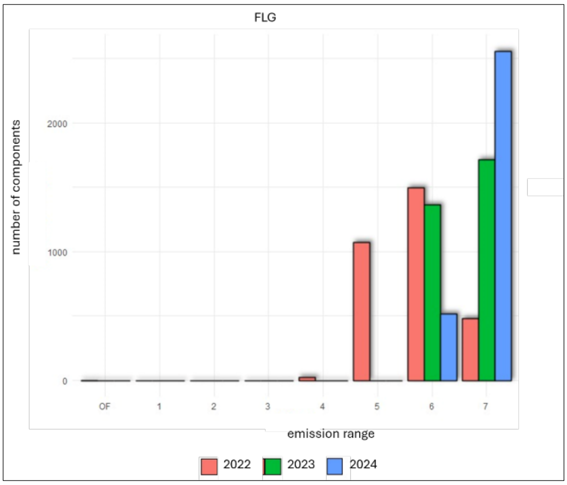
		PL3		
		2022	***2023***	***2024***
n. of censed sources		95,721	95,721	92,290
n. of accessible monitorable sources		71,610	71,461	66,304
percentage of accessible monitorable sources, %		74.8	74.7	71.8
pre-maintenance	n. of divergent components	49	33	28
	percentage of divergent components, %	0.07	0.05	0.04
post-maintenance	n. of divergent components	6	3	3
	percentage of divergent components, %	0.01	0.004	0.005

After maintenance on the leaky components, they decreased to 0.01% in 2022, to 0.004% in 2023, and to 0.005% in 2024, starting from a percentage above 70% (Table 4); this means that maintenance was essential for these components repair. This reduction led to a decrease in the estimated VOC emission flux.

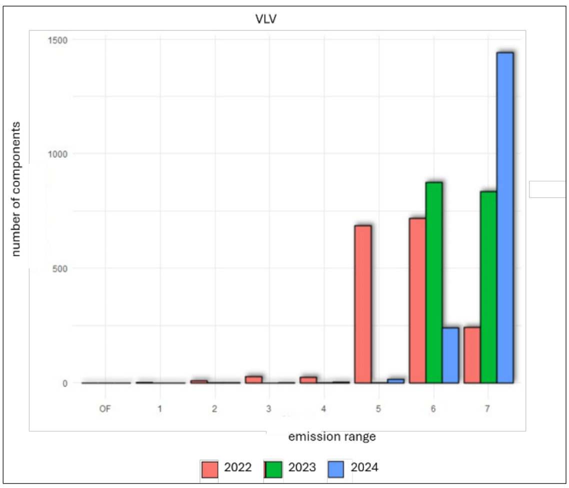
Table 5. PL1 emission range classification

Status	**Component range, ppmv**
OF	Overflow ppmw > 100,000
1	10,000 < ppmv < 99,999
2	5,000 < ppmv < 9,999
3	1,000 < ppmv < 4,999
4	5000 < ppmv < 999
5	100 < ppmv < 499
6	10 < ppmv < 99
7	Ppmv < 10

Based on the measurements performed on the components, each component can be classified according to its emission range. Considering that valves and flanges are the most critical components, as well as the most frequently present components within an industrial plant, Figure 2 show the distribution of valves (Fig. 2a) and flanges (Fig. 2b) within their respective emission ranges (as reported in Table 5) for the PL1 plant for the years 2022-2024. These conditions were chosen to highlight how, despite there being no components outside the threshold for valves and only one component outside the threshold for flanges, over the years, thanks to the maintenance performed, the number of components within class 8 and therefore with lower emissions has increased. This highlights the importance of the maintenance phase in reducing fugitive emissions.



a)



b)

Fig. 2. Comparison of components classified according to the emission range during 2022-2024 for PL1 for: a) flanges and b) valves

6. Concluding remarks

The results confirm the effectiveness of systematic monitoring of fugitive emissions as a key tool for identifying emission sources that exceed regulatory thresholds within industrial plants. Targeted maintenance interventions on leaking components have shown a direct and measurable reduction in emissions from those sources. Moreover, the regular implementation of preventive maintenance activities has led, over the years, to a significant increase in the number of components falling within the lowest emission range, highlighting the importance of a continuous and proactive approach to emission control.

Among the monitored components, flanges and valves emerged as the most critical in terms of both frequency and intensity of emissions. This is partly due to their widespread presence in process plants and their structural complexity. Valves can present multiple potential leakage points, including flanged connections at both ends, the joint between the valve body and bonnet, and the stem sealing area, making them a potential fugitive emission source and in need of regular inspection and prompt repair.

Given that substances detected in leaks often include compounds with high odor impact, such as ammonia (NH_3), sulfur dioxide (SO_2), hydrochloric acid (HCl), and BTEX aromatics it becomes evident that the implementation of a Leak Detection and Repair (LDAR) program is an effective strategy for reducing and mitigating odorous emissions. LDAR programs thus prove to be not only a tool for regulatory compliance and environmental control but also a valuable approach to protecting air quality and the well-being of communities living near industrial plants.

References

ATSDR, (2010), Toxicological profile for chlorine, U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES Public Health Service Agency for Toxic Substances and Disease Registry, On line at https://www.atsdr.cdc.gov/toxprofiles/tp172.pdf.

Goedkoop M., (2006), *SimaPro 7 Demo Manual*, PRé Consultants, The Netherlands.

Durmusoglu E., Taspinar F., Karademir A., (2010), Health risk assessment of BTEX emissions in the landfill environment, *Journal of Hazardous Materials,* **176**, 870–877, doi:10.1016/j.jhazmat.2009.11.117.

European Commission, (2024), *The revised Industrial and Livestock Rearing Emissions Directive* (Directive 2010/75/EU or 'IED 2.0') as amended by Directive 2024/1785.

IPCC, (2006), *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, Simon Eggelston, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tanabe (Eds.), Institute for Global Environmental Strategies (IGES) for the IPCC, https://strategies.org/.

IPCC, (1996), *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories,* Houghton J.T., Meira Filho L.G., Lim B., Treanton K., Mamaty I., Bonduki Y., Griggs D.J., Callender B.A. (Eds), Intergovernmental Panel on Climate Change, UK Meteorological Office, Brackne.

Jiang D., Chen Y., Chen Q., Deng S., (2024), Derivation of human health and odor risk control values for soil ammonia nitrogen by incorporating solid-liquid partitioning, ammonium/ammonia equilibrium: A case study of a retired nitrogen fertilizer site in China, *Ecotoxicology and Environmental Safety*, **273**, 116133, https://doi.org/10.1016/j.ecoenv.2024.116133.

Kashyapa R.K, Chugh P., Nandakumar T., (2016), Opportunities and challenges in capturing landfill gas from an active and un-scientifically managed land fill site - A case study, *Procedia Environmental Sciences*, **35**, 348-367.

Lotrecchiano N., Pecci A., Zappimbulso N., Ilacqua M.A., Ferranti F., (2025), Efficacy of the leak detection and repair program in the Italian industrial plants, *Chemical Engineering Transactions*, **116**, 823-828.

UNI EN 15446, (2008), Measurement of fugitive emission of vapours generated from equipment and piping leaks, On line at: https://standards.iteh.ai/catalog/standards/cen/ca30d7f9-a531-46eb-9ce1-5786a5270bf1/en-15446-2008?srsltid=AfmBOooKpOv3TmLqBCJJlkIePN22cHXWNHgWQkUV-QZvUERCTWBiUVlB.

UNI EN 17628, (2022), Fugitive and diffuse emissions of common concern to industry sectors - Standard method to determine diffuse emissions of volatile organic compounds into the atmosphere, On line at: https://standards.iteh.ai/catalog/standards/cen/1134347e-e278-42cd-9967-2a4f34ac0fe6/en-17628-2022?srsltid=AfmBOoqbMmr-MHDkHTBNUacJ-Q9DYpSbRBwhi0xjx6R7nrGIofBlcvsq.

USEPA, (1995), Protocol for Equipment Leak Emission Estimates, EPA 453/R-95-017, United States Environmental Protection Agency, On line at: https://www.epa.gov/sites/default/files/2020-09/documents/protocol_for_equipment_leak_emission_estimates.pdf

WHO, (2005), *Air Quality Guidelines Global Update 2005*, EUR/05/5046029, World Health Organization, On line at https://iris.who.int/server/api/core/bitstreams/74e5a36c-1ff4-4c42-b5f4-f0db0e2be800/content.

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VALORIZATION OF WASTE COFFEE GROUNDS IN SUSTAINABLE GYPSUM COMPOSITES: HYGROTHERMAL RESPONSE AND CIRCULAR ECONOMY APPROACH*

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Abstract

This study analyses the deployment of spent coffee grounds (SPENT Coffee Grounds, SCGs) as an environmentally friendly additive in composite gypsum panels intended for sustainable building applications. Two different types of SCG were used, coming from the coffee varieties Coffea arabica and Coffea canephora (Robusta), in order to evaluate the influence of botanical composition on the physical-mechanical and thermo-hygrometric properties of the materials. Four formulations containing SCG in increasing percentages (0–15%) were subjected to experimental trials to determine compressive strength and moisture regulating ability. The samples showed a significant ability to absorb ambient moisture, attributable to the increase in porosity induced by the addition of SCG. Trials conducted in a controlled environment showed an increase in density and water content, confirming the potential of panels containing SCG to contribute to the hygroscopic regulation of indoor environments. The results indicate that the Robusta variety retains a higher amount of water than Arabica, but results in a reduction in mechanical strength. This decrease, although detectable, was found to be compatible with the performance requirements required for non-structural applications. The integration of SCGs in gypsum materials is therefore configured as a promising solution for the development of building products with low environmental impact and with advanced hygroscopic functionalities.

Keywords: biowaste utilization, circular economy, coffee waste applications, recycled organic waste, sustainable materials

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1. Introduction

The growing environmental awareness and the need to mitigate the ecological impact of industrial processes have incentivized the adoption of strategies based on the circular economy, a paradigm that aims to reduce the production of waste and enhance waste materials through their reintegration into production cycles (Idiano D'Adamo, 2024). In the construction sector, this approach translates into the search for alternative and sustainable construction solutions, capable of replacing or integrating the virgin resources traditionally used in the production of building materials.

In particular, the valorization of agri-food waste is redefining the sector of sustainable building materials. Recent studies on the use of bio-additives derived from olive leaves in bitumen demonstrate how natural compounds can increase the durability of road pavements, contributing to the reduction of the environmental impact of road infrastructures (Valeria Loise, 2024). The research conducted by Luigi Madeo (2025) also takes place in this context, which has deepened the use of vegetable fibers obtained from waste from the processing of liquorice root, treated exclusively with physical methods, in order to guarantee a completely eco-sustainable approach. Such studies contribute to consolidate a design vision oriented towards the transformation of agri-food waste into functional resources, promoting the circular economy and green building through the development of eco-materials capable of improving the thermo-hygrometric and mechanical performance of building elements. In this perspective, particular attention is paid to SCGs (Spent Coffee Grounds), a by-product of coffee preparation, generated in significant quantities on a global scale.

It is estimated that for every ton of prepared coffee, approximately 650 kg of SCG are produced (Reena Saxena, 2024), with a significant environmental impact if they are disposed of in landfill (Osazee, 2021). The chemical-physical composition of this material, rich in cellulose, lignin, lipids, proteins and phenolic compounds allows it to be valorized in numerous application areas, including bioenergy, cosmetics, agriculture, composite materials and construction (Iwona Ryłko-Polak, 2022). Numerous studies have investigated the use of SCGs in polymer and cement composites, highlighting promising properties in terms of thermal insulation, mechanical resistance and environmental sustainability. The integration of SCGs into mortars and plasters, for example, has led to a reduction in thermal conductivity of up to 50%, contributing to the improvement of the energy efficiency of buildings (Saeli et al., 2022). In addition, the extraction of bioactive oils and compounds from SCGs has opened new perspectives in the production of multifunctional materials, with applications also in the architectural and decorative fields (Saeli, 2023).

This study investigates the integration of heat-treated spent coffee grounds (SCGs) into a chalk-based matrix for the development of eco-friendly building panels. Focusing on both mechanical strength and thermo-hygrometric behavior, the research evaluates how varying SCG percentages, specifically Arabica and Robusta varieties, affect panel performance. In line with eco-innovation and circular economy principles (Matrapazi, 2020), the approach aims to reduce organic waste, enhance energy efficiency, and promote sustainable construction through the analysis of key parameters such as density and moisture absorption.

This paper is divided into three main phases. The study focuses on the chemical-physical characterization of two types of spent coffee grounds and their incorporation into gypsum-based panels at varying percentages. Laboratory tests assessed the mechanical strength and thermo-hygrometric behavior of the prototypes to evaluate their structural and thermal performance.

2. Materials and methods

To ensure the reproducibility and validity of the results obtained, it is essential to describe in detail the materials used, the tools used and the procedures adopted for the preparation and characterization of the specimens. Such documentation allows to understand the experimental context and to evaluate the reliability of the analyses conducted. The following are the materials, tools and methods of characterizing and preparing the specimens. The following are the materials, tools and methods of characterizing and preparing the specimens.

2.1 Materials

A commercial gypsum ($CaSO_4 \cdot 2H_2O$ – Rasaben MGM) was used to create the matrix (Fig. 1a). The types of used coffee used are Arabica and Robusta, both deriving from post-consumer waste. Before deployment, the bottoms were stove dried at 105°C for 24 hours, in order to avoid fermentative phenomena and ensure the chemical-biological stability of the material. The two varieties have a visibly different color (Fig. 1b). In particular, Robusta coffee is distinguished by a darker shade than Arabica.

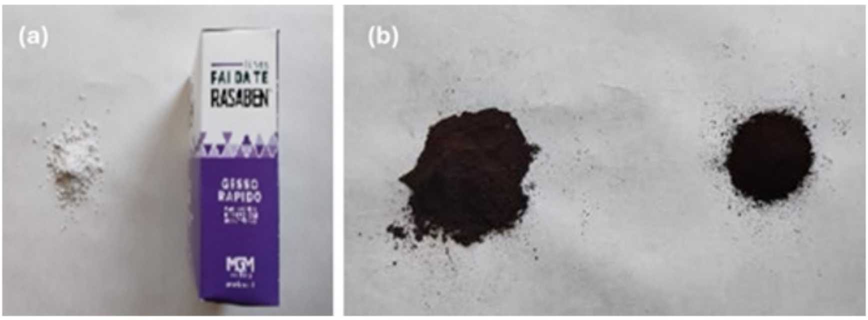

Fig. 1. (a) Gypsum; (b) Types of coffee from left Arabica and Robusto respectively

2.2. Instruments

Morphological and compositional analyses were performed using scanning electron microscopy with microanalysis (ESEM Quanta 200 FEG coupled to EDAX GENESIS 2000 EDS system, Eindhoven, The Netherlands). Mechanical strength was assessed with a benchtop durometer (Fig. 2a) on samples matured for three days. Hygrometric properties were measured using the PocketLab Weather sensor (Fig. 2b), enabling real-time monitoring of temperature and humidity to evaluate the materials' response to environmental conditions.

2.3. Preparation of samples

The preparation of the test pieces began with the careful mixing of chalk, water and spent coffee grounds, in different proportions. For each sample, the amount of gypsum was progressively reduced in favor of adding coffee grounds, both Arabica and Robusta. In order to ensure uniform workability between the different blends, it was necessary to gradually increase the amount of water added, so as to compensate for the absorption of coffee grounds and keep the water/gypsum ratio constant. After obtaining a homogeneous mixture, the compound was poured into the silicone molds (Fig. 3), allowed to harden for 48 hours and subsequently conditioned for 24 hours at a temperature of 23 °C and relative humidity of 50 wt. %, before proceeding to the mechanical tests. Quantitative details are given in Table 1.

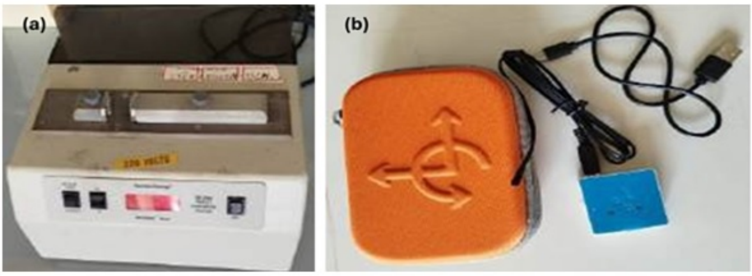

Fig. 2. (a) hardness tester VK200; (b) PocketLab Weather

Fig. 3. Chalky matrix specimens with different SCG contents with silicone mold size (2.1x10.0 x 5.1) cm

Table 1. Systems for the preparation of chalky matrix specimens at different % of SCG

Type coffee SCG	*SCG %*	*Plaster [g] ± 0.01*	*SCG [g] ± 0.01*	*Distilled water [g] ± 0.01*	*Δ Distilled water [%] **
Arabica	0	60.00	0.00	33	0.00
	5	57.00	4.65	40	21.21
	10	54.00	9.30	45	36.36
	15	51.00	13.95	50	51.52
Robust	0	60.00	0.00	33	0.00
	5	57.00	4.65	40	21.21
	10	54.00	9.30	45	36.36
	15	51.00	13.95	50	51.52

* increase as a percentage of the quantity of water compared to the system without SCG necessary for adequate workability of the chalky mixture and consequently the making of the test pieces under examination.

2.4. Parameter determination methods

2.4.1 Density of sample and coffee primary

The density of the samples was calculated by dividing the measured mass by the known volume of the specimen, equal to approximately 107 cm³, determined by the dimensions of the silicone mold (2.1 × 10.0 × 5.1 cm). After extraction, each sample was dried and stabilized in sealed chamber at 23°C and 50 wt. % relative humidity, then weighed with analytical balance (accuracy ±0.01 g). With the constant volume of the mold, it was possible to obtain the density value directly. For the determination of the bulk density of spent coffee grounds (SCG), the bulk volume method was adopted. A mass of 2 g of dried SCG was poured into a graduated cylinder until the volume of 50 ml was reached, avoiding any compaction of the material. Subsequently, the contents were weighed, and the effective mass was obtained by subtracting the tare weight of the cylinder. The ratio between the measured mass and the occupied volume allows the apparent density of spent coffee (ρSCG) to be calculated.

2.4.2 Analysis of thermo-hygrometric behavior

The thermo-hygrometric behavior of the materials, with particular reference to the ability to adsorb humidity, was analyzed both in spent coffee grounds in natural form and in samples obtained through manufacturing processes. Before measurements, both materials were subjected to drying until the constant weight was reached: the coffee grounds were treated at 105 °C, while the composite samples were dried at approximately 50 °C, in order to preserve their structure. Experimental trials were conducted to evaluate the response of materials to variations in ambient temperature and humidity, with the aim of characterizing their hygroscopic properties and dimensional stability. To quantify the moisture absorption capacity, the equilibrium moisture content (Equilibrium Moisture Content, EMC) was measured, a parameter representing the amount of water retained by a material when it reaches hygroscopic equilibrium with its surroundings, maintained at constant conditions of temperature and relative humidity. Each specimen, after being extracted from the mold and completely dried, is Each specimen was weighed using an analytical scale with precision ±0.01 g. Next, the samples were placed inside a sealed chamber of size 43 × 33 × 24 cm (volume equal to 34,056 cm³), maintained at 23°C and 50 wt. % relative humidity for 24 hours. For spent coffee grounds, the measurement was carried out by inserting a quantity of material of known weight inside the chamber, in order to ensure repeatability and comparability of the results.

The PocketLab Weather sensor, a portable and multifunctional meteorological device used for continuous monitoring of environmental conditions, was placed inside the chamber. The sensor detected the temperature and relative humidity values in real time, ensuring constant control of the parameters during the entire exposure period. To stabilize and maintain uniform relative humidity level inside the chamber, an open container containing 100 ml of water was inserted, inside which a paper towel cone was placed. The latter facilitated moisture dispersion, helping to create a controlled and homogeneous microclimate, necessary to assure repeatability and reliability of measurements. The operating diagram is shown in Fig. 4.

At the end of the exposure, the test pieces were weighed again to determine the mass increment due to moisture absorption. This increase was expressed as a percentage of the dry mass and compared with the theoretical value of EMC, calculated according to Eq. (1).

$$EMC = \frac{m_{eq} - m_{dry}}{m_{dry}}$$

where: m_{eq} of the sample after exposure in a controlled environment (23°C, 50 wt.% RH) and m_{dry} mass of the oven-dried sample.

2.4.3. pH analysis

The determination of the pH of spent coffee grounds (SCG) was conducted using 2 g Arabica powder and 2 g Robusta powder, each dried at 105 °C until constant weight was reached. The samples were suspended separately in 10 ml of distilled water and subjected to vigorous stirring for two minutes.

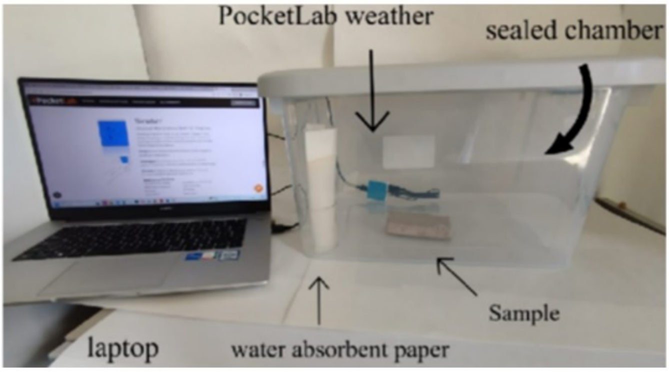

Fig. 4. System diagram for measuring (Equilibrium Moisture Content, EMC)

Subsequently, the suspensions were left to settle for five minutes, in order to obtain a clear supernatant. A litmus paper was immersed in the liquid for one second, waiting about 45 seconds to allow full color development. The pH value was determined by visual comparison with the color scale provided by the manufacturer. The entire procedure was repeated three times for each variety, with map renewal and re-blending before each reading.

The mean pH value was calculated by estimating an uncertainty of ±0.1 unit, in line with the resolution of the papers used and the variability found between the replicates. This analysis was conducted in order to evaluate the possible influences that the addition of coffee grounds can exert on the pH of the system, and consequently on the final properties of the material in which these wastes are incorporated. Understanding these effects is essential to optimize the processing conditions and predict the behavior of the compound in its final use.

3. Results and discussion

3.1. SEM - EDS characterization of the two types of SCG

The preliminary characterization of Arabica's spent coffee grounds (SCG) e Robusta, conducted through SEM and EDS analysis, allowed us to highlight differences morphological and compositional between the two varieties (Fig. 5). These chemical-physical differences are relevant to evaluate the reactivity of SCGs and them behavior within composite matrices, affecting properties such as adhesion, water absorption and density. This information guides the targeted selection of the type of SCG more suitable depending on the desired performance in the final material.

3.2. Preliminary pH analysis of Arabica and Robusta coffee grounds

In the context of the study on the integration of Arabica and Robusta type spent coffee grounds in chalky matrices, an analysis was conducted aimed at evaluating their possible influence on the pH of the mixtures. To obtain a useful reference parameter, the pH of the coffee grounds dispersed in water was measured, following the methodology described previously. The results, obtained from an average of five measurements for each type of coffee, they showed that both bottoms present slightly acidic pH values, with Arabica recording an average pH of about 5 and Robusta an average value around 6.

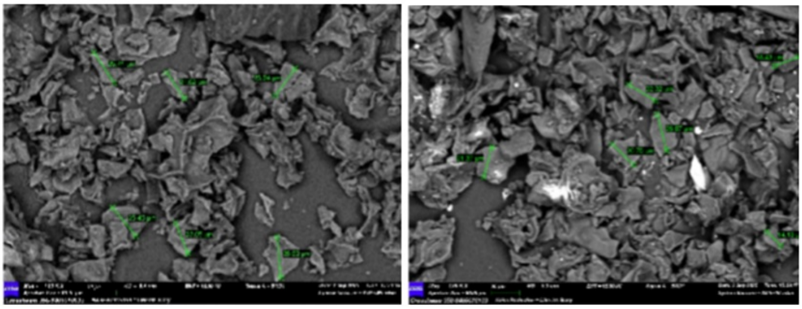

Fig. 5. SEM images on the left Arabica coffee and on the right Robusto type coffee give us information on the dimensions of our subject under examination

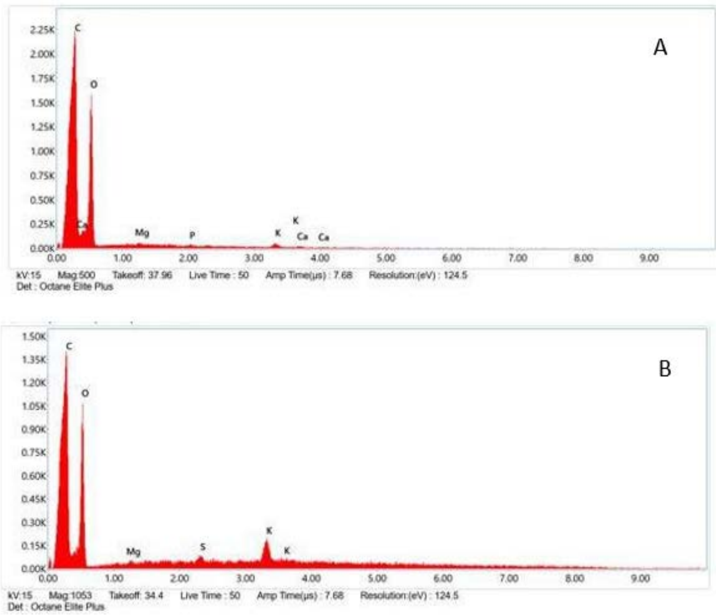

Fig. 6. EDX measurements in section (A) robust coffee and section (B) Arabica coffee

This difference is attributable to the different organic composition of the two coffees. Measurement of pH in aqueous dispersion then provided a preliminary indication of the potential acidifying action of bottoms within chalk mixtures, contributing to the understanding of their chemical behavior and their impact on the final properties of composite materials.

3.3. Density of coffee grounds and test pieces

As a preliminary, the apparent densities of the coffee grounds were measured, obtaining even values at 0.45 g/cm³ for the Arabica variety and 0.50 g/cm³ for the Robusta variety. This data provides a first useful reference for interpreting the behavior of materials in the compound. Below the density values of the samples made are shown, depending on the two types of coffee used and quantities added (Table 2). Data analysis highlights clear and consistent behavior: adding coffee waste (SCG), both Arabica and Robusta cause a progressive reduction in the density of the specimens. This declines it follows a linear trend, proportional to the amount of SCG incorporated, with values decreasing as we go from 5% to 15%.

While sharing this general trend, the two varieties of coffee show differences significant. Specimens containing Arabica maintain higher density values than those with Robusta, despite the latter having a higher bulk density as a material dry. This suggests that the initial density of the component is not sufficient to determine the behavior of the final compound. More complex factors come into play, such as microstructure of the material and its ability to integrate with the chalky matrix.

Table 2. Density of samples depending on the type and quantity of coffee grounds (SCG) used

% SCG	*Type of SCG*	*ρ_sample [g/cm³] ± 0.02*
0	Gypsum matrix	0.92
5	Arabica	0.88
5	Robusta	0.85
10	Arabica	0.86
10	Robusta	0.82
15	Arabica	0.84
15	Robusta	0.78

In contrast, Arabica distributes more evenly, contributing to a higher volume mass stable and compact. From an environmental point of view, these results are particularly encouraging. The employment of SCGs it allows you to obtain lighter materials, with concrete advantages in terms of transport and reduction energy consumption and overall sustainability. In addition, the integration of organic waste into building products is an effective strategy to value waste and reduce impact environmental construction.

The density of the test pieces does not only depend on the amount of SCG added, but also by the nature of the material and its interaction with the matrix. The results demonstrate what it looks like it is possible to obtain lighter and more sustainable solutions, without compromising the functionality of compound.

3.4. SEM observation of samples with % SCG

The analysis of the samples under an electron microscope (Fig. 7) allowed us to observe in detail the internal structure of materials. The images clearly show that samples made with Robusta coffee grounds present a less compact structure than those with Arabica, in line with previously reported data and assessments regarding density. This visual finding reinforces the validity of the measurements made, confirming the consistency between qualitative observations and quantitative data. In any case, the coffee grounds are well distributed and integrated within the chalky matrix, regardless of the type used. This homogeneous integration represents a significant element for the validity of the material obtained, since it suggests a good compatibility between the organic filler and the mineral matrix. This aspect is particularly relevant in view of potential applications, where internal cohesion and structural uniformity are fundamental requirements to ensure mechanical performance and durability over time.

3.5. Equilibrium Moisture Content (EMC) of samples

Table 3 clearly shows how the moisture content (EMC) increases progressively with the addition of spent coffee grounds (SCGs) in gypsum samples. We start from a minimum value of 0.10% in pure plaster, up to ’1.06% in samples containing 15% Robusta. This trend indicates that coffee grounds, being organic materials, contribute significantly to the compound's ability to retain moisture. At the same percentage, samples with Robusta show increasingly higher humidity values than those with Arabica. For example, with 10% SCG, the humidity is 0.74% for Robusta, versus 0.59% for Arabica. This suggests that Robusta has a more porous structure or a more hydrophilic composition, which makes it more effective at retaining moisture.

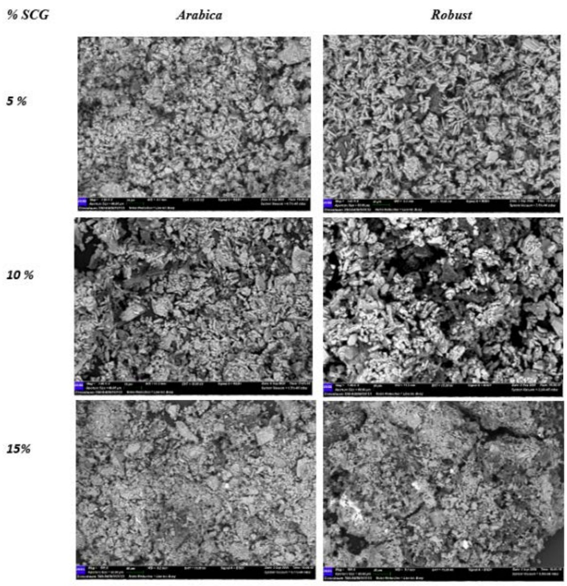

Fig. 7. SEM images of the chalky matrix samples obtained with different types and quantities of SCG

Table 3. Change in moisture content (EMC) in gypsum samples as a function of percentage and type of spent coffee grounds (SCG) added

% SCG	*Sample*	*EMC (% by mass)*
0	Gypsum matrix	0.10
5	Arabica	0.34
5	Robusta	0.42
10	Arabica	0.59
10	Robusta	0.74
15	Arabica	0.84
15	Robusta	1.06

From the point of view of eco-construction, this figure is particularly relevant. The use of materials capable of regulating the internal humidity of closed environments contributes to living comfort, the healthiness of spaces and the prevention of phenomena such as condensation and mold. In this context, the integration of SCG in gypsum not only enhances an organic waste, but also offers a sustainable solution to improve the indoor microclimate. Indeed, the ability to modulate humidity is one of the key characteristics of hygroscopic materials, highly valued in bio-architecture and in the design of buildings with low environmental impact.

3.6. Compressive strength of samples

Table 4 gives the compressive strength values obtained from tests conducted on pellets of 1 cm diameter and 0.5 cm thickness. Although the analyses were not performed according to official regulatory standards, they were carried out with the aim of making an initial comparison between the mechanical properties of the different systems analyzed. The results, although preliminary, still made it possible to highlight the differences between the formulations and to collect useful indications for future experimental investigations.

Table 4. Compressive strength of chalky matrix samples as the type and quantity of SCG added varies

Sample	***% SCG***	***Compressive Strength [kp] ±0.1***
Gypsum matrix	0	80.8
Arabica	5	70.2
Arabica	10	60.7
Arabica	15	50.4
Robusta	5	73.2
Robusta	10	66.5
Robusta	15	59.6

The measures show a progressive reduction in compressive strength as the SCG content increases, from a maximum of 80.8 kp for pure gypsum to 50.4 kp with 15 per cent Arabica, but, for the same load, the values obtained with Robusta are only slightly higher than those with Arabica (for example 66.5 kp vs 60.7 kp at 10 per cent), a minimal difference that makes the two materials substantially comparable from a mechanical point of view. This small advantage of Robusta appears apparently contradictory with its lower bulk density compared to Arabica, but is explained by a better filler-matrix interaction. Robusta particles, equipped with a more porous microstructure and more irregular surfaces, offer a greater number of “jams” in which calcium dihydrate crystals can anchor.

During the setting phase, this mechanical interlocking limits the formation of discontinuities and microcracks along the interface, giving the panel a slightly higher load-bearing capacity, while maintaining performance similar to that of samples loaded with Arabica.

4. Conclusion

The inclusion of spent coffee grounds (SCG) in the chalk matrix has produced encouraging results, both from a technical and environmental point of view, confirming the potential of this organic waste as a functional resource for sustainable construction. The trials conducted have highlighted significant trends that deserve attention and further investigation. The density of samples decreases progressively with increasing percentage of SCG, with a more marked reduction in specimens containing Robusta bottoms. This lightening effect can be advantageous in contexts where lighter materials are preferred, for example to facilitate handling, processing or thermal insulation.

In parallel, the moisture content increases proportionally to the amount of SCG added, with higher values in Robusta samples. This behavior is particularly relevant in eco-building, where the ability to regulate environmental humidity contributes to living comfort and the healthiness of indoor spaces. Mechanically, a decrease in compressive strength is observed with increasing SCG content, as expected.

However, samples with Robusta show slightly higher performance than those with Arabica, suggesting better internal cohesion of the material, probably related to the more irregular structure. Overall, the use of spent coffee grounds represents a concrete strategy for the valorization of a widely available organic waste, reducing the environmental impact and promoting the use of renewable resources.

The results obtained confirm the validity of this approach for non-structural applications, paving the way for new formulations and contexts of use, in line with the principles of the circular economy and green building.

References

D'Adamo I., Sica D., (2024), Driving EU sustainability: Promoting the circular economy through municipal waste efficiency, *Sustainable Production and Consumption*, **46**, 462–474.

Loise V., Madeo L., Abe A., Rossi C., Caputo P., (2024), Plant waste-based bioadditive as an antioxidant agent and rheological modifier of bitumen, *Materials*, **17**, 2303, https://doi.org/10.3390/ma17102303

Madeo L., Macario A., Candamano G., De Luca F., (2025), Recovery of vegetable fibers from licorice processing waste and a case study for their use in green building products, *Clean Technologies*, **7**, 55, https://doi.org/10.3390/cleantechnol7030055

Matrapazi V.K., Zorpas A., (2020), Experimental and feasibility study of spent coffee grounds upscaling via pyrolysis towards proposing an eco-social innovation circular economy solution, *Science of The Total Environment*, **718**, 137278, https://doi.org/10.1016/j.scitotenv.2020.137316.

Osazee I.T., (2021), Landfill in a sustainable waste disposal, *European Journal of Environment and Earth Sciences*, **2**, 67–74.

Ryłko-Polak I., Kwiatkowski W., (2022), The reuse of biomass and industrial waste in biocomposite construction materials for decreasing natural resource use and mitigating the environmental impact of the construction industry: A review, *Materials*, **15**, 4078, https://doi.org/10.3390/ma15124078.

Saeli M., Noto M., (2022), Architectural technologies for life environment: Spent coffee ground reuse in lime-based mortars. A preliminary assessment for innovative green thermo-plasters, *Construction and Building Materials*, **319**, 126079, https://doi.org/10.1016/j.conbuildmat.2021.126079.

Saeli V., Scolaro M., (2023), The coffee-house: Upcycling spent coffee grounds for the production of green geopolymeric architectural energy-saving products, *Energy and Buildings*, **286**, 112956, https://doi.org/10.1016/j.enbuild.2023.112956.

Saxena R., Lal H., (2024), Sustainable management of spent coffee grounds: Applications, decomposition techniques and structural analysis, *Journal of Material Cycles and Waste Management*, **27**, 19–33.

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BUTTS OFF THE SHORES: TESTING GREEN NUDGES TO REDUCE CIGARETTE LITTER AT LAKE TRASIMENO*

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Abstract

Cigarette butts pose significant environmental threats, despite public awareness of the environmental damage caused by their improper disposal remains limited. This issue is particularly pressing in Umbria, the Italian region with the highest percentage of smokers, where cigarette littering contributes to serious ecosystem damages. Aiming to find a non-coercive alternative to traditional waste reduction policies, this study involves a field experiment involving green nudges that encourage proper disposal of cigarette butts in water ecosystems. The experiment was conducted in summer throughout four weeks at various beach sites around Lake Trasimeno in Umbria, Italy. Two distinct nudges were tested: one aimed at fostering pro-environmental behavior, focusing on the ecological consequences of cigarette litter; the other focused on promoting pro-recycling behavior, by highlighting the recycling potential of cigarette butts. An econometric analysis, based on a panel data regression model, demonstrated that both interventions were effective in reducing cigarette butt littering. However, the recycling-focused nudge showed a stronger and more consistent impact, with an average reduction of 32% in littering when applied. Our findings highlight the potential of green nudges as cost-effective tools for promoting environmentally responsible behaviors. They offer valuable insights for local policymakers seeking effective strategies to tackle cigarette littering in similar contexts.

Keywords: behavioural economics, cigarette butts, field experiment, green nudges

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1. Introduction

It is well-known that cigarettes are harmful to both humans and the environment. According to the latest WHO Tobacco report, there are 1.25 billion adult tobacco users globally. While tobacco use has declined since 2000, from 1 in 5 adults consumer in 2022 to 1 in 3 in 2000 (World Health Organization, 2024), tobacco consumption still causes over 8 million deaths annually. Smoking in Italy causes over 93.000 deaths, including 43.000 from cancer, and its annual costs amount to more than 26 billion euros (Ministero della Salute, 2025). In Umbria — where our study site Lake Trasimeno is located — 29.1% of the population smokes, the highest rate among Italian regions (Centro Regionale per la Salute Globale, 2024). Nevertheless, while the direct health risks of tobacco use are nowadays widely recognized worldwide, the environmental damage from its production and consumption receives less attention. Of the whole process, the final stage of smoking plays a crucial role: according to the National Oceanic and Atmospheric Administration (2024), cigarette butts (CBs) are the most common form of marine litter the world, with an estimated 4.5 trillion CBs thrown away every year worldwide (Slaughter et al., 2011a). Efficiently collecting CBs is hence necessary not only because it helps protect the environment and prevent chemical pollution in water ecosystems (Lucia et al., 2023; Slaughter et al., 2011b) but also because recent studies have shown that CBs collected can be reused into strong building materials, although this kind of technology is still expensive (Cavagnoli et al., 2024; Shah et al., 2023). Because of all these damages CBs littering can be thought as a classical example of a negative environmental externality. In addressing these externalities, traditional policies based on market incentives or command-and-control strategies, as opposed to voluntary choice-based approaches, represent the most effective top-down solutions on the supply side of the market (Swaney, 1992; Walter, 2020). Among the alternative ways of reducing the impact of environmental littering, we find nudges. Theyr are proven to be an effective libertarian way to alter individuals' behaviors by changing the decision choice architecture (Thaler and Sunstein, 2008). In particular, green nudges are behavioral interventions designed to reduce negative externalities, and they are used as a tool in environmental policy to encourage more sustainable behaviors (Carlsson et al., 2021).

In order to provide policy suggestions for a more appropriate disposal of CBs, a field experiment was run based on nudges, with the aim of testing whether such nudges lead to reduced littering in a fragile ecosystem like Lake Trasimeno. Two nudges were developed to test different non-monetary incentives that can alter people's behavior without imposing bans or changing their economic incentives. The first highlights the environmental impact of discarding CBs into water bodies, while the second informs participants about the recycling potential of CBs to improve building insulation and generate thermal energy savings. The effectiveness of two nudges was evaluated through a small-scale field experiment conducted on nine beaches along the shores of Lake Trasimeno in Italy.

2. Materials and methods

2.1. Site identification

The experiment took place in August 2024 in lake Trasimeno, a tectonic-origin lake within the Tiber river basin in Umbria (a region in central Italy). With an area of 128 km², it is the Italian largest laminar lake and fourth largest lake in Italy. It is a shallow lake, with an average depth of 4.72m and a maximum one of 6.3m, and a catchment area of 396 km². The combination of its ecological importance, vulnerability to climatic conditions, and unique environmental characteristics underscores its significance as a natural and protected area. This is why it is really important to preserve this ecosystem from the negative effects of anthropogenic activities. Lake Trasimeno offers several swimming areas where bathing is possible, and we selected three out of the nine.

2.2. Nudges

Given the effectiveness of green nudges (Schubert, 2017) in promoting pro-environmental behavior (Gay et al., 2024; Saulītis et al., 2024) and recycling (Wee et al., 2021), the following hypotheses to reduce cigarette littering (represented in this case by an increase in the rate of butts properly collected) were tested. It is the first time that a field experiment on this topic is run in a lake contest.

H1: the first treatment Nudge_1, has a positive effect on littering.

The message in the nudge refers to toxicological studies on cigarettes (Sánchez-Hernández et al., 2011, Dobaradara et al., 2021). As concluded by Morgan et al. (2022), anti-littering messages motivate smokers to not litter cigarette butts.

H2: the second treatment Nudge_2, has a positive effect on littering.

The message in the nudge refers to the potential of cigarette butt recycling in the development of highly efficient materials capable of insulating buildings. As a matter of fact, some recent published papers proved that the use of small quantities of recycled cigarette butts in building materials can lead to an improvement of the thermal properties for insulation (Albayati et al., 2022; Mohajerani et al., 2016). The message in Nudge_2 refers to a recycling study by Cavagnoli et al. (2024), which assessed an insulating panel made with a cigarette butts-to-gypsum-to-water ratio of 1:2:3. The nudges in Figure 1 shows the two signs with nudges that were used in the experiment.

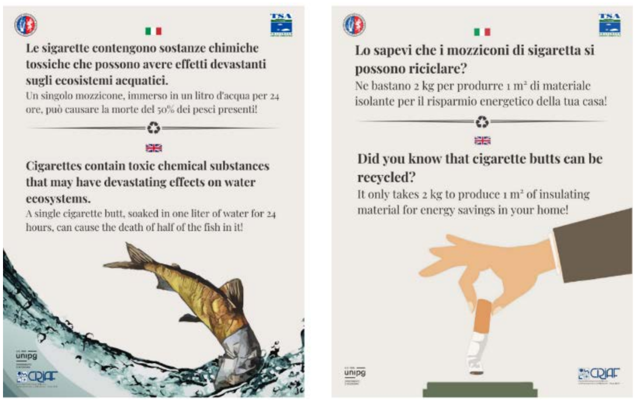

Fig. 1. Nudges used in the experiment

2.3. Experimental design

The design of the experiment was carefully crafted in the months before the start of the experiment, and then accurately explained to the beach owners and staff. The establishments were contacted before starting, and the owners and staff members were met in person by the researchers, to explain the experiment and clear out any doubt about it. In the week prior to the start of the experiment, the necessary materials to the beaches were delivered, i.e. ashtrays, sand buckets, colored bags in two colors, and colored stickers for daily butts' data cataloging.

These items were either crafted by our team, or provided by the local waste collection company Trasimeno Servizi Ambientali (TSA). During the preliminary meetings with the beach owners and staff, the experimental protocol for data collection was thoroughly explained. We conceived a specific treatment rotation scheme to isolate the effect of the nudges on each individual establishment, as they differed in certain characteristics that would have complicated the analysis of the nudges' effectiveness afterwards.

3. Statistical analysis

The impact of the treatments by analyzing daily variations in littering behavior at each beach was assessed. In addition to collecting cigarette butts from the ground and from ashtrays (with assistance from beach workers), data on several other variables, that would influence the improper disposal of cigarettes, were also gathered. Following similar studies in the behavioral economics literature, which analyses the impact of treatments on given dependent variables (Castaldi et al., 2021; Saulītis et al., 2024), the econometric model was designed, as given by Eq. (1).

$$CB_{it} = \alpha + \beta_1 T_1 + \beta_2 T_2 + \delta E_{it} + \theta Z_i + \mu W_t + SiteFE_i + DayWFE_{it} + WeekFE_{it} + \varepsilon_{it} \quad (1)$$

and the dependent variable is specified as given by Eq. (2).

$$CB_{it} = \frac{CBGround_{it}}{CBGround_{it} + CBAsh_{it}} \quad (2)$$

The dependent variable in our model represents the amount of littering found on beach *i* at the end of day *t*. Littering is calculated as the ratio between the number of cigarette butts found on the ground and the total number of cigarette butts, which includes both those found on the ground and those found in ashtrays. The model includes three dummy variables. The first one indicates whether the environmental awareness nudge treatment was applied. The second dummy variable captures the presence of the recycling potential nudge treatment. The third dummy variable reflects whether an event took place at the beach on that day, which could influence the amount of cigarette waste due to increased visitor attendance. To control for potential confounding factors, the model includes a set of climate-related covariates.

These covariates include the daily mean temperature and the amount of rainfall recorded on that day. The model follows a multilevel structure and incorporates fixed effects at various levels. These fixed effects account for habitual patterns, such as increased visitor numbers on specific days due to recurring events or the presence of occasional smokers during weekends. Finally, the model includes an error term, which is assumed to follow a normal distribution.

4. Results

Figure 2 shows the trend of the variable Litter throughout our period of analysis, respectively for site 1, 2 and 3, highlighting the weeks in which the different treatments were administered.

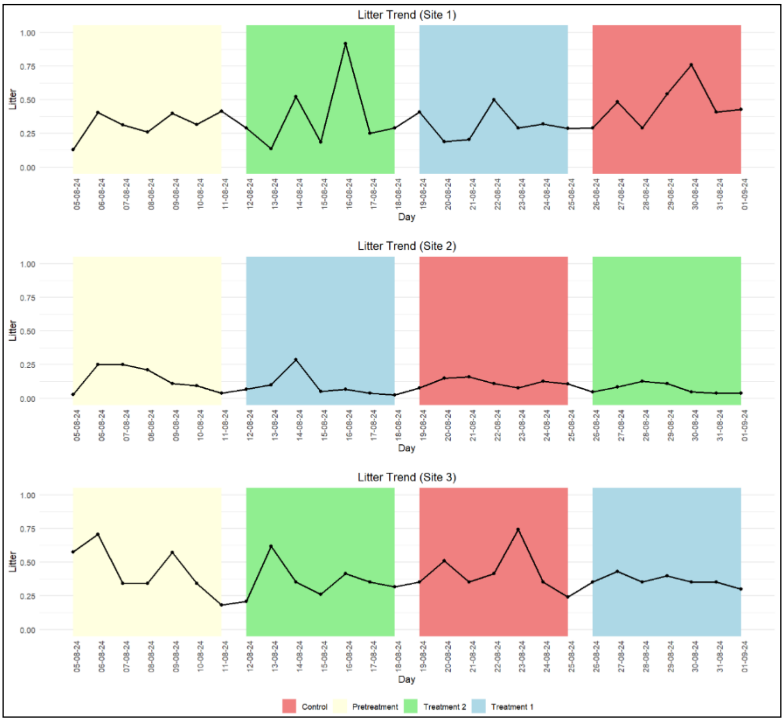

Fig. 2. Daily litter trend by site with colored week treatment

Table 1 shows the results of our regression estimations, differentiated according to the different model specifications we employed. The findings indicate that both treatments have negative coefficients, although they differ in magnitude, with the second one being consistently higher. The second treatment, however, is statistically significant throughout most of the models, while the first one does not show the same level of consistency.

These results lead to conclude that, holding all other factors constant, the first treatment has a negative but inconsistent effect on littering. However, the presence of the second treatment leads to a consistent reduction in loglitter ranging from 0.323 to 0.561, which respectively represent approximately 23.75% and 41.19% of the mean value of the dependent variable. This impact is particularly evident in the latter models, which employ site-level clustered standard errors and various types of fixed effects.

5. Discussion

The results of the statistical analysis show that the most effective nudge is that related to the recycling pro-energy-savings, while the nudge based on environmental concerns has lower significant effect on the litter reduction. This means that people are more responsive to practical issues, as the production of a recycled panel to insulate buildings, rather than ecological concepts, which are perceived to have no direct impact on the life quality of the human beings. In this sense, an improvement in the ecological knowledge of citizenry seems to be still necessary in fostering sustainable behaviors.

While the findings of this paper indicate that a specific type of nudge (i.e. the recycling pro-energy-savings focused one) has a greater impact on litter reduction, it can be integrated with other actions to address the littering issue comprehensively.

Table 1. Estimates of the dependent variable loglitter with β coefficient and standard error in brackets

	Dependent variable: loglitter								
	(1)	***(2)***	***(3)***	***(4)***	***(5)***	***(6)***	***(7)***	***(8)***	***(9)***
T1	-0.235	-0.371	-0.387	**-0.270***	**-0.269***	**-0.387*****	-0.269	**-0.363*****	-0.360
	(0.224)	(0.199)	(0.195)	(0.131)	(0.126)	(0.014)	(0.104)	(0.066)	(0.113)
T2	-0.355	**-0.480***	**-0.512***	**-0.340***	**-0.323***	**-0.512*****	**-0.323***	**-0.561*****	**-0.430***
	(0.224)	(0.202)	(0.200)	(0.134)	(0.130)	(0.101)	(0.069)	(0.050)	(0.067)
Event		**-0.693*****	**-0.841*****	-0.222	-0.156	**-0.841***	-0.156	**-0.801***	-0.153
		(0.183)	(0.210)	(0.129)	(0.151)	(0.350)	(0.127)	(0.342)	(0.148)
Rain		0.009	0.019	0.008	0.002	**0.019****	0.002	**0.019***	-0.003
		(0.021)	(0.024)	(0.014)	(0.016)	(0.007)	(0.013)	(0.009)	(0.011)
Temperature		**-0.092***	**-0.104***	-0.002	-0.014	**-0.104****	-0.014	**-0.137***	0.006
		(0.039)	(0.040)	(0.028)	(0.028)	(0.035)	(0.019)	(0.059)	(0.029)
Constant	**-1.362*****	1.449							
	(0.130)	(1.087)							
Week day FE			X		X	X	X	X	X
Site FE				X	X		X		X
SE Cluster						X	X	X	X
Week FE								X	X
Observations	87	87	87	87	87	87	87	87	87
R^2	0.032	0.283	0.364	0.697	0.744	0.364	0.744	0.378	0.749
Adjusted R^2	0.009	0.238	0.271	0.670	0.698	0.271	0.698	0.257	0.692

$^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

The behavioral intentions promoted by nudges can be effectively supported and reinforced by an enabling institutional framework, and should not substitute more traditional and substantial measures (as suggested first by Gowdy, 2008, and then by Ferraro and Miranda, 2013). Therefore, while nudges are proved to be beneficial to some extent, they must be complemented by educational and institutional campaigns led by local authorities to emphasize the importance of proper cigarette disposal, recognizing that this small individual action has a substantial collective impact.

6. Conclusions

In this study, a field experiment was conducted to evaluate the impact of two nudges on reducing the proportion of littered cigarette butts across several beaches located around Lake Trasimeno, Italy. Despite their small size, CBs inflict considerable environmental damage, which often goes unnoticed or unperceived by the public. Therefore, it is crucial to assess interventions aimed at modifying human behavior to mitigate the environmental harm caused by littered CBs, and to harness their recycling potential within the framework of the circular economy. These interventions are particularly significant for Lake Trasimeno, situated in Umbria, the Italian region with the highest smoking prevalence, and currently experiencing substantial environmental stress due to its unique characteristics and the escalating impacts of climate change.

The results indicate that the first treatment, which focuses on environmental awareness, shows a negative but inconsistent effect on the dependent variable. Conversely, the second treatment, which emphasizes the recycling pro-energy-saving potential of cigarette butts, demonstrates a negative, consistent and statistically significant correlation with littering, averaging a reduction of 32%. These findings provide greater support for the second research hypothesis. Beyond the statistical implications, the experiment, in terms of overall effectiveness (reduction of littered cigarette butts in absolute terms), has been successful, allowing for the collection of 2,434 cigarette butts, equivalent to around 0.730 kg of secondary raw materials useful for recycling purposes.

The findings contribute significantly to the experimental economics literature, as no previous study has evaluated the effects of nudges on reducing cigarette littering in a sensitive lake environment like Lake Trasimeno. The results offer insights not only into the effectiveness of green nudges, but also into which of the two tested nudges is more successful in altering people's behavior. Specifically, emphasizing the implications for the circular economy may be a more promising approach to addressing this issue acting on a potential virtuous cycle that, while reducing energy losses in buildings, generates monetary savings for households.

Paving the way for a new line of research on natural ecosystems, the research highlights the need of a holistic approach that combines nudging with other initiatives, such as educational programs and community engagement, to achieve meaningful and enduring behavioral change, given its beneficial effects on the community. Future research should further investigate these multifaceted strategies to develop more effective and sustainable solutions for environmental protection, and we look forward to research that replicates and extends our findings.

References

Carlsson F., Gravert C., Johansson-Stenman O., Kurz V., (2021), The use of green nudges as an environmental policy instrument, *Review of Environmental Economics and Policy*, **15**, 216–237.

Castaldi G., Cecere G., Zoli M., (2021), “Smoke on the beach”: On the use of economic vs behavioral policies to reduce environmental pollution by cigarette littering, *Economia Politica*, **38**, 1025–1048.

Cavagnoli S., Pazzaglia A., Fabiani C., de Albuquerque Landi F.F., Castellani B., Pisello A.L., (2024), Sustainable approach to cigarette butts management: From waste to new building material component, *Sustainable Energy Technologies and Assessments*, **72**, 104039.

Centro Regionale per la Salute Globale, (2024), *Giornata mondiale senza fumo*, Perugia. On line at: https://www.uslumbria1.it/giornata-mondiale-senza-tabacco-in-umbria-labitudine-da-fumo-e-ancora-una-criticita/Dewies M., Schop-Etman A., Rohde K.I.M., Denktaş S., (2021), Nudging is ineffective when attitudes are unsupportive: An example from a natural field experiment, *Basic and Applied Social Psychology*, **43**, 213–225.

Elia A.C., Dörr A.J.M., Abete M.C., Prearo M., (2010), Seasonal variability of detoxificant response and heavy metal accumulation in tissues of both sexes in *Tinca tinca* (L.) from Lake Trasimeno, *Reviews in Fish Biology and Fisheries*, **20**, 425–434.

Ferraro P.J., Miranda J.J., (2013), Heterogeneous treatment effects and mechanisms in information-based environmental policies: Evidence from a large-scale field experiment, *Resource and Energy Economics*, **35**, 356–379.

Gay A., Pascual A., Salanova T., Felonneau M.L., (2024), What about using nudges to reduce cigarette butts pollution?, *Journal of Human Behavior in the Social Environment*, **34**, 528–535.

Gowdy J.M., (2008), Behavioral economics and climate change policy, *Journal of Economic Behavior & Organization*, **68**, 632–644.

Kurz V., (2018), Nudging to reduce meat consumption: Immediate and persistent effects of an intervention at a university restaurant, *Journal of Environmental Economics and Management*, **90**, 317–341.

Lucia G., Giuliani M.E., d’Errico G., Booms E., Benedetti M., Di Carlo M., Fattorini D., Gorbi S., Regoli F., (2023), Toxicological effects of cigarette butts for marine organisms, *Environment International*, **171**, 107733, https://doi.org/10.1016/j.envint.2023.107733.

Ministero della Salute, (2025), *Fumo – Prodotti del tabacco – Sigarette elettroniche*, On line at: https://www.salute.gov.it/portale/fumo/dettaglioContenutiFumo.jsp?lingua=italiano&id=5579&area=fumo&menu=vuoto

Mohajerani A., Kadir A.A., Larobina L., (2016), A practical proposal for solving the world's cigarette butt problem: Recycling in fired clay bricks, *Waste Management*, **52**, 228–244.

National Oceanic and Atmospheric Administration, (2024), *Marine Debris Program*, On line at: https://oceanservice.noaa.gov/facts/most-common-ocean-litter.html

Saulītis A., Silkāne V., Gaile G.A., (2024), Nudging pro-environmental behaviour in a subsidized waste recycling system: A field experimental study, *Journal of Environmental Psychology*, **99**, 102416, https://doi.org/10.1016/j.jenvp.2024.102416.

Schubert C., (2016), Green nudges: Do they work? Are they ethical?, *Ecological Economics*, **130**, 329–342.

Shah G., Bhatt U., Soni V., (2023), A comprehensive review on triple R eco-management strategies to reduce, reuse and recycle of hazardous cigarette butts, *Heliyon*, **9**, e16642, https://doi.org/10.1016/j.heliyon.2023.e16642.

Slaughter E., Gersberg R.M., Watanabe K., Rudolph J., Stransky C., Novotny T.E., (2011), Toxicity of cigarette butts, and their chemical components, to marine and freshwater fish, *Tobacco Control*, **20**, i25–i29.

Swaney J.A., (1992), Market versus command and control environmental policies, *Journal of Economic Issues*, **26**, 623–633.

Thaler R.H., Sunstein C.R., (2008), *Nudge: Improving decisions about health, wealth, and happiness*, Yale University Press, New Haven.

Walter J.M., (2020), Comparing the effectiveness of market-based and choice-based environmental policy, *Journal of Policy Modeling*, **42**, 173–191.

Wansink B., Just D.R., (2016), The limits of defaults: Why french fries trump apple slices, *BMC Research Notes*, **9**, 263, https://doi.org/10.1186/s13104-016-2061-z.

Wee S.C., Choong W.W., Low S.T., (2021), Can "nudging" play a role to promote pro-environmental behaviour?, *Environmental Challenges*, **5**, 100364, https://doi.org/10.1016/j.envc.2021.100364

World Health Organization, (2024), WHO global report on trends in prevalence of tobacco use 2000–2030, On line at: https://www.who.int/publications/i/item/9789240088283

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CROSSTEX: CROSS-SECTORAL PLATFORM FOR SUSTAINABLE AND CIRCULAR TEXTILE*

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Abstract

The textile and fashion sector, a pillar of Made in Italy, is at the center of an accelerated regulatory transformation driven by the "EU Strategy for a Sustainable and Circular Textile" of 2023. This strategy defines a new operational paradigm requiring the systemic integration of production digitalization with advanced collaborative ecosystems. This contribution illustrates an innovative approach developed within the MICS partnership through collaboration between the University of Florence - Service Design Lab and Italtel spa, which led to the creation of a cross-sectoral digital platform “CROSSTEX” to help Made in Italy SMEs into the transition towards sustainable and circular business models. The project addresses European regulatory challenges in traceability through the implementation of Digital Product Passport, supported by blockchain and IoT technologies, ensuring transparency and verifiability throughout the entire value chain.

The central element of innovation is represented by the Digital Waste Passport (DWP), a breakthrough solution that revolutionizes end-of-life processes and catalyzes systemic circularity in the textile supply chain. The DWP constitutes the technological core to facilitate end-of-life processes and achieve circularity, ensuring that every data is accessible, verifiable and useful for improving recycling and eco-design solutions.

The achieved results highlight the effectiveness of a systemic approach that transforms waste into growth opportunities through innovation, diversification and valorization of local resources. The platform positions itself as a strategic bridge between regulatory ambitions and companies' operational reality, providing regulatory clarity and concrete tools for implementing circular models. In conclusion, this case study demonstrates how industrial symbiosis, supported by advanced digital technologies and innovative collaborative networks, can constitute an effective systemic tool for competitiveness, innovation and resource efficiency, contributing to the relaunch of European industry in compliance with climate neutrality and environmental sustainability objectives.

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Keywords: circular economy, design service, digital product passport, ecodesign, textile waste

1. Introduction

In 2019, the Italian textile manufacturing sector produced an estimated 100,000 tons of waste, with approximately 73% being recycled and the remaining 27% either landfilled or converted into energy. The implementation of Extended Producer Responsibility (EPR) frameworks shifts the responsibility for waste management onto manufacturers, compelling them to fund systems for the collection, sorting, and recycling of textile materials. The presence of strategic industrial clusters, such as those in the automotive, packaging, and construction sectors, offers significant market opportunities for recycled textile products. Nonetheless, companies involved in textile waste processing continue to face challenges in delivering high-quality recycled outputs and establishing market positioning (Fashion for Good, 2022a, b; Textile Exchange, 2022; Wielechowski et al., 2023). This research investigates the growing need for small and medium-sized enterprises (SMEs) within the textile and fashion sector, particularly those contributing to the Made in Italy brand to comply with emerging European regulations focused on circularity and product traceability. The study proposes a service-oriented ecosystem to assist SMEs in maintaining competitiveness by enhancing traceability at the end-of-life stage and fostering cross-sectoral market applications for recycled textile materials (UNECE, 2022; Köhler et al., 2021). Specifically, the study examines the role of traceability technologies and the Digital Product Passport (DPP) in facilitating the transition toward circular supply chains and closed-loop recycling models. The DPP introduces enhanced levels of transparency and traceability throughout the textile product lifecycle by enabling the structured collection, analysis, and sharing of data among all stakeholders, in alignment with current EU regulatory frameworks. Despite these advancements, several unresolved challenges persist, particularly concerning the traceability of textile waste and its integration into new value chains (Dellabella, 2022; Zannoni, 2018).

Accordingly, the central objective of this research is to define a collaborative service ecosystem aimed at supporting networks of SMEs, start-ups, and research institutions within textile production districts in transitioning toward circular and sustainable practices (Buchel et al., 2022). The research encompasses key thematic areas, including secondary raw materials, innovative textile recycling processes, regulatory frameworks, and SME preparedness for these transitions. The project further outlines the conceptualization of a digital platform to promote eco-design in the textile sector by leveraging and enhancing existing digital tools and infrastructures tailored for the textile and fashion industry (EFA, 2023; Le Feber and Smit, 2023).

2. Materials and methods

This research was conducted within the MICS partnership, Project 1.5: Academia Meets Industry, through a collaboration between the University of Florence – Service Design Lab and Italtel S.p.A. The aim was to support the transition of Italian SMEs in the textile sector toward a circular economy, focusing on the valorization of pre-consumer and post-industrial textile waste through increased traceability and cross-sector collaboration. The methodology followed a three-phase structure (CDCA, 2022; EC, 2020; EC, 2023; Eisenreich et al., 2021):

- Phase 1 – Exploration: A state-of-the-art analysis was carried out across five key research areas: (1) EU regulations for sustainable textiles, (2) traceability technologies (e.g., Digital Product Passport), (3) textile recycling machinery and techniques, (4) cross-sectoral market opportunities, and (5) circular business models in industrial districts. This phase combined desk research, using literature reviews, regulatory analysis, and ecosystem mapping with field research including stakeholder interviews, focus groups, company visits, and surveys.

Outcomes included identifying gaps between policy and industry practice, mapping the local stakeholder ecosystem (Prato District), and formulating a preliminary platform concept.

- Phase 2 – Co-design: The identified gaps and proposed service concepts were validated through a participatory co-design process involving regional stakeholders from across the textile value chain. Methods included workshops, interviews, and site visits. Co-design methodologies enabled the emergence of cross-sectoral collaboration opportunities and user-driven innovations, such as tools for material composition detection and recycling optimization.
- Phase 3 – Infrastructure Design: Based on previous findings, a prototype for a digital service platform was developed in collaboration with Italtel S.p.A. The platform integrated blockchain-based traceability (Digital Waste Passport), eco-design tools, and functionalities supporting: (1) data collection on textile waste, (2) accessible digital tools for traceability and design, and (3) cross-sectoral networking for recycling opportunities.

Service Design and UI/UX methodologies guided the iterative development and testing of the platform, ensuring alignment with real user needs and confirming both usability and scalability potential through stakeholder validation (Meroni and Sangiorgi, 2011). A central outcome of the research was the development of the Ecosystem Map (McKinsey & Company, 2022). This tool proved essential for shaping the concept of the platform, as it enabled a clear identification of relevant stakeholders, their current roles within the textile value chain, and the relationships that structure existing networks. Beyond mapping the present state, the Ecosystem Map also highlighted opportunities for new cross-sectoral collaborations, showing how additional actors and services could be integrated into future networks (Taplin and Clark, 2012). By visualizing these dynamics, the Ecosystem Map provided the analytical foundation for aligning platform services with stakeholder needs, ensuring that CROSSTEX is grounded in real industrial interactions while also opening pathways for expanded cooperation (Tassi, 2019).

3. Experimental

Our case study addresses EU's mandatory textile waste collection from 2025, targeting 5.8 million tonnes of annual textile disposal (11 kg per capita) against global incineration rates of one truckload per second (Kew, 2023). The experimental framework operates within EU's Green Deal and Strategy for Sustainable and Circular Textiles, aiming for durable, recyclable products by 2030. The EURATEX's proposition of Recycling Hubs (ReHubs) concept provides our theoretical foundation, though concerns persist regarding material quality and data accuracy. Current statistics show 25–40% of textiles discarded during manufacturing, with less than 1% reused and only 20% downcycled (EC, 2022; JRC, 2021). The experimental platform integrates blockchain, IoT, Digital Product Passports (DPP) for supply chain transparency. DPP implementation, mandated under ESPR, captures material composition, production methods, and ownership histories for regulatory compliance. Key challenges include the textile industry's complex global value chains with limited transparency and pressure from stakeholders driving technological adoption. Results show persistent SME barriers including high costs, long payback periods, and regulatory uncertainty, while large corporations can invest more easily in these technologies (Eppinger, 2022).

The study distinguishes pre-consumer (production offcuts) and post-consumer waste streams, with multi-material fiber processing, especially elastane blends, requiring AI, Near-Infrared Spectroscopy, and thermo-chemical methods. Mechanical recycling dominates but requires virgin material blending, while chemical and biochemical alternatives show promise but face adoption barriers. Cross-sector applications span automotive, construction, and packaging industries. The Prato district processes 36,000 tons annually, demonstrating regional recycling capabilities despite chemical contamination challenges (Dei Ottati, 2009; Duhoux et al., 2021).

The platform leverages Italian textile cluster heritage, particularly SME networks in districts like Prato (Dei Ottati, 2009), building on networked industrial efficiency, artisanal quality preservation, and embedded socio-cultural relationships (Becattini, 2004). Circular Business Models (CBMs) focus on "more use per user," "more users per product," and "beyond physical product" strategies (Ellen MacArthur Foundation, 2021). Implementation challenges include competition with fast fashion models, though SMEs show CBM innovation potential despite resource limitations requiring district-level platform support (Bellandi et al., 2021; Bellandi and Storai, 2022).

4. Results and discussion

The CROSSTEX platform was conceived as a digital ecosystem to accelerate the transition of textile districts toward circularity and cross-sectoral sustainability. The results presented here reflect the outcomes of desk and field research, stakeholder engagement, and prototype development.

4.1. From concept to prototype

Initial research highlighted four major gaps hindering textile circularity (EEA, 2023; ISPRA, 2021):

- Regulations: fragmented rules on textile waste management, the recovery of exported materials, and the certification of recycled products across sectors;
- Circular networks: the absence of local supply chains for processing and valorizing textile waste, increasing dependence on imported secondary raw materials;
- Circular products and materials: limited awareness and regulatory barriers restricting the use of recycled textiles in other industries;
- Technologies and digital platforms: the need for advanced tracking systems and integration of tools such as AI, LCA, and blockchain to ensure transparency and compliance with EU regulations.

To address these challenges, the project designed a service platform integrating technical solutions and stakeholder needs. A participatory co-design process with representatives from the Prato and Biella textile districts guided the service definition. Interactive methods, such as card-based workshops, helped stakeholders explore potential services, prioritize long-term goals, and identify enabling conditions. This process revealed two strategic opportunities: building a shared database of cross-sector case studies to connect companies, and providing SMEs with traceability and eco-design tools aligned with emerging Digital Product Passport (DPP) requirements (Menci et al., 2007; Sangiorgi and Prendiville, 2017).

The CROSSTEX platform adopts an integrated strategy that connects textile companies with firms from other industries, enabling both local resource valorization and global competitiveness. Its mission is to support SMEs, start-ups, and research centers in adopting circular business models, promoting eco-design, and transforming textile waste into opportunities for innovation. The platform is structured into three complementary sections (Fig. 3) (EFA, 2023; Eisenreich et al., 2021; Levänen et al., 2021):

1) Digital Library: a hub for managing textile waste through blockchain-enabled traceability and a certified marketplace powered by the Digital Waste Passport (DWP);
2) Eco-Toolkit: a suite of digital tools, including LCA software, best practices, and consulting services on sustainability and compliance;
3) Eco-Network: a dynamic space for collaboration, offering interactive networking tools, challenges, and knowledge-sharing features.

Stakeholder mapping further organized participants into primary, secondary, and indirect actors, distributed across three ecosystem layers: “core business,” “extended enterprises,” and "wider business." This mapping clarified the interactions between companies and platform services, while exposing untapped opportunities for engagement across the textile value chain (EMF, 2021).

User research, including surveys, interviews, and site visits with 224 companies, identified service needs in traceability, waste management, eco-design, and digitalization. Six user archetypes were developed, such as wool-yarn producers, garment manufacturers, waste processors, start-ups, consultants, and association leaders to align the platform's architecture with real-world requirements (Italia del Riciclo, 2021).

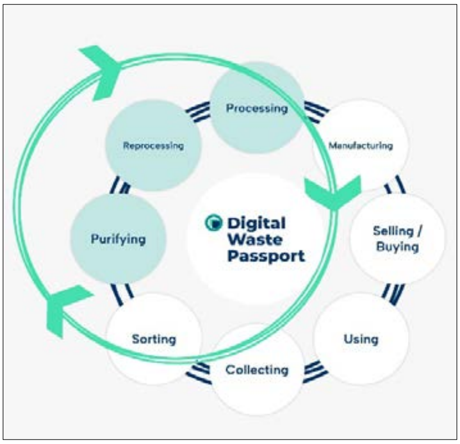

Fig. 1. Project concept: facilitates cross-sector textile recycling through certified tracking of textile waste and the dissemination of eco-design practices for its reuse and end-of-life operations.

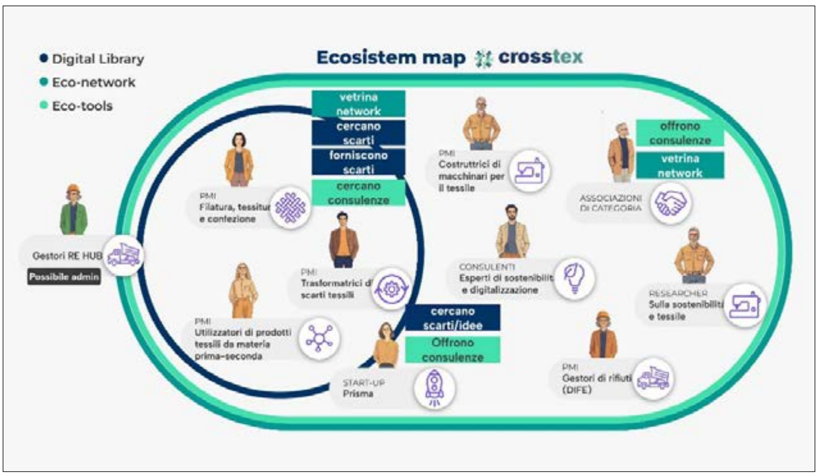

Fig. 2. Ecosystem Map - Descriptive map of interactions between potential stakeholders and the services offered by the Crosstex platform

The first tangible output of the project is the Digital Waste Passport (DWP), developed in partnership with Italtel spa under the MICS project. The DWP serves as the core functionality of the CROSSTEX platform, providing a blockchain-based system for generating verified information on textile waste. This enables secure transactions in a certified marketplace and facilitates cross-sector reuse of pre-consumer materials (Ljungkvist et al., 2018). In the absence of a standardized

Digital Product Passport for textiles, the DWP has been designed around existing sustainability metrics such as LCA indicators, ecolabel requirements, and supply chain traceability. Data is stored on blockchain to guarantee integrity, security, and transparency. Ongoing activities focus on refining the DWP architecture, mapping the requirements necessary for compliance with future DPP regulations, and developing a mock-up for stakeholder validation. The aim is to ensure that the DWP not only meets regulatory demands but also responds to the operational needs of SMEs and other ecosystem actors. The proposed intervention addresses the critical need for sustainable solutions in the textile sector, where regulatory uncertainty complicates authorization processes and restricts the reuse of secondary raw materials. Key barriers, such as high investment costs, long payback periods, and fragmented regulations continue to challenge SMEs and industrial clusters.

In this context, the gradual rollout of the Digital Product Passport (DPP) holds transformative potential, but its application to textiles remains slow, fragmented, and without a unified framework. As a step forward, the Digital Waste Passport (DWP) developed in this research illustrates how digital tools can support traceability, facilitate end-of-life processes, and enable circular supply chains.

Fig. 3. Three pillars of the Crosstex platform: organized into three main sections - Digital Library with Digital Waste Passport, Eco-Tool, and Eco-Network.

5. Concluding remarks

The CROSSTEX platform demonstrates how cross-sectoral collaboration, technological innovation, and design-oriented methodologies can concretely translate European regulatory ambitions into achievable and scalable industrial practices. By bridging the existing gap between EU policy frameworks and the operational conditions of small and medium-sized enterprises (SMEs), the platform establishes a replicable model for integrating circularity within regional and national textile ecosystems. The initiative positions *Made in Italy* not only as a symbol of quality and craftsmanship but also as a global reference for sustainable and circular textile production.

At the heart of this transition lies the Digital Waste Passport (DWP), an innovative digital solution designed to trace materials and manage textile waste throughout its lifecycle. By ensuring data integrity, accessibility, and interoperability, the DWP directly addresses the longstanding traceability and end-of-life challenges that have hindered circular progress in the textile value chain. This tool supports the regulatory evolution toward the Digital Product Passport (DPP), providing a practical and scalable framework that can be adapted across industries and aligned with the European Green Deal's sustainability goals.

Beyond technological innovation, CROSSTEX represents a shift toward systemic circularity, an integrated vision where eco-design, reuse of pre-consumer waste, and intersectoral cooperation are strategically interconnected. The platform enables SMEs and designers to operate within a clear regulatory context, providing them with digital instruments that enhance material efficiency, product transparency, and compliance readiness. Through its Digital Library, Eco-Toolkit, and Eco-Network, the platform promotes capacity building, digital literacy, and innovation, encouraging companies to adopt circular business models grounded in resource efficiency and design thinking. By reinforcing the connection between academic research, industrial practice, and public policy, the platform fosters public–private synergy and creates an enabling environment for knowledge exchange and innovation diffusion. It enhances the competitiveness of local production systems, stimulates the creation of new market opportunities for recycled materials, and reinforces the resilience of the Italian textile sector in the face of global sustainability transitions.

Ultimately, CROSSTEX exemplifies how digital ecosystems can serve as catalysts for industrial symbiosis, supporting the transformation of waste into value while safeguarding cultural heritage and environmental integrity. The integration of traceability, eco-design, and collaboration within a single operational framework marks a significant advancement toward climate neutrality and sustainable growth. Through this approach, *Made in Italy* redefines its global identity—merging tradition, innovation, and circularity to pave the way for a more responsible and regenerative textile future.

References

Becattini G., (2004), *Industrial Districts: A New Approach to Industrial Change*, Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA.

Bellandi M., Ruiz-Fuensanta M.J., Santini E., (2021), *Factors of Environmental Sustainability in Italian Industrial Districts: A Composite Environmental Sustainability Index*, In: *Rethinking Clusters. Place-Based Value Creation in Sustainability Transitions*, Sedita S.R., Blasi S. (Eds.), Springer, Cham, pp. 111–124.

Bellandi M., Storai D., (2022), Structural change and agency in territorial development: The case of mature industrial districts, *Regional Studies*, **56**, 1–13.

Buchel S., Hebinck A., Lavanga M., Loorbach D., (2022), Disrupting the status quo: A sustainability transitions analysis of the fashion system, *Sustainability: Science, Practice and Policy*, **18**, 231–246.

CDCA, (2022), *Sfide per un tessile circolare. Dall'eco-design alla seconda vita dei materiali*, I Quaderni di Economia Circolare, Collana Saggi N.2, Centro Documentazione Conflitti Ambientali, Rome, Italy.

Dei Ottati G., (2009), An industrial district facing the challenges of globalization: Prato today, *European Planning Studies*, **17**, 1817–1835.

Dellabella S., (2022), *Sfide per un tessile circolare. Dall'eco-design alla seconda vita dei materiali*, I Quaderni di Economia Circolare, Collana Saggi N.2, Centro Documentazione Conflitti Ambientali CDCA.

Duhoux T., Maes E., Hirschnitz-Garbers M., Peeters K., Asscherickx L., Christis M., Sachdeva A., (2021), Study on the technical, regulatory, economic and environmental effectiveness of textile fibres recycling, *European Commission Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs*, **10**, 828412.

EC, (2020), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, *A new circular economy action plan for a cleaner and more competitive Europe*, On line at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

EC, (2022), *Strategy for Sustainable and Circular Textiles*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, On line at: https://eur-lex.europa.eu/legal-content/IT/TXT/HTML/?uri=CELEX:52022DC0141&from=EN

EC, (2023), *Directive Proposal for a Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste*, Targeted revision of the Waste Framework Directive, On line at: https://environment.ec.europa.eu/publications/proposal-targeted-revision-waste-framework-directive_en

EEA, (2023), *EU Exports of Used Textiles in Europe's Circular Economy*, European Environmental Agency, On line at: https://www.eea.europa.eu/publications/eu-exports-of-used-textiles

EFA, (2023), *Positioning on Ecodesign for Sustainable Products Regulation*, European Fashion Alliance, On line at: www.europeanfashionalliance.org

Eisenreich A., Füller J., Stuchtey M., (2021), Open circular innovation – How companies can develop circular innovations in collaboration with stakeholders, *Sustainability*, **13**, 13456, https://doi.org/10.3390/su132313456

Eppinger E., (2022), Recycling technologies for enabling sustainability transitions of the fashion industry: Status quo and avenues for increasing post-consumer waste recycling, *Sustainability: Science, Practice and Policy*, **18**, 114–128.

EMF, (2021), *Circular Business Models: Redefining Growth for a Thriving Fashion Industry*, Ellen MacArthur Foundation, On line at: https://ellenmacarthurfoundation.org/fashion-business-models/overview

Fashion for Good, (2022a), *Sorting for Circularity Europe: Sorters Handbook – How to Conduct a Sorting Analysis Using Hand-Held Near Infrared Scanning Technology*, On line at: https://reports.fashionforgood.com/wp-content/uploads/2022/09/Sorting-For-Circularity-Europe_Sorters-Handbook_Fashion-for-Good.pdf

Fashion for Good, (2022), *Sorting for Circularity Europe: An Evaluation and Commercial Assessment of Textile Waste Across Europe*, On line at: https://reports.fashionforgood.com/report/sorting-for-circularity-europe/

ISPRA, (2021), *Rapporto Rifiuti Urbani 2021 (dati 2020)*, Istituto Superiore per la Protezione e la Ricerca Ambientale, Rome, Italy.

Italia del Riciclo, (2021), *Provenienza Rifiuti Tessili (dati 2019)*, Fondazione per lo Sviluppo Sostenibile e Fise Unicircular, On line at: https://www.consorziosea.it/presente-futuro-del-riciclo-dei-rifiuti-tessili/

Köhler A., Watson D., Trzepacz S., Löw C., Liu R., Danneck J., Faraca G., (2021), Circular economy perspectives in the EU textile sector, *Publications Office of the European Union*, Luxembourg.

Le Feber N., Smit M.J., (2023), Fashion companies pioneering with eco innovations in the Swedish fashion industry: Motivations, resources, and cooperation, *Circular Economy and Sustainability*, **3**, 1885–1905.

Levänen J., Uusitalo V., Härri A., Kareinen E., Linnanen L., (2021), Innovative recycling or extended use? Comparing the global warming potential of different ownership and end-of-life scenarios for textiles, *Environmental Research Letters*, **16**, 054069, http://doi.org/10.1088/1748-9326/abfac3.

Ljungkvist H., Watson D., Elander M., (2018), Developments in global markets for used textiles and implications for reuse and recycling, *Mistra Future Fashion*.

McKinsey & Company, (2022), *Scaling Textile Recycling in Europe – Turning Waste into Value*, McKinsey & Company, London.

Menci A., Miraglino P., Pieri L., Piscitelli C., Ponzecchi F., (2007), *I processi produttivi e di supporto del sistema tessile-abbigliamento a Prato. Analisi dei processi e delle figure chiave del settore*, Tipografia La Marina.

Meroni A., Sangiorgi D., (2011), *Design for Services*, Routledge, London.

Sangiorgi D., Prendiville A., (2017), *Designing for Service. Key Issues and New Directions*, Bloomsbury, UK.

Taplin D.H., Clark H., (2012), *Theory of Change Basic*, ActKnowledge, New York.

Tassi R., (2019), *Service Designer. Il progettista alle prese con sistemi complessi*, Franco Angeli, Milan, Italy.

Textile Exchange, (2022), *Guide to Recycled Inputs GRS-202-V1.0-2021.09.22 | RCS-202-V1.0-2021.09.22*, On line at: https://textileexchange.org/knowledge-center/documents/textile-exchange-guide-to-recycled-inputs/

UNECE, (2022), *Recommendation No. 46: Enhancing Traceability and Transparency of Sustainable Value Chains in the Garment and Footwear Sector*, United Nations Economic Commission for Europe, Geneva, Switzerland, On line at: https://unece.org/trade/publications/recommendation-no46-enhancing-traceability-and-transparency-sustainable-value.

Wielechowski R., Cozzolino G., Layden A., (2023), *Following the Thread*, Planet Tracker, On line at: https://witcher.fandom.com/wiki/Following_the_Thread_(The_Witcher_3)

Zannoni M., (2018), *Progetto e interazione: il design degli ecosistemi interattivi*, Unirsm Design, Quodlibet, Macerata, On line at: https://www.perlego.com/it/book/3060901/progetto-e-interazione-il-design-degli-ecosistemi-interattivi-pdf.

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SUSTAINABLE MORTAR DEVELOPMENT USING MINERALIZED SPENT LIME*

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Abstract

In contemporary times, the concepts of sustainability and recycling have become increasingly important in economic strategies, reinforcing the importance of the circular economy as a central way to reduce the environmental impacts of industrial processes, through the valorization of waste. For the Italian economy, hard-to-abate sectors such as ceramic tile manufacturing play a crucial role, and in the context of ecological transition, they require innovative solutions both to reduce carbon dioxide emissions and to valorize the by-products generated during emission abatement processes. Within this framework, the CCS4CER project (Carbon Capture, Storage and CO_2 Mineralization for the Ceramic Industry), funded by the European Regional Program PR-FESR 2021–2027 of Emilia-Romagna was launched. The project aims to develop an effective approach to capturing CO_2 from ceramic tile plants while, simultaneously, valorizing spent lime, an industrial waste currently disposed to landfill for hazardous waste. Spent lime is generated by the reaction of lime normally employed for the removal of acidic flue gases released during the firing stage. However, spent lime still contains a significant fraction of calcium hydroxide that can be exploited for CO_2 capture through mineralization. The present work addresses the formulation of low-carbon cement by reusing spent lime, once mineralized with CO_2 under laboratory-scale pilot conditions. Reducing the environmental impact of Portland cement-based materials is of particular interest, given the substantial greenhouse gas emissions associated with their production. The proposed approach follows this rationale by developing cements with a reduced clinker content (the primary constituent of Portland cement) and calcium carbonate produced via mineralization. Hydrated lime, spent lime, and mineralized spent lime from the production cycle of a selected ceramic manufacturer were characterized by laser granulometry, ICP-OES analysis for evaluation of the major compositional oxides

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and calcimetric analysis. In a second time, following this characterization, low-carbon cement formulation was developed and standardized mortar specimens were prepared in accordance with EN 196-1. After 28 days of curing, the mortars were evaluated through compression tests and water absorption measurements. All tests were benchmarked against a commercial limestone cement (CEM II-B/LL) containing an identical clinker content to the investigated low-carbon formulations. As second reference, a mortar containing the same amount of clinker content and calcium carbonate instead of mineralized spent lime was prepared, characterized and compared with the others formulations.

Keywords: circular economy, construction industry, environmental impact, hazardous waste, spent lime

1. Introduction

Since the Paris Agreement (2015) (Council of the European Union, 2015), hard-to-abate industrial sectors have been at the center of discussions as key targets for greenhouse gas (GHG) emission mitigation (Sousa et al., 2024). Among these sectors, there is ceramic tile manufacturing industry, whose production in Italy is concentrated in the Emilia-Romagna region for approximately 90%. For energy-intensive industries such as ceramic tile production, two major challenges emerge: the development of effective carbon capture and storage (CCS) strategies, and the identification of viable reuse pathways for industrial by-products and waste. Although the ceramic industry already recycles the majority of its process residues (Boschi et al., 2023), there is a material which is still commonly disposed of as hazardous waste, i.e., spent lime (Zanelli et al., 2021), which is also produced in other energy-intensive sectors such as steelmaking (Manocha and Ponchon, 2018) and pulp and paper industry (Wu et al., 2024). In ceramic tile manufacturing (Boschi et al., 2023), hydrated lime is used in flue gas scrubbers to capture acidic flue gases from firing processes, including SO_x, NO_x, HCl, and HF (Breedveld et al., 2007), generating a large amount of exhaust lime.

In this context, the Carbon Capture, Storage, and CO_2 Mineralization for the Ceramic Industry (CCS4CER) project, funded through the PR-FESR 2021–2027 program of Emilia-Romagna region (Italy), aims at characterizing spent lime from selected porcelain stoneware tiles production plants and to subject it to controlled CO_2 mineralization, for carbon capture properties (Bignozzi et al., 2025). The resulting mineralized product is then characterized and evaluated as a possible filler for eco-cements. This article investigates, firstly, the effects of CO_2 mineralization on the chemical and physical properties of spent lime, and secondly, the potential of the mineralized product to be reintegrated into construction materials, contributing to a circular economy approach.

2. Outline of the work

In this study a comparative characterization of three lime samples is carried out: starting hydrated lime (collected before its application in flue gas scrubbers), spent lime, and spent lime subjected to a mineralization reaction. The characterization was performed through three complementary analytical techniques: particle size distribution analysis, inductively coupled plasma optical emission spectroscopy (ICP-OES), and calcimetry. Both the hydrated and spent lime were sourced from the same production chain, located in the Sassuolo ceramic district (Italy), ensuring consistency of provenance. The mineralization process was developed and conducted by Centro Interdipartimentale per la ricerca Industriale Fonti Rinnovabili, Ambiente, Mare ed Energia (CIRI-FRAME) (Allegri et al., 2025). Once characterized, the mineralized lime was incorporated into Ordinary Portland cement (OPC), in a percentage equal to the calcium carbonate content of a commercial limestone Portland cement, used as reference material. Mortar samples were prepared with the new and reference cements and their mechanical performances were evaluated. The results provide insights into the feasibility of using mineralized exhaust lime as an additive in cement-based composites.

3. Materials and methods

3.1. Materials

Both the hydrated and spent lime samples were sourced from the same industrial production chain, located within the Sassuolo ceramic district (Italy). The reference commercial cement selected was a CEM II-B/LL 32.5R Portland-limestone cement (Heidelberg Materials – Evobuild, Germany), which was found to contain 34% $CaCO_3$ from calcimetric analysis. This amount was the value used to design both the control mixture containing pure laboratory-grade calcium carbonate and the experimental mortar incorporating mineralized lime. The cement formulated in this study was obtained by mixing CEM I 52.5R Ordinary Portland Cement (OPC) (SuperB, Buzzi, Vernasca, Italy), and mineralized lime in the 34% amount. As second reference, a cement prepared using CEM I 52,5R Ordinary Portland Cement and 34% of reagent-grade calcium carbonate was also prepared. The three cements were labelled as REF, MINER and REF-L, respectively.

These three cements were used to prepare standard mortars according to EN 196-1 (Ente Italiano di Normazione (UNI), 2016).

3.2. Methods

Particle size distribution of hydrated lime spent lime and mineralized spent lime was measured using a Malvern Mastersizer 2000 laser granulometer equipped with a Hydro 2000 MU wet dispersion unit. The powder sample, analyzed as received, was dispersed in a 0.05% aqueous solution of sodium hexametaphosphate ($(NaPO_3)_6$. The imaginary refractive index (i.e. absorption index, in accordance with Mie theory) was set to 0.01, and obscuration was optimized between 6–10%. Data acquisition was followed by processing the data in Microsoft Excel. Chemical composition of the three lime samples was determined using an Avio 550 Max ICP-OES spectrometer (PerkinElmer) equipped with Syngistix software for simultaneous multi-wavelength acquisition. Both borate fusion and acid digestion were employed for the determination of major oxides, with additional analysis performed on residual material after acid digestion.

The carbonate content of the limes (expressed as calcium carbonate) was quantified using a Dietrich-Fruhling calcimeter. For each test, 1 g of sample was used. Mortars were prepared in accordance with EN 196-1. A batch of 450 g of cement was mixed with 225 g of distilled water and 1350 g of CEN standard silica sand, using a Hobart automatic mortar mixer (Matest E093N). For the MINER mortar, a superplasticer (Mapei – Dynamon Cube 804) was also required, in an amount of 1.5% w/w with respect to cement, to achieve the same workability of the REF and REF-L mortars. The flowability was assessed by the flow table test following UNI EN 12350-5 (Ente Italiano di Normazione (UNI), 2009) by applying 15 drops. The superplasticer was previously mixed with water and then added directly in the mixing phase. The mortar specimens were cured for 24 hours before demolding, then stored in a humid chamber (RH>95%, 20°C). After 28 days of curing, compressive strength test was carried out using an Amsler–Wolpert testing machine. Finally, the water absorption was measured on REF-, REF-L- and MINER-based mortar prisms, in triplicate, according to UNI 7699 (Ente Italiano di Normazione (UNI), 2018).

5. Results and discussion

Three complementary analyses were conducted to provide an integrated assessment of the differences between hydrated lime, spent lime, and its mineralized form. Granulometric analysis was performed to assess the changes in particle size distribution across the three lime samples. Table 1 reports the statistical parameters d(10), d(50), and d(90), corresponding to the particle diameters below which 10%, 50%, and 90% of the sample grains falls, while Figure 1 shows the cumulative particle size distribution curves. A clear reduction in particle size was observed when passing from the hydrated to the spent lime, with all three parameters decreasing significantly, and a further reduction was seen in the mineralized product, which exhibited the smallest values, with a d(50) of approximately 8 μm and a d(90) of 22.56 μm. In d(90) is also clear a downward trend, from 61.29 μm of hydrated lime to 22.56 μm of mineralized product. This could be ascribed to some shrinkage owing to progressive carbonation (see below), and/or to chemical and physical transformation occurring during the operation phase of the lime filters.

Table 1. Statistical grain size distribution parameters for the three samples analyzed

Sample	*d(10) (μm)*	*d(50) (μm)*	*d(90) (μm)*
Hydrated lime	12.03	27.93	61.29
Spent lime	3.38	10.05	52.41
Mineralized product	3.69	8.58	22.56

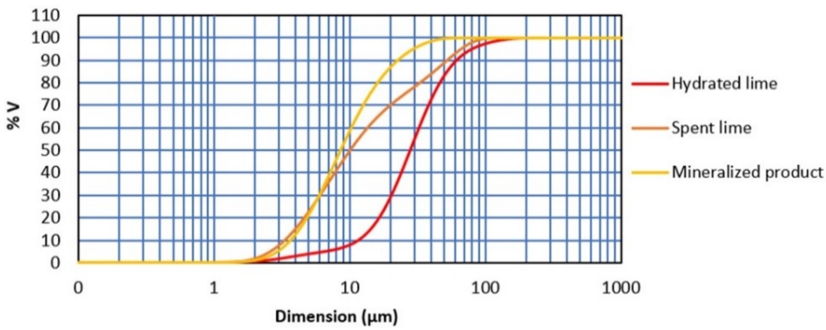

Fig. 1. Cumulative grain size distribution curves of the three samples analyzed

Chemical analysis of major oxides is summarized in Table 2, offering an insight into compositional differences among the three lime samples. In all cases, calcium oxide (CaO) was the predominant oxide, as expected, while in both spent and mineralized lime the second most abundant oxide was SO_3, likely linked to the presence of anhydrite.

Calcimetric analysis provided a rapid and direct quantification of calcium carbonate content, as illustrated in Fig. 2, and demonstrated a progressive increase in $CaCO_3$ content from hydrated lime to spent lime. However, interestingly, spent lime still contains a remarkable amount of calcium hydroxide (from XRD analysis, non-reported here for brevity's sake), offering a chance for mineralization. The mineralization process was very effective in reducing portlandite content and leading to calcium carbonate formation.

Compressive strength tests were carried out on the three formulations previously described, i.e., the mortars containing the three binders: commercial Portland-limestone cement CEM II-B/LL (limestone content 34%) named REF, cement prepared by mixing OPC with 34% of reagent-grade $CaCO_3$ (REF-L), and cement prepared by mixing OPC with 34% of mineralized spent lime (MINER).

Table 2. ICP-OES results for the quantification of major oxides present in the three samples, expressed both as % of the total composition, and ppm

	Hydrated lime		*Spent lime*		*Mineralized product*	
	%	*ppm*	*%*	*ppm*	*%*	*ppm*
SiO_2	0.57	5700	0.14	1400	1.12	11200
Al_2O_3	0.52	5200	0.47	4700	1.93	19300
TiO_2	0.14	1400	0.12	1200	0.14	1400
Fe_2O_3	0.11	1100	0.17	1700	0.12	1200
CaO	96.5	965000	86.3	863000	84.22	842200
MgO	0.9	9000	1.03	10300	0.29	2900
K_2O	0.28	2800	0.2	2000	0.11	1100
Na_2O	0.28	2800	0.28	2800	0.12	1200
Li_2O	0.01	100	0	0	0	0
P_2O_5	0.05	500	0.04	400	0.04	400
SO_3	0.34	3400	10.92	109200	11.8	118000
Other oxides	<0.01		<0.01		<0.01	

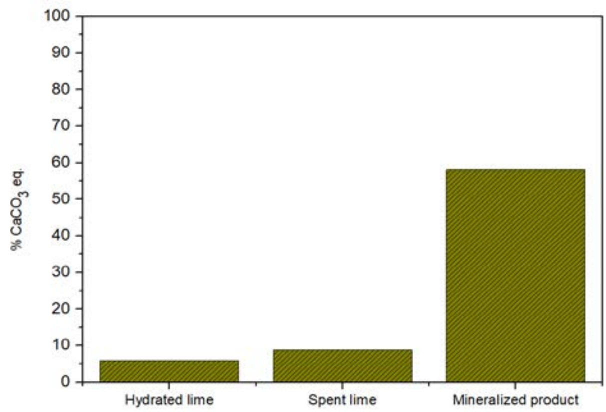

Fig. 2. Comparison of the percentage content of equivalent $CaCO_3$, evaluated in the three samples

The results, presented in Table 3, showed that the mortar containing mineralized lime achieved compressive strengths exceeding those of the commercial reference, and comparable to those of the laboratory mixture containing pure $CaCO_3$, indicating that the mineralized product is promising substitution option for limestone in cements.

Table 3. Results of the compressive tests for the three mortar in analysis

Sample	*Compressive strength (MPa)*	*Standard deviation (MPa)*
REF	35.3	0.8
REF-L	42.9	1.5
MINER	41.6	1.5

Finally, water absorption testing, summarized in Table 4, indicated that both REF and REF-L absorbed slightly less water than MINER, but these values shall be confirmed by more detailed analysis.

Table 4. Percentage of water absorption for the mortar with mineralized lime and the commercial one

Sample	*Water absorption (%)*	*Standard deviation (%)*
REF	8.9	0.08
MINER	10.6	0.09
REF-L	8.6	0.09

6. Concluding remarks

The characterization of hydrated, spent, and CO_2-mineralized lime revealed a progressive reduction in particle size from hydrated to spent to mineralized lime, which, in agreement with calcimetric analysis, corresponded to an increase in total calcium carbonate content—slightly higher in spent lime and substantially increased after mineralization—confirming the effectiveness of the mineralization process. In fact, although the chemical analysis showed a basically constant concentration of calcium oxide, the decrease of portlandite content in favor of calcium carbonate was assessed. An increase in sulfur oxide content in spent lime was highlighted too, which remains in the mineralized lime but is anyway in line with the amount of gypsum commonly used in OPC.

Mortar prepared with mineralized lime following EN 196-1 standard, and subsequently tested for compressive strength, demonstrated values higher than those of a commercially available Portland-limestone cement having an equal amount of limestone and comparable to those of a laboratory-formulated cement containing pure calcium carbonate. These results indicate the potential use of mineralized spent lime as a filler for eco-cements, also showing its capacity to capture and store carbon dioxide. Water absorption testing showed comparable values between the commercial and experimental mortars.

Future work will include leaching tests on both lime samples and mortar formulations to investigate the release of heavy metals and ions, such as chlorides and fluorides, which are expected given the role of lime filters in porcelain stoneware tile production process. Overall, this study demonstrates the potential of spent lime, a by-product of energy-intensive industrial processes, to react effectively with CO_2, one of the principal greenhouse gas emissions driving climate change, and to be repurposed as an active component in other industries. Such valorization could reduce the environmental burden associated with landfilling, contributing to circularity and environmental sustainability.

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References

Allegri A., Bignozzi M.C., Dal Pozzo A., De Angelis A.R., Millini R., Albonetti S., (2025), Simultaneous waste remediation and carbon capture via CO_2 mineralization over industrial basic wastes, *Book of Abstracts*, © 2025 Brussels, Belgium: ERIC aisbl Press, ISBN 979-12-210-9763-4, *ICEC 2025 – 13th International Conference on Environmental Catalysis*, Isola delle Femmine (PA - Sicily), Italy, 2–5 June.

Bignozzi M.C., Artale A., Allegri A., Albonetti S., Dal Pozzo A., Scognamiglio V., De Angelis A.R., Millini R., (2025), Carbonated industrial waste by CO_2 mineralization as new constituent for cements, *C3 Symposium 2025*, Chicago, 2–5 October, On line at: https://docs.lib.purdue.edu/c3_2025/2025/carbon/8

Boschi G., Bonvicini G., Masi G., Bignozzi M.C., (2023), Recycling insight into the ceramic tile manufacturing industry, *Open Ceramics*, **16**, 100471, https://doi.org/10.1016/j.oceram.2023.100471.

Breedveld L., Timellini G., Casoni G., Fregni A., Busani G., (2007), Eco-efficiency of fabric filters in the Italian ceramic tile industry, *Journal of Cleaner Production*, **15**, 86–93.

Council of the European Union, (2015), *Paris Agreement on Climate Change*, On line at: https://www.consilium.europa.eu/en/policies/paris-agreement-climate/

UNI, (2009), *UNI EN 12350-5:2009 Testing Fresh Concrete – Part 5: Flow Table Test*, Ente Italiano di Normazione, Milan, Italy.

UNI, (2016), *UNI EN 196-1:2016 Methods of Testing Cement – Part 1: Determination of Strength*, Ente Italiano di Normazione, Milan, Italy.

UNI, (2018), *UNI 7699:2018 Prova sul Calcestruzzo Indurito – Determinazione dell'Assorbimento di Acqua alla Pressione Atmosferica*, Ente Italiano di Normazione, Milan, Italy.

Manocha S., Ponchon F., (2018), Management of lime in steel, *Metals*, **8**, 686, https://doi.org/10.3390/met8090686.

Sousa J., Azevedo I., Camus C., Mendes L., Viveiros C., Barata F., (2024), Decarbonizing hard-to-abate sectors with renewable hydrogen: A real case application to the ceramics industry, *Energies*, **17**, 3661, https://doi.org/10.3390/en17153661.

Wu R., Carrejo E., Sumon Reza M., Woods E., Razavi S., Park S., Fanxing L., Sagues W.J., (2024), Kinetic assessment of pulp mill-derived lime mud calcination in high CO_2 atmosphere, *Fuel*, **373**, 132372, https://doi.org/10.1016/j.fuel.2024.132372.

Zanelli C., Conte S., Molinari C., Soldati R., Dondi M., (2021), Waste recycling in ceramic tiles: A technological outlook, *Resources, Conservation & Recycling*, **168**, 105289, https://doi.org/10.1016/j.resconrec.2020.105289.

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INTEGRATING CIGARETTE BUTT WASTE INTO GYPSUM PANELS: A LIFE CYCLE APPROACH TO SUSTAINABLE CONSTRUCTION MATERIALS*

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Abstract

Cigarette butts (CBs) are the most common form of litter worldwide, persisting in the environment due to their cellulose acetate filters, plastic additives, and heavy metals. This study evaluates the potential of recycling CBs into gypsum-based building panels through a life cycle assessment (LCA). The aim is to determine whether partial substitution of mineral filler with shredded CBs can reduce environmental impacts compared to conventional gypsum board production and insulation materials. Gypsum panels incorporating 2.5% and 50% CBs by weight were previously produced and tested for thermal and acoustic properties. The LCA, conducted according to ISO 14040/44 standards under a gate-to-gate approach, considered raw material supply, transport, and panel production. Firstly, two scenarios were modeled: one representing a conventional gypsum panel and another including 2.5% (by mass) of processed cigarette butts as a partial substitute for mineral filler. The functional unit was 1 m² of panel.
Furthermore, the recycled panel containing 50% of cigarette butts was compared to alternative insulation panels currently available in the market, demonstrating a comparable performance in terms of environmental impact across several key indicators. In this case, the functional unit is the mass (in kilograms) of insulation material required to provide the same thermal resistance (R) over an area of 1 m². This mass varies depending on the thermal conductivity and density of the material. Results indicate that CB inclusion reduces several impact categories, mainly due to resource savings and waste valorization, while the 50% CB panel shows comparable environmental performance to commercial insulation products. This approach offers a circular solution for CB waste and supports sustainable construction practices.

Keywords: cigarette butts, gypsum, insulation materials, LCA, waste

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1. Introduction

Cigarette butts, the most widely littered consumer item in the world, pose significant environmental and health concerns due to their non-biodegradable nature and the toxic chemicals they contain (Arat, 2024; Becherucci et al., 2017; Green et al., 2023; Pazzaglia and Castellani, 2024; Vanapalli et al., 2023). According to estimates from the Istituto Superiore di Sanità (2015), more than 15 billion cigarettes are smoked worldwide each day. In parallel, the United States Department of Agriculture has reported that cigarette butts generate around 1.2 million tonnes of waste annually (Kadir and Sarani, 2015). In cities, these residues are commonly discarded in public spaces such as roads, beaches, and parks. Due to their slow decomposition, cigarette butts tend to persist in the environment, leading to long-term pollution issues (Dobaradaran et al., 2021). Despite their ubiquity, cigarette butts are often overlooked in waste management strategies, with many municipalities lacking effective methods for their disposal. However, recent research has highlighted the potential for cigarette butts to be repurposed in recycling processes, offering a promising avenue for reducing waste and mitigating environmental impacts (Marinello et al., 2020; Moroz et al., 2021).

Tataranni and Rahman investigated the use of shredded cigarette butts (CBs) as a sustainable additive in Stone Mastic Asphalt mixtures (Rahman et al., 2020; Tataranni et al., 2021). Their findings revealed that incorporating CBs not only acts as a stabilizing agent but also enhances the mechanical performance of bituminous blends. Rahman et al. further demonstrated that mixtures of CBs and bitumen exhibited superior physical and rheological properties compared to conventional blends without CBs (Rahman et al., 2020).

An alternative approach explored by multiple authors involves the integration of CBs into fired clay bricks. In these studies, CBs were added in varying amounts—up to 10%—to assess their influence on brick properties. As the CB content increased, both compressive strength and density declined, while water absorption rose from 5% to 18% (Kadir and Mohajerani, 2010). Nevertheless, adding up to 5% CBs did not significantly reduce flexural strength. Thermal conductivity showed a notable decline, with a 58% reduction observed at a 10% CB content (Mohajerani et al., 2016; Kurmus and Mohajerani, 2021). Leachability of heavy metals was minimal, likely due to the firing temperature (~1050 °C) transforming metals into stable oxides (Aeslina and Mohajerani, 2012).

Promising outcomes have also been reported in the incorporation of CBs into gypsum-based composites. Initial investigations showed that adding shredded CBs enhanced mechanical characteristics such as surface hardness, strength, and density (Morales-Segura et al., 2020). Optimal performance was found with a 2.5% w/w CB-to-gypsum ratio. Further research demonstrated that up to 3.5% CBs improved both flexural and compressive strengths while also reducing the thermal conductivity coefficient relative to control samples (Romero-Gomez et al., 2022).

In a previous study of the authors (Cavagnoli et al., 2024), CBs were incorporated into gypsum panels at concentrations up to 2.5 wt% and higher CB:matrix:water ratios (1:2:3). The resulting composites exhibited improved thermal insulation and acoustic absorption compared to conventional materials. Despite these studies, a life cycle assessment of these materials is still lacking. For this reason, the aim of this study is to assess the production of a gypsum panel with the addition of cigarette butts in the material mix. This study builds on previous research that examined the thermal and acoustic properties of gypsum and cement panels with the addition of cigarette filters in concentrations of 2.5% and 50% w/w (Cavagnoli et al., 2024). Firstly, two scenarios were modeled: one representing a conventional gypsum panel and another including 2.5% (by mass) of processed cigarette butts as a partial substitute for mineral filler. Additionally, a recycled panel containing 50% cigarette butts was compared to alternative insulation panels currently available on the market. This research could be a significant step forward in the field of LCA applied to cigarette butt recycling, as it is the first time this material has been analyzed with this approach.

2. Materials and methods

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental impacts associated with all the stages of a product's life, from raw material extraction (cradle) through materials processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling (grave). The primary goal of LCA is to provide a comprehensive picture of the environmental impacts of a product or process, helping stakeholders make informed decisions to minimize negative environmental effects. A Life Cycle Assessment (LCA) involves several key components. It starts with Goal and Scope Definition, where the purpose, boundaries, product system, functional unit, and assumptions of the study are established. The next phase is Inventory Analysis (LCI), which involves collecting and quantifying inputs and outputs such as materials, energy, emissions, and waste throughout the product's life cycle.

Following this, Impact Assessment (LCIA) evaluates the potential environmental impacts of these inputs and outputs, categorizing them into areas like global warming potential, ozone depletion, acidification, and human toxicity. Finally, Interpretation analyzes the results to identify significant environmental issues, ensure data accuracy, and assess the robustness of the findings, often incorporating sensitivity and uncertainty analyses. This comprehensive approach helps improve environmental performance and supports sustainable decision-making. This paper follows ISO 14040 and ISO 14044 standards, which provide guidelines and requirements to ensure consistency, transparency, and scientific validity in the assessment process.

2.1. Goal and scope definition

The primary objective of this research is to compare the environmental impact of producing a gypsum panel (GP) with that of a GP incorporating cigarette butts (GP-CBs). Specifically, it evaluates the environmental repercussions of manufacturing a GP containing 2.5% recycled and shredded CBs by weight. Furthermore, the recycled panel containing 50% of CBs was compared to alternative insulation panels currently available in the market.

2.2. Functional unit and system boundaries

According to ISO 14040 standard, a specific functional unit (f.u.) has to be defined. It is the reference unit through which a system performance is quantified in a LCA. For the first analysis (GP vs GP-CBs), the functional unit considered for this study is a gypsum panel with an area of 1 m^2 and a thickness of 2 cm, resulting in a volume of 0.02 m^3. For the comparison among 50% CBs panel and other insulation panels, the functional unit (f.u.) of the has been defined, according to a proposal of the Council for European Producers of Materials for Construction (Pargana et al., 2014; CEPMC, 2000) as the mass in kg of insulating panel that involves a thermal resistance R equal to 1 m^2 K/W (Eq. 1).

$$\text{f.u.} = R \cdot \lambda \cdot \rho \cdot A \qquad (1)$$

where R is the thermal resistance equal to 1 m^2 K/W; λ is the thermal conductivity of the panel in W/mK; ρ is the density of the panel in kg/m^3; A is the area equal to 1 m^2. This functional unit indicates the quantity of insulation material needed to achieve a defined thermal resistance over the panel's service life. It is especially suitable for this analysis, as it allows for the environmental impacts of various panels to be compared based on a standardized insulation performance.

The system boundaries include the collection of cigarette butts, the shredding of cigarette butts (CBs), and the mixing of materials to produce the gypsum panels with cigarette butts (GP-CBs). The end-of-life of GP-CBs has not been considered in this analysis due to the lack of data on this topic. The geographical boundaries are defined by the area covered by Gesenu Spa in waste collection within the Umbria region of Italy. Specifically, the municipality of Todi, Umbertide, Perugia, Torgiano, Bettona, Bastia Umbra, Gubbio, Assisi, Castiglion del Lago, Corciano, Marsciano, Passignano, Magione, Panicale, Deruta, Città della Pieve, Valfabbrica, Piegaro, Città di Castello. The mean distance from these municipalities and the waste company has been calculated as 24.64 km.

2.3. Environmental impact assessment

To evaluate the environmental impact of the two panels, we employed the Recipe 2016 Endpoint (H) V1.09/World (2010) H/A, Recipe 2016 Midpoint (H) V1.09/World (2010) H and GWP100 methodologies. Midpoint indicators focus on specific environmental problems. They provide a more detailed and precise analysis of impact categories. Endpoint indicators aggregate the midpoint results into broader categories that reflect their effects on areas of protection, such as human health, ecosystems, and resource availability. GWP100 measures the potential contribution to climate change by quantifying the amount of greenhouse gases (GHGs) emitted over a 100-year time horizon.

2.4. Life cycle inventory

This section shows used data for the environmental assessment. Data are standardized with respect to functional unit of a gypsum panel of 1 m^2 and 2 cm thickness for the first analysis. For the comparison among insulation panels, the other functional unit has been used as reference.

Table 1. Life cycle inventory of gypsum panel of 1 m2 and 2 cm thickness

Inputs for gypsum panel		
	Quantity	Unit
Tap water {Europe without Switzerland}| market for tap water | Cut-off, S	15.34	kg
Stucco {GLO}| market for stucco | Cut-off, S	25.50	kg
Inputs for gypsum panel with 2.5% CBs		
	Quantity	Unit
Avoided products		
Process-specific burdens, municipal waste inceneration {Europe without Switzerland}| market for process-specific burdens, municipal waste inceneration | Cut-off, U	0.62	kg
Inputs		
Tap water {Europe without Switzerland}| market for tap water | Cut-off, S	15.34	kg
Stucco {GLO}| market for stucco | Cut-off, S	24.88	kg
Electricity, medium voltage {Europe without Switzerland}| market group for | Cut-off, U	35.83	kJ

Municipal waste collection service by 21 metric ton lorry {GLO}| market m unicipal waste collection service by 21 metric ton lorry | Cut-off, U	15.27	kgkm

Table 2. Life cycle inventory of insulation panels

Inputs for gypsum panel with 50% CBs		
Avoided products	Quantity	Unit
Process-specific burdens, municipal waste inceneration {Europe without Switzerland}| market for process-specific burdens, municipal waste inceneration | Cut-off, U	14.73	kg
Inputs		
Tap water {Europe without Switzerland}| market for tap water | Cut-off, S	44.18	kg
Stucco {GLO}| market for stucco | Cut-off, S	29.45	kg
Electricity, medium voltage {Europe without Switzerland}| market group for | Cut-off, U	848.26	kJ
Municipal waste collection service by 21 metric ton lorry {GLO}| market m unicipal waste collection service by 21 metric ton lorry | Cut-off, U	362.96	kgkm
Wood fibreboard (Schulte et al., 2021)		
Inputs	Quantity	Unit
Fibreboard, soft {RER}| market for fibreboard, soft | Cut-off, S	3.23	kg
Stone wool (Ardente et al., 2008; Arellano-Vazquez et al., 2020; Cekon et al., 2017; Intini and Kühtz, 2011; Mattoni et al., 2019; Ricciardi et al., 2014)		
Inputs	Quantity	Unit
Stone wool {GLO}| market for stone wool | Cut-off, S	2.00	kg
EPS (Cekon et al.,2017; Gomes et al., 2020; Intini and Kühtz, 2011; Mattoni et al., 2019; Pargana et al., 2014)		
Inputs	Quantity	Unit
Polystyrene foam slab for perimeter insulation {GLO}| market polystyrene foam slab for perimeter insulation | Cut-off, S	0.84	kg
Kenaf (Ardente et. al, 2008)		
Inputs	Quantity	Unit
See Ardente et al, 2008	1.52	kg
Glass wool (Ardente et al., 2008; Arellano-Vazquez et al., 2020; Mattoni et al., 2019; Papadopoulos and Giama, 2007; Ricciardi et al., 2014)		
Inputs	Quantity	Unit
Glass wool mat {GLO}| market for glass wool mat | Cut-off, S	0.81	kg
Flax (Schulte et al., 2021)		
Inputs	Quantity	Unit
Fibre, flax, long, scutched {RER}| market for fibre, flax, long, scutched | Cut-off, S	3.90	kg
Cork (Pargana et al., 2014)		
Inputs	Quantity	Unit
Cork slab {RER}| market for cork slab | Cut-off, S	4.40	kg
Cellulose (Ardente et al., 2008; Mattoni et al., 2019; Ricciardi et al., 2014)		
Inputs	Quantity	Unit
Cellulose fibre {CH}| market for cellulose fibre | Cut-off, S	1.90	kg

3. Results and discussion

In the first part of this section, the comparison between the gypsum panel and gypsum panel fortified with 2.5% wt CBs has been analyzed. From the ReCiPe endpoint analysis, the CBs panel consistently exhibited slightly lower impacts across all three damage categories. In particular, the Human Health impact decreased from 135.53 to 132.36 mPt (−2.34%), while Ecosystems and Resources decreased by 2.4% and 1.97% respectively (Fig. 1).

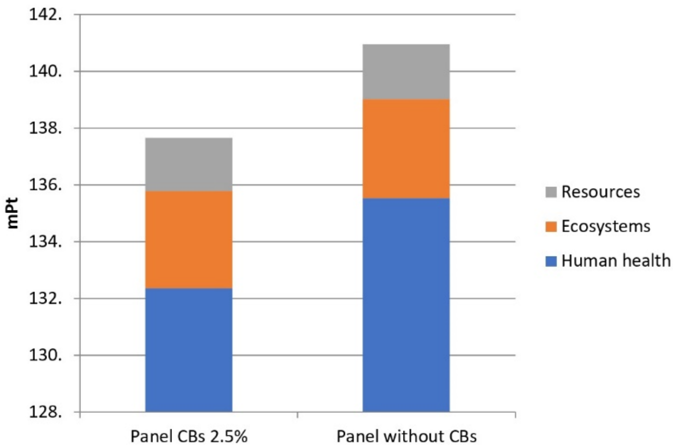

Fig 1. Comparison between panel with and without CBs using ReCiPe endpoint analysis

These improvements, although modest, suggest that incorporating CBs into the panel formulation can slightly reduce overall damage potential, particularly in human-related and resource categories. Midpoint indicators further support these trends. Notably, the Global Warming Potential (GWP) slightly dropped from 0.000331 to 0.000325 kg CO_2 eq per panel. Similarly, reductions were observed in categories such as stratospheric ozone depletion, ionizing radiation, and ozone formation (human health), albeit all within a margin of less than 5%. These variations indicate that cigarette butt inclusion does not introduce additional toxicity burdens and may slightly alleviate some impact pathways due to the displacement of virgin gypsum. The GWP100 analysis from the IPCC 2021 methodology confirms a ~2% reduction in fossil-related climate change impact with CBs addition (from 100 to 97.95%). The biogenic and land transformation contributions remained stable, while CO_2 uptake was accounted symmetrically in both systems.

The second part of this section shows the LCA comparison among different thermal insulation panels, with a focus on a novel gypsum-based panel incorporating 50% CBs by weight. Environmental impacts were assessed using the ReCiPe 2016 Endpoint and Midpoint methods, as well as the IPCC 2021 GWP100 indicator. The ReCiPe Endpoint analysis revealed that the panel incorporating 50% CBs demonstrated an intermediate environmental profile, with a total impact of 177.76 mPt. This is significantly lower than bio-based alternatives such as flax (433.2 mPt) and wood fiber (310.4 mPt), and moderately higher than conventional materials like EPS (133.3 mPt) and stone wool (154.2 mPt). The CB-enhanced gypsum panel outperformed several natural materials particularly in the "Human Health" category (170.5 mPt vs. 359.2 mPt for flax), likely due to the avoided burden associated with waste CBs disposal and reduced demand for virgin resources (Fig. 2).

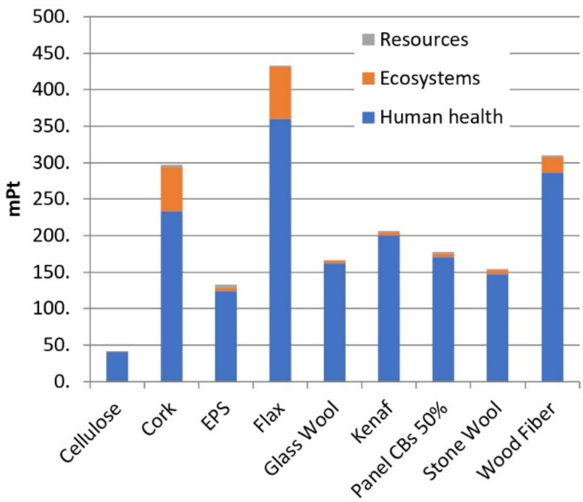

Fig 2. Comparison among different insulation materials through ReCiPe endpoint analysis.

From the Midpoint perspective, the CB panel exhibited balanced performance across categories. For example, it showed reduced impact in stratospheric ozone depletion (3.49%) and ionizing radiation (10.5%), compared to materials like cork (5.92% and 100%, respectively) or EPS (0.87% and 5.12%). However, in ozone formation for human health, the CB panel scored 47.0%, placing it closer to the average, and better than cork (66.1%) or flax (100%).

GWP100, expressed as kg CO_2-eq, followed a similar trend. The CB panel registered a GWP_fossil value of 61.25 kg CO_2-eq/f.u., which is substantially lower than that of cork (76.6) and flax (62.9), and comparable to synthetic alternatives like glass wool (42.2) and EPS (67.7). Notably, the negative CO_2 uptake values observed for some bio-based materials (e.g., flax and cork) highlight the complexity of biogenic carbon accounting, which may vary with system boundaries and temporal considerations (Fig. 3).

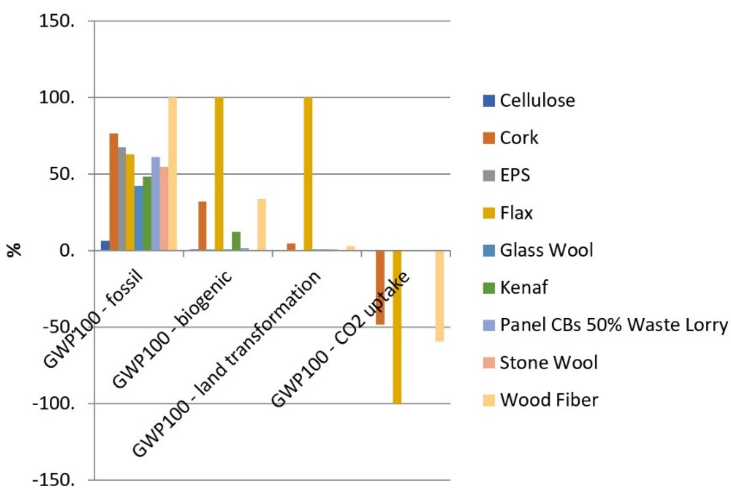

Fig 3. Global warming potential of the insulation materials analyzed in the paper

The integration of waste cigarette butts in construction materials represents a promising waste valorization strategy. Cigarette filters are composed mainly of cellulose acetate, a plastic that is slow to degrade and poses significant environmental pollution risks when improperly discarded. By embedding CBs into gypsum panels, this solution diverts hazardous waste from landfills and water bodies while reducing the need for virgin raw materials. Moreover, the environmental performance of the CB panel suggests that such waste-derived products can be competitive with, or even superior to, some commercial insulation alternatives, especially when evaluated under a gate-to-gate scope.

4. Conclusion

The environmental impacts associated with the production of gypsum panels with and without the incorporation of 2.5 wt% cigarette butts were assessed using a gate-to-gate Life Cycle Assessment (LCA). Furthermore, a second LCA of different thermal insulation panels has been performed, with a focus on a novel gypsum-based panel incorporating 50% cigarette butts by weight. Three LCA perspectives were analyzed: ReCiPe 2016 at endpoint and midpoint levels, and IPCC 2021 GWP100. Overall, the inclusion of 2.5% CBs into gypsum panels appears environmentally favorable, albeit with marginal benefits. Given that cigarette butts are a challenging waste stream, their valorization in building materials may contribute positively to waste management strategies and circular economy goals.

Overall, the gypsum panel incorporating 50% cigarette butts exhibits an environmentally competitive profile, combining waste reduction with functional insulation performance. Its environmental impacts are lower than or comparable to several traditional and bio-based panels, highlighting the potential of circular economy strategies in the construction sector. This study adopted a gate-to-gate perspective, excluding use-phase emissions and end-of-life scenarios. While this provides clear insight into manufacturing impacts, further work is necessary to assess the full life cycle, especially regarding the long-term behavior and potential leaching of toxic substances from embedded CBs.

References

Aeslina A.K., Mohajerani A., (2012), Leachability of heavy metals from fired clay bricks incorporated with cigarette butts, *IEEE BEIA Symposium 2012*, 872–877.

Ardente F., Beccali M., Cellura M., Mistretta M., (2008), Building energy performance: A LCA case study of kenaf-fibre insulation board, *Energy and Buildings*, **40**, 1–10.

Arellano-Vazquez D.A., Moreschi L., Del Borghi A., Gallo M., Islas Valverde G., Mayorga Rojas M., Romero-Salazar L., Arteaga-Arcos J.C., (2020), Use of EPD system for designing new building materials: The case study of a bio-based thermal insulation panel from the pineapple industry by-product, *Sustainability*, **12**, 6864, https://doi.org/10.3390/su12176864.

Becherucci M.E., Rosenthal A.F., Seco Pon J.P., (2017), Marine debris in beaches of the Southwestern Atlantic: An assessment of their abundance and mass at different spatial scales in northern coastal Argentina, *Marine Pollution Bulletin*, **119**, 299–306.

Cavagnoli S., Pazzaglia A., Fabiani C., de Albuquerque Landi F.F., Castellani B., Pisello A.L., (2024), Sustainable approach to cigarette butts management: From waste to new building material component, *Sustainable Energy Technologies and Assessments*, **72**, 104039, https://doi.org/10.1016/j.seta.2024.104039

Cekon M., Struhala K., Slávik R., (2017), Cardboard-based packaging materials as renewable thermal insulation of buildings: Thermal and life-cycle performance, *Journal of Renewable Materials*, **5**, 84–93.

CEPMC, (2000), *Guidance for the Provision of Environmental Information on Construction Products*, Council for European Producers of Materials for Construction, Brussels, On line at: https://www.cepco.es/Uploads/docs/EWG%2800%29038%20Rev1.pdf.

Dobaradaran S., Soleimani F., Akhbarizadeh R., Schmidt T.C., Marzban M., Basirian-Jahromi R., (2021), Environmental fate of cigarette butts and their toxicity in aquatic organisms: A comprehensive systematic review, *Environmental Research*, **195**, 110881, https://doi.org/10.1016/j.envres.2021.110881

Gomes R., Silvestre J.D., de Brito J., (2020), Environmental life cycle assessment of the manufacture of EPS granulates, lightweight concrete with EPS and high-density EPS boards, *Journal of Building Engineering*, **28**, 101031, https://doi.org/10.1016/j.jobe.2019.101031.

Green D.S., Almroth B.C., Altman R., Bergmann M., Gündoğdu S., Warrier A.K., Boots B., Walker T.R., Krieger A., Syberg K., (2023), Time to kick the butt of the most common litter item in the world: Ban cigarette filters, *Science of The Total Environment*, **865**, 161256, https://doi.org/10.1016/j.scitotenv.2022.161256.

Intini F., Kühtz S., (2011), Recycling in buildings: An LCA case study of a thermal insulation panel made of polyester fibre recycled from post-consumer PET bottles, *The International Journal of Life Cycle Assessment*, **16**, 306–315.

ISO 14044, (2006), (2006), *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*, *ISO 14044:2006*, International Organization for Standardization, Geneva, Switzerland.

ISO 14040, (2006), *Environmental Management – Life Cycle Assessment – Principles and Framework*, *ISO 14040:2006*, International Organization for Standardization, Geneva, Switzerland.

Kadir A.A., Mohajerani A., (2010), Possible utilization of cigarette butts in light-weight fired clay bricks, *Proceedings of the Institution of Civil Engineers - Construction Materials*, **164**, 219–229.

Kadir A.A., Sarani N.A., (2015), Cigarette butts pollution and environmental impact – A review, *Applied Mechanics and Materials*, **773–774**, 1106–1110.

Kurmus H., Mohajerani A., (2021), Energy savings, thermal conductivity, micro- and macro-structural analysis of fired clay bricks incorporating cigarette butts, *Construction and Building Materials*, **283**, 122755, https://doi.org/10.1016/j.conbuildmat.2021.122755.

Marinello S., Lolli F., Gamberini R., Rimini B., (2020), A second life for cigarette butts? A review of recycling solutions, *Journal of Hazardous Materials*, **384**, 121245, https://doi.org/10.1016/j.jhazmat.2019.121245.

Mattoni B., Bisegna F., Evangelisti L., Guattari C., Asdrubali F., (2019), Influence of LCA procedure on the green building rating tools outcomes, *IOP Conference Series: Materials Science and Engineering*, **609**, 072044, http://doi.org/10.1088/1757-899X/609/7/072044.

Mohajerani A., Kadir A.A., Larobina L., (2016), A practical proposal for solving the world's cigarette butt problem: Recycling in fired clay bricks, *Waste Management*, **52**, 228–244.

Morales-Segura M., Porras-Amores C., Villoria-Sáez P., Caballol-Bartolomé D., (2020), Characterization of gypsum composites containing cigarette butt waste for building applications, *Sustainability*, **12**, 7022, https://doi.org/10.3390/su12177022.

Moroz I., Scapolio L.G., Cesarino I., Leão A.L., Bonanomi G., (2021), Toxicity of cigarette butts and possible recycling solutions - A literature review, *Environmental Science and Pollution Research*, **28**, 10450–10473.

Papadopoulos A.M., Giama E., (2007), Environmental performance evaluation of thermal insulation materials and its impact on the building, *Building and Environment*, **42**, 2178–2187.

Pargana N., Duarte Pinheiro M., Dinis Silvestre J., de Brito J., (2014), Comparative environmental life cycle assessment of thermal insulation materials of buildings, *Energy and Buildings*, **82**, 466–481.

Pazzaglia A., Castellani B., (2023), Review of the policy, social, operational, and technological factors affecting cigarette butt recycling potential in extended producer responsibility programs, *Recycling*, **8**, 95, https://doi.org/10.3390/recycling8060095

Rahman M.T., Mohajerani A., Giustozzi F., (2020a), Possible recycling of cigarette butts as fibre modifier in bitumen for asphalt concrete, *Materials*, **13**, 734, https://doi.org/10.3390/ma13030734.

Rahman M.T., Mohajerani A., Giustozzi F., (2020b), Possible use of cigarette butt fibre-modified bitumen in stone mastic asphalt, *Construction and Building Materials*, **263**, 120134.

Ricciardi P., Belloni E., Cotana F., (2014), Innovative panels with recycled materials: Thermal and acoustic performance and life cycle assessment, *Applied Energy*, **134**, 150–162.

Romero-Gómez M.I., Silva R.V., Costa-Pereira M.F., Flores-Colen I., (2022), Thermal and mechanical performance of gypsum composites with waste cellulose acetate fibres, *Construction and Building Materials*, **356**, 129308, https://doi.org/10.1016/j.conbuildmat.2022.129308.

Rossi S., Pizzi E., Mastrobattista L., Spoletini R., Carosi G., Pacifici R., (2005), *Consumo di tabacco: mondiale e nazionale*, Istituto Superiore di Sanità, Rome, Italy.

Schulte M., Lewandowski I., Pude R., Wagner M., (2021), Comparative life cycle assessment of bio-based insulation materials: Environmental and economic performances, *GCB Bioenergy*, **13**, 979–998.

Seren Acarer Arat A., (2024), A review on cigarette butts: Environmental abundance, characterization, and toxic pollutants released into water from cigarette butts, *Science of The Total Environment*, **928**, 172327, https://doi.org/10.1016/j.scitotenv.2024.172327

Tataranni P., Sangiorgi C., (2021), A preliminary laboratory evaluation on the use of shredded cigarette filters as stabilizing fibres for stone mastic asphalts, *Applied Sciences*, **11**, 5674, https://doi.org/10.3390/app11125674.

Vanapalli K.R., Sharma H.B., Anand S., Ranjan V.P., Singh H., Dubey B.K., Mohanty B., (2023), Cigarette butt littering: The story of the world's most littered item from the perspective of pollution, remedial actions, and policy measures, *Journal of Hazardous Materials*, **453**, 131387, https://doi.org/10.1016/j.jhazmat.2023.131387.

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IMPROVING URBAN WASTE MANAGEMENT IN VENICE AIRPORT: CITY MODELLED SERVICES AND INNOVATIVE TECHNOLOGICAL SOLUTIONS TOWARDS SUSTAINABILITY*

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Abstract

Venice Airport (VCE) has developed an integrated waste management system inspired by urban models, combining door-to-door collection, centralized monitoring, and technological innovation. All sub-concessionaires, including airlines, retail operators, and service providers, are involved in the system, which is tailored based on activity type and operational area. Each bin is equipped with RFID transponders for traceability, and the pricing model includes both fixed and variable components, designed to discourage residual waste production. Collaborations play a key role in the airport's sustainability strategy. While engagement with airlines focuses primarily on CO_2 reduction due to regulatory heterogeneity across countries, retail partners are actively involved in waste reduction initiatives. These include the elimination of single-use items, distribution of reusable coffee mugs to staff, and participation in food waste programs such as *Too Good To Go*. Water dispensers have also been installed to promote refillable bottle use among passengers and employees. VCE is currently part of a European project with the airports of Budapest, Dubrovnik, Madrid, Tenerife, and partners Ecoscience Provence and Venetian Cluster. This initiative has enabled the creation of an "Employees Waste Yard" and will soon introduce AI-powered smart bins capable of autonomous waste sorting. Ten units will be deployed by the end of 2026, aiming to reduce residual waste to an average of 35%. A preliminary data analysis comparing 2024 and 2025 shows a 12% increase in total waste, aligned with a rise in passenger traffic. Seasonal peaks persist, but some fractions, such as paper and plastic show inverse trends in specific months. These findings form the basis for future strategies, supported by AI-based monitoring systems under development. New KPIs, including kg waste per passenger and per movement, will enable more precise, fraction-specific performance tracking and predictive waste management.

Keywords: AI, airport, door-to-door collection, risk of contamination, urban waste

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1. Introduction

SAVE S.p.A. was founded in 1987 to manage Venice Marco Polo Airport, the company has evolved into a leading group overseeing a network of airports that play a crucial role in the North-East Area of Italy about economy, employment, and sustainability. Over the years, SAVE transitioned from managing a single airport to creating the North-East Airport Hub, including Venice, Treviso, Verona, and Brescia airports, which handled around 18 million passengers in 2024 covering flights all over the World. Venice Marco Polo is an intercontinental airport that, handling over 11 million passengers yearly, is the sixth airport in Italy and the principal airport of the group. Due to its position in the company belongings and its national relevance as airport, Venice Marco Polo represents an optimal environment to test and develop innovative solutions to improve sector's sustainability (Zero Waste Europe, 2017).

Sustainability has always been part of the company's core business, and in the recent years it has become a reality through a sustainability plan that covers almost all of the UN's SDGs, additionally Venice Marco Polo obtained the 4+ ACA certification, almost the maximum degree achievable in this aviation-based certification, and set to become Net Zero and Plastic Free by 2030. Even if different strategies have already been implemented to increase sustainability, it isn't an easy task for a service used, every year, by more than 11 million from all over the world (ACA, 2021; ACI EUROPE, 2019).

Waste management is one of the main challenges to be addressed since it represents a relevant issue for public used infrastructure of this size (ICAO, 2020). SAVE's airports, especially Venice Marco Polo, represent an interesting case study because of the technology and systems implemented, the active collaboration with contractors and airlines and the participation in European projects on sustainability and circular economy (ACI EUROPE, 2019. This work aims to present the strategies implemented, and to be implemented, by Venice Airport to purchase sustainability through the reduction of produced waste and the introduction of innovative technologies that should help improving separate collection enabling a higher percentage of recyclability and reuse.

2. Case studies

Airports are complex infrastructures where a variety of activities are performed. This condition has an important impact on the types and quantity of produced waste that include both Solid Urban Waste and Special, dangerous and non, Waste. Because of its origin, mainly maintenance activities, special waste is easier to manage than urban one that is produced in higher quantities and frequencies and with lower possibilities of control. Since urban waste represents the biggest challenge in waste management towards sustainability and circularity, the company is focused on this topic, investing in new solutions and technologies. It is fundamental, for a better and more complete understanding of the topic, to quantify the dimension of Venice Airport, based on passengers and movements, and the quantity of urban waste produced. As urban waste is considered Unsorted, Glass-Plastic-Cans, Paper and Cardboards and Organic waste (Table 1) (ICAO, 2020).

This work will present the solutions adopted, and designed, in the airport to manage waste and will use as reference the comparison between 2024 and the first 8 months of 2025. In Venice Airport waste collection service covers both passengers (pax) and operative areas even if the two services are structured differently. Pax areas are equipped with multi-containers bins (Fig. 1), 220L in volume, available in two layouts:

- 3 containers: designed to collect Unsorted waste, Glass-Plastic-Cans (GPC) waste and paper
- 4 containers: designed to collect Unsorted waste, GPC waste, paper and organic waste

Table 1. Venice Airport is here described by numbers. Table shows passengers, movements and urban waste produced in the two years considered by this work, 2024 and 2025

Year	*Passengers (Million)*		*Movements (Thousands)*	*Urban waste (T)*
2024	11.59		89	1687
2025 (Gen-Jul)	7.94		54	1017

There are 80 bins in total distributed around the two floors of the terminal and the other areas open to public as the external pathways and the water gate. These bins are emptied multiple time a day according to the filling level and waste fraction is defined by the operator after a visual check. The procedure is necessary to reduce the risk of contamination because of bins location and users who are not trained and not necessarily used to Veneto’s separate collection system, for these reasons waste produced in public areas are mainly unsorted waste.

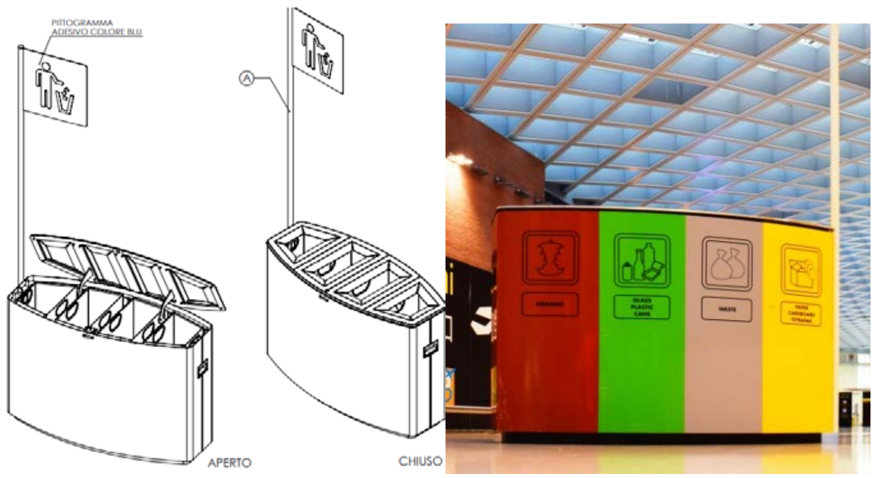

Fig. 1. Multi-containers bins, layouts and picture.
This typology of bin is used in public areas as airport terminals and pathways

Separate collection has higher quality in the professional areas, as restaurants, shops and offices because of different boundary conditions, there is always the same trained people and waste production is monitored through door-to-door collection. Door-to-door is one of the solutions implemented by Venice Airport to handle solid urban waste in a more efficient, monitored and innovative way.

2.1. Door to door collection system

The door-to-door collection service was introduced between 2018 and 2019 following a city-inspired model, with the distribution of dedicated bins and a centralized organization responsible for collection and monitoring. It has been extended to include all professional users at the airport, such as administrative staff, maintenance and operational services, restaurants, shops, and other offices. Participation in the service is mandatory for accessing the airport and is formalized during the finalization of the partnership agreement (European Commission, 2023). Given the wide variety of operational contexts within the airport, the door-to-door service is tailored based on the type of activity and the size of the sub-concession area. Based on the area of the user space and its activity the following aspect that define the service, are defined: number and types of bins, the weekly collection times (called size) and consequently the price of service, composed by a fixed and a variable fee. The three available sizes are described in Table 2, where there are indicated how many times waste are collected based on waste types.

Table 2. Door-to-door collection service available sizes.

	Size S	***Size M***	***Size L***
Organic	2	7	21
Paper	1	7	7
G-P-C	1	7	21
Unsorted	1	7	14

Size is partially customizable with external packs that increase collection rounds to fit some specific needs. Size considers the 4 types of waste even if a relevant part of the contractors has bins for just three types since organic is an exclusive for restaurants and coffee machine areas. The volume of the bins, as well as the area that has to be dedicated to the bin's collocation, are determined on the space covered by the user's activity (Fig. 2).

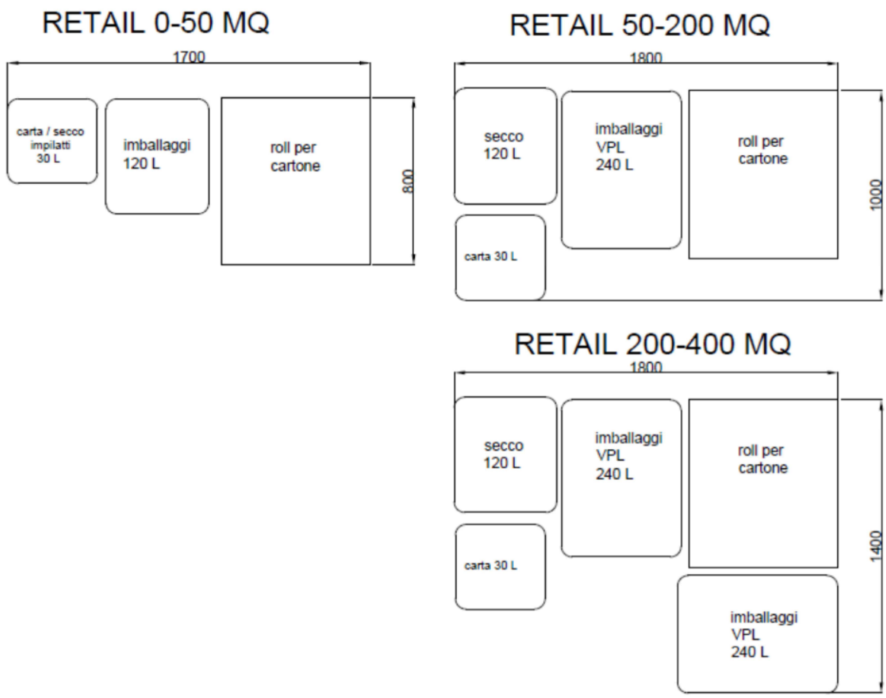

Fig. 1. Scheme to dimension bins and waste area based on the surface of the shop

The peculiarity of the service is that each bin has a code associated to the agreement (Fig. 3). Transponders must be scanned every time the bin is emptied to monitor the waste produced by the user. In this way it is possible to estimate the volume of waste produced by the user and verify that it respects the scheduled collections. Thanks to this system it becomes possible to apply the penalties referred to extra production with a special attention to unsorted waste (Zero Waste Europe, 2017).

Fig. 2. Detail of a bin used in the door-to-door collection service.
Each bin has a bar code associated to the user.

As anticipated, the pricing system includes a fixed fee, determined by the occupied surface, the service size and the extra pack, and a variable fee based on unsorted unscheduled collection, damages or incorrect separate collection. The system is designed to economically discourage the production of unsorted waste since its collection costs twice the other waste types. Monitoring is also ensured by the periodic audits that are conducted by the sustainability direction to verify the quality of the collection and the furniture status (International Airport Review, 2022).

2.2. Pneumatic plant

The waste pneumatic plant, introduced in 2022, represents a major innovation in airport waste management and is currently the second system of its kind installed in a European airport (Envac, 2025; International Airport Review, 2025). This advanced infrastructure is composed of a network of pipes integrated into the airport's utility corridors, which allows for the automated transport of waste from designated collection points, strategically located on each floor of the terminal to a dedicated ecological area (Fig. 4).

Access to these collection points (Fig. 5) is strictly limited to authorized personnel, ensuring controlled and secure waste disposal. The system has drastically improved operational efficiency by significantly reducing the number of manual waste transport within the terminal and minimizing the use of service vehicles for the trips from the terminal to the waste yard. This not only optimizes logistics but also contributes to reducing emissions and traffic in sensitive operational areas. Although originally designed to handle approximately 30% of the terminal's total waste output, the pneumatic plant currently manages up to 40%, demonstrating its robustness and adaptability to increasing demand. Its success has led to its inclusion in the airport's long-term development plan, which foresees the expansion of the system to cover all terminal zones and operational areas.

The waste managed through the pneumatic system is subject to regular inspections and monitoring by the municipal waste management company. These controls ensure accurate tracking of the quantity of waste processed and allow for detailed analysis of the quality of waste separation. This monitoring is essential for maintaining high standards of recycling and for identifying areas where further improvements in waste sorting practices may be needed.

Fig. 3. Waste yard dedicated to the pneumatic plant. The picture shows the container change

Fig. 4. Picture shows one of the four the drop-off points distributed in the terminal. The three doors, as well as the area, are accessible only to authorized personnel

Overall, the pneumatic waste collection system stands as a key component of the airport’s sustainability strategy, combining technological innovation with environmental responsibility and operational efficiency (Lakhouit et al., 2025).

2.3. Collaboration with airlines and retails

As one of Italy’s main intercontinental airport, the facility collaborates with a wide range of airlines, from low costs to majors, and retail operators. These partnerships are essential for advancing sustainability initiatives across the terminal. The relationship between the airport and its sub-concessionaires is built on continuous dialogue and shared responsibility, enabling the development of targeted environmental actions and long-term strategies. However, collaboration with airlines presents unique challenges. Due to their international scope and frequent movement between countries with different waste management regulations, it is difficult to implement standardised waste sorting practices. The limited space on aircraft and short operational times make in-house sorting difficult because it is rather impossible to separate waste and store it in different bags during the flight or turnaround. Although some pilot projects have been initiated in collaboration with major European airlines, they have not produced the expected results. Consequently, sustainability efforts with airlines primarily focus on reducing CO_2 emissions and improving operational efficiency rather than waste separation. Nevertheless, the airport maintains an open dialogue with the aim of identifying feasible actions and promoting awareness (IATA, 2019).

All sub-concessionaires operating within the airport, including retail outlets, food services, and offices, are integrated into the door-to-door waste collection system. This system not only ensures proper waste separation and traceability but also represents a shared sustainability commitment between the airport and its partners. In particular, retail operators have been actively involved in the development of targeted strategies aimed at reducing waste and promoting circular practices. Among these initiatives is the adoption of the "Too Good To Go" platform, which helps minimize food waste by redistributing unsold products (Zero Waste Europe, 2017).

In recent months, additional measures have been introduced to reduce the use of single-use consumables. These include the almost complete elimination of disposable cutlery and plates, and the distribution of reusable coffee mugs made from recycled plastic to employees, replacing traditional plastic cups. Furthermore, new water dispensers have been installed throughout the terminal and in office areas, encouraging the use of refillable bottles. Expansion plans are underway to extend this initiative to retail points, reinforcing the airport's commitment to reducing plastic waste and supporting sustainable consumption habits among staff, passengers, and commercial partners. Since 2023 water dispensers have distributed 409 thousand m^3 of water enabling to save up to 204 thousand water bottles.

2.4. LIFE TRIPL-AIR and future development – Smart bins and monitoring system

The airport is actively participating in LIFE TRIPLE-AIR, a European project focused on developing and implementing innovative strategies for waste reduction and sustainable resource management within airport environments (Fig. 6). Venice Airport is part of this project alongside several international partners, including the airports of Budapest, Dubrovnik, Madrid, and Tenerife, as well as Ecoscience Provence and Venetian Cluster who handles certifications and communication. Thanks to this collaboration, the airport has already introduced an "Employees Waste Yard," a dedicated facility that allows staff to responsibly dispose of used clothing, electronic waste (WEEE), light bulbs and batteries. This initiative supports circular economy principles and promotes environmentally conscious behaviour among employees.

In the coming months, the project will enable the phased deployment of smart bins in passenger areas (Fig. 7). These devices, equipped with artificial intelligence, autonomously sort the waste deposited by users, compensating for the lack of attention or knowledge passengers may have regarding proper disposal. By improving the accuracy of waste separation, the smart bins are expected to significantly reduce the volume of unsorted waste. A total of ten units will be installed by the end of 2026, with a gradual rollout planned to ensure effective integration. Additionally, the project includes the implementation of a monitoring system for the four-compartment bins located throughout passenger areas. This system will provide real-time data on the quantity and quality of waste collected, allowing for precise tracking of recycling performance and identification of the most frequently generated waste types.

Fig. 5. Two of the projects with the retailers. On the left Too-good-to-go, on the right the recycled plastic mug given to the employees.

Fig. 6. Smart bins leaflet. It will be located near the bins to explain how to use them

To further enhance waste management capabilities, a KPI-based monitoring and forecasting model is currently under development. This system will allow the airport to anticipate waste generation trends, optimize collection schedules, and continuously improve operational strategies. The integration of predictive analytics represents a significant step forward in building a smarter, more sustainable airport infrastructure.

3. Results and discussion

3.1. Results

This section presents data about waste production to state the present situation and set the starting point for the statics and the future improvements. In order to have a comparison between this year and the past the analysis was conducted considering 2024 and the first 8 months of 2025. The comparative analysis (Fig. 8) reveals a consistent trend across both years, with a noticeable peak in waste generation occurring around July and August. This seasonal increase aligns with the airport's passenger flow, which typically intensifies during the summer months. Overall, there is an average increase of approximately 12% in total waste production in 2025 compared to 2024.

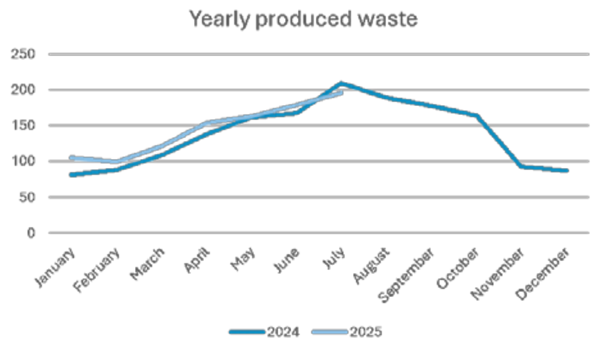

Fig. 7. Comparison between tons of waste produced in 2024 (dark blue) and waste produced during the first 8 months of 2025 (light blue). The similar trend can be detected as well as the general increase in production

Despite this general growth, some waste fractions show divergent monthly trends (Fig. 9). For instance, paper waste experienced a significant drop of 21% in May, while plastic waste saw a 23% decrease in July. These trends suggest that specific sustainability actions taken in the last period may be influencing waste generation patterns. It is important to note that passenger traffic at VCE has increased compared to 2024 which naturally contributes to the rise in waste production. This correlation reinforces the need for scalable and adaptive waste management strategies that can respond to fluctuations in airport activity.

3.2. Discussion

This initial analysis provides a snapshot of the current state of waste production and serves as a foundation for defining future strategies. While the data highlights general trends and specific anomalies, it also underscores the importance of developing more refined monitoring tools. To this end, the airport is investing in AI-based monitoring systems designed to enhance this preliminary analysis. These systems will introduce new KPIs such as kg of waste per passenger (kg_{Waste}/pax) and kg of waste per aircraft movement (kg_{Waste}/mov), broken down by waste fraction. These indicators will allow for more precise and actionable insights.

Moreover, the upcoming deployment of smart bins is expected to contribute to a gradual reduction in residual waste. The goal is to lower the share of unsorted waste to between 20% and 50%, with a target average of 35%. In parallel, although plastic waste may initially increase due to improved sorting, it is expected to decline over time thanks to recent initiatives launched in collaboration with retail partners.

Fig. 8. Comparison between tons of waste produced in 2024 (dark blue) and waste produced during the first 8 months of 2025 (light blue). Each graph describes one type of urban waste.

4. Conclusions

Venice Marco Polo Airport demonstrates how large-scale infrastructures can successfully adopt urban-inspired models to enhance waste management efficiency and sustainability. Through the integration of technological innovation, digital monitoring, and multi-stakeholder collaboration, the airport has established a comprehensive system that aligns environmental goals with operational efficiency. The combination of door-to-door collection, pneumatic transport, and continuous engagement with sub-concessionaires has allowed for the development of a traceable, transparent, and adaptable waste management framework.

The results confirm that while waste generation increases in correlation with passenger traffic, improvements in waste separation quality and the introduction of monitoring mechanisms have laid the groundwork for more precise management strategies. The economic model based on variable tariffs and penalties for unsorted waste has proven effective in encouraging proper separation, while continuous audits and traceability technologies ensure accountability across all users.

Ongoing participation in the LIFE TRIPL-AIR project represents a major step forward in integrating artificial intelligence and smart technologies into airport waste management. The forthcoming deployment of AI-powered smart bins and predictive monitoring systems will enable the airport to move from reactive to proactive waste management, allowing real-time optimization of collection and recycling operations. These tools are expected to significantly reduce residual waste and increase recyclability rates, contributing to the broader objectives of circular economy implementation within airport environments.

Moreover, the airport's partnerships with retail operators and employees have demonstrated that sustainability requires a shared cultural shift, extending beyond infrastructure to everyday practices. Initiatives such as the elimination of single-use plastics, the introduction of reusable cups and water dispensers, and the establishment of the Employees Waste Yard exemplify how behavioural change complements technological progress.

Despite the positive outcomes achieved so far, key sustainability targets, such as Net Zero and Plastic-Free by 2030, remain challenging. Their achievement will depend on the effective deployment of ongoing projects, continuous performance evaluation through new KPIs, and the full integration of AI-based systems across all operational areas. Nevertheless, the case of Venice Airport provides a replicable model for other European airports and public infrastructures, demonstrating that innovation, data-driven decision-making, and stakeholder engagement can collectively drive the transition toward sustainable and circular waste management systems.

References

ACI EUROPE, (2019), *Sustainability Strategy for Airports*, Airports Council International Europe, Brussels, On line at: https://www.aci-europe.org/downloads/resources/aci%20europe%20sustainability%20strategy%20for%20airports.pdf

ACA, (2022), *Airport Carbon Accreditation Annual Report 2021–2022*, ACI EUROPE, On line at:https://www.airportcarbonaccreditation.org/wp-content/uploads/2023/08/AIRPORT-CARBON-ACCREDITATION-ANNUAL-REPORT-2021-2022.pdf

ACA, (2021), *Airport Carbon Accreditation Annual Report 2019–2021*, ACI EUROPE, On line at:https://www.airportcarbonaccreditation.org/wp-content/uploads/2023/08/AIRPORT-CARBON-ACCREDITATION-ANNUAL-REPORT-2019-2021.pdf

Envac, (2025), *Marco Polo Airport, Venice: Pneumatic Waste Collection System (PWCS)*, On line at: https://www.envacgroup.com/projects/marco-polo-airport-venice-italy/

European Commission, (2023), *European Green Capital "Inspiration" cases: Treviso—door-to-door collection with PAYT*, Directorate-General for Environment, On line at: https://environment.ec.europa.eu/topics/urban-environment/european-green-capital-award/inspiration/treviso-consumer-waste-separation_en

IATA, (2019), *Cabin Waste Handbook*, International Air Transport Association, On line at: https://www.iata.org/contentassets/821b593dd8cd4f4aa33b63ab9e35368b/iata-cabin-waste-handbook.pdf

ICAO, (2020), *Waste Management at Airports (Guidance Booklet)*, International Civil Aviation Organization, Montréal. On line at: https://www.icao.int/sites/default/files/sp-files/environmental-protection/Documents/Waste_Management_at_Airports_booklet.pdf

International Airport Review, (2022), Venice Marco Polo Airport obtains Level 4+ (Transition) of the ACI Europe Airport Carbon Accreditation programme, 12 October 2022, On line at: https://www.internationalairportreview.com/news/179916/venice-airport-obtains-level-4-of-the-aci-europe-aca-programme/

International Airport Review, (2025), Venice Marco Polo Airport advances zero-emissions plan with new pneumatic waste collection system, On line at: https://www.internationalairportreview.com/news/259204/venice-marco-polo-airport-advances-zero-emissions-plan-with-new-pneumatic-waste-collection-system/

Lakhouit A., (2025), A review of smart solutions for waste collection, sorting and management (AI & IoT), *Cleaner Waste Systems*, **15**, 100106, https://doi.org/10.1016/j.clwas.2025.100106

Zero Waste Europe, (2017), *Leaders in Municipal Waste Management: Contarina case study* (RFID-enabled PAYT; >80% separate collection), Zero Waste Europe, On line at: https://zerowasteeurope.eu/wp-content/uploads/2019/10/zero_waste_europe_cs4_contarina_en.pdf

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NEW CIRCULAR STRATEGIES TO REDUCE FOOD WASTE*

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Abstract

This study quantifies the economic impact of surplus food donations from companies to the Banco Alimentare of Catania. It examines how these donations reduce operational costs and promote the development of a circular economy model within the agribusiness sector. Food waste generates substantial financial losses for companies. These losses arise from product depreciation, logistical inefficiencies, storage and disposal costs. Implementing integrated recovery systems can effectively mitigate these expenses. Donating surplus food transforms a cost center into an economic opportunity. Companies benefit from fiscal incentives, including tax deductions and credits, which improve the financial sustainability of food donation. The research aims to quantify circular economy indicators according to the UNI/TS 11820:2022 standard applying them to the case of the Banco Alimentare of Eastern Sicily. The analysis is based on a comparative examination of the organization's 2023 and 2024 Social Report with a view to assessing the level of circularity and the socio-economic impact generated in the two financial years. The methodology integrates participant observation, semi-structured interviews with business executives and third-sector operators. Supply chain analysis highlights progressive improvements in logistics but shows also persistent gaps in territorial coordination and the management of unsold fresh produce. In conclusion, the presented model is scalable and adaptable to heterogeneous urban contexts. It generates economic, social, and environmental value by promoting sustainable food systems and circular economy principles.

Keywords: circularity indicators, food donation, food waste reduction, third sector organizations,

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1. Introduction

Food waste represents one of the main economic, environmental, and social challenges of our time (Camoni, 2023). It is estimated that every year more than one third of the food produced for human consumption is wasted, although most of it is still edible, amounting to about 1.05 billion tons according to the Food Waste Index Report (UNEP, 2024). At the same time, nearly 800 million people continue to suffer from food insecurity, and 200 million from micronutrient deficiencies (Sassi and Sassi, 2018). Therefore, food insecurity is not only a problem with the quantity of food produced and available but also an issue of access, which can only be addressed by shifting the focus from global and national levels to the household or individual level (Sassi and Sassi, 2018).

In recent years, there has been a growing need for radical transformation, placing social values of food at the center through the identification of four key concepts: diversity, circular and solidarity economy, co-creation and sharing of knowledge, and responsible and transparent governance. These principles are essential to guide society towards plausible pathways of regeneration for sustainable agriculture and food systems (Wezel et al. 2020). This model involves local and community action, engaging those who live in the territory to build relationships of reciprocity, thus creating a convivial society organized to ensure its members the opportunity to define both the forms and purposes of the socio-economic process (Illich, 1973).

To reverse this trend, it is necessary to adopt an approach centered on human rights and sustainability, promoting investments in small-scale agriculture and drastically reducing greenhouse gas emissions produced by intensive farming practices. Moreover, it is crucial to support family farmers, especially in the most vulnerable countries, in adapting to increasingly extreme climate changes (Biondi, 2025). As with the circular economy, there is no single agreed-upon definition of food waste. In 1981, during a conference at the FAO headquarters focused on preventing food waste among perishable crops, the first definition of "postharvest food losses" was established. This initial definition can be summarized as follows: food waste is "wholesome edible material intended for human consumption, arising at any point in the Food Supply Chain (FSC) that is instead discarded, lost, degraded or consumed by pests" (FAO, 2011).

However, this definition was expanded in a 2011 study commissioned by the FAO and conducted by the Swedish Institute for Food and Biotechnology (SIK), where a distinction was introduced between food losses and food waste (FAO, 2011). Food losses refer to "losses occurring during agricultural production, postharvest, and food processing stages," while food waste refers to "food discarded during the final stages of the food supply chain (distribution, retail, and final consumption). The first are mainly due to logistical and infrastructural limitations, while the second depends on behavioral factors. In 2013, the FAO introduced a broader definition of food wastage, meaning the sum of food losses and food waste (FAO, 2013). In Italy, the total economic value of food waste exceeds 15 billion euros, with most of this waste originating from households, which make up the largest share (Waste Watcher, 2025).

Food waste has also been classified into three categories: avoidable, possibly avoidable, and unavoidable (Cappelletti et al., 2022). Additionally, there is a distinction between "absolute waste," referring to products disposed of as waste with no economic value, and "relative waste". Absolute waste means the disposal of food surplus that generates none of the potential benefits. Relative waste refers to surplus food whose destination allows obtaining at least one of two potential benefits: economic return or use for human consumption (Segrè and Falasconi, 2011).

Relative waste can follow three different routes: products disposed of as waste (without economic value, not intended for human consumption); products destined for animal feed, biogas production, or composting (having economic value but not for human consumption); products recovered and donated for human consumption (Pesenti and Rovati, 2015). The latter contribute to reducing the social and environmental impacts of food waste, even though they do not produce a direct economic return.

2. The economic cost of food waste

Food waste and the related waste management generate a significant economic impact for the businesses involved, affecting operational costs and company resources allocated to treatment and disposal (Costantino, 2024). Companies face costs not only from product loss but also from logistical inefficiencies and waste management. Waste in production and trade accounts for about 41.5% of the total supply chain waste cost, equivalent to 5.85 billion euros (Il Pais, 2025). This share includes losses due to logistical inefficiencies, damage during transport, storage, and commercialization.

Losses are common and can happen at any stage: production, distribution, or consumption. Causes include accidental damage, incidents, miscalculations, unexpected events and conditions. To prevent food losses, it is important to distinguish between reuse and recovery: reuse involves immediate use of a still-usable product for its original purpose, while recovery implies transforming waste material to give it a new life in the form of new products or objects (Waste Watcher, 2025).

These principles shape the foundation of strategies implemented by many food banks, which play a crucial role in recovering and redistributing surplus food. Recovery and donation of these surpluses to third-sector organizations represent an efficient and sustainable approach, turning waste into a valuable resource and generating economic, social, and environmental benefits (Rizzi, 2024). According to the Council for Agricultural Research and Economics (CREA, 2024), in 2022 large, medium, and small companies donated 138,678 tons of food, excluding beverages and animal feed. The Italian legal framework for food surplus donation is mainly defined by Law No. 166/2016, also known as the Gadda Law (Parlamento Italiano, 2016). Surplus food benefits from tax incentives for both businesses and individuals (Maino et al., 2020; Maino, 2021). Businesses enjoy VAT exemption and deductibility of purchase costs, while individuals can deduct or deduct donations in cash or in kind. This context encourages collaboration between businesses and nonprofit organizations, creating a circular economy model based on solidarity and resource optimization (Pirolo, 2023),Ombuen, 2023).

However, challenges remain in managing food donations, particularly regarding fragmented information flows, limited territorial integration, and a lack of shared digital tools to facilitate coordination among the many actors involved in the supply chain (Berti and Fidolini, 2023; Lizzi, 2022). This operational complexity highlights the urgent need for more effective solutions to improve communication and collaboration. The global relevance of the issue is confirmed by the examination of United Nations Sustainable Development Goal 12, which aims to “ensure sustainable consumption and production patterns.” Specifically, the goal is to “halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains by 2030” (United Nations, 2015).

Sustainable Development Goal 2 aims to “end hunger, achieve food security and improved nutrition, and promote sustainable agriculture,” targeting the eradication of world hunger by 2030. However, global data show a concerning trend: since 2015, food insecurity has significantly increased, driven by factors such as the COVID-19 pandemic, armed conflicts, climate change, and worsening socio-economic inequalities (FAO, 2023). This scenario underscores the urgent need to act on both food production and distribution as well as surplus recovery and redistribution (European Commission, 2015).

Though distinct, these two goals are closely linked: reducing food waste not only supports more sustainable resource management but also represents a concrete opportunity to increase food availability for the most vulnerable populations. Integrated policies that promote supply chain efficiency, surplus recovery, and consumer awareness can offer a synergistic approach to tackling both environmental and social issues related to hunger (Heydari, 2024; Quaglia and Bartezzaghi, 2025). Integration of these goals is therefore essential for achieving sustainable development globally.

The paper aims to assess the financial effects of surplus food donations made by companies to the Banco Alimentare of Catania. It explores how these donations lower operational expenses and encourages the growth of a circular economy framework within the agribusiness sector. The research seeks to apply circular economy metrics based on the UNI/TS 11820 (2022) standard to evaluate the social, economic, and environmental outcomes of food donation activities. Additionally, the study emphasizes the importance of integrated recovery systems and partnerships among businesses, nonprofits, and institutions to build sustainable food networks and effectively curb food waste. It also discusses the potential benefits of digital platforms and sophisticated measurement tools for improving surplus food management and sustainability practices.

The paper is divided into three main sections. The first part introduces the challenge of food waste, emphasizing its economic, social, and environmental impacts, and the relevance of circular economy principles. The second section details the methodology, with a focus on quantifying circularity indicators using the UNI/TS 11820:2022 standard (Amicarelli and Bux, 2023; Matarazzo et al., 2024). This includes collecting and analyzing data on various indicators categorized as core, specific, and optional, which together provide a comprehensive assessment of the organization's circularity level. The third section presents a case study on the Banco Alimentare of Catania, examining the economic benefits of surplus food donations, operational logistics, and the overall sustainability impact. The paper concludes by discussing the scalability of the model and future technological enhancements for better surplus management.

4. Materials and methods

The methodology is based on quantifying circularity indicators defined by the UNI/TS 11820 (2022) standard. This standard was published by the Italian Standards Body (UNI) on November 30, 2022. It was then updated in 2024. The indicators are applied to the activities of Banco Alimentare. The 2024 revision of UNI/TS 11820 retains the evaluation method and expands the indicator system from 71 to 81, improving alignment with the international ISO 59004 standard (Consorzio Carpi, 2024; ISO 59004, 2024; UNI/TS 11820, 2024). This update makes circularity measurement more flexible and adaptable to different business contexts, facilitating clearer communication through structured reports. However, this increased flexibility introduces complexity in selecting indicators and managing exclusions, requiring companies to have strong interpretative skills to ensure consistency and reliability in evaluation (Fantin et al., 2024). For these reasons, this study uses the 2022 version parameters, considered appropriate for its objectives. UNI/TS 11820 provides a structured method and a set of indicators to assess the circularity level of an organization or group of organizations, regardless of sector, size, or products/services offered. It enables monitoring progress, identifying improvement areas, and communicating results.

Relevant indicators are selected and measured for recovery, managing, and redistributing food surpluses. These cover categories such as material resources, energy and water, waste and emissions, logistics, products and services, human resources, and sustainability policies.

Necessary data are collected through internal monitoring and management records, ensuring quality, completeness, and traceability. Each indicator is calculated using standard formulas that normalize values on a scale from 0 to 1, classified as core (mandatory), specific (partially mandatory), and rewarding (optional) indicators. Complete evaluation of core indicators and at least half of the specific indicators is ensured, integrating rewarding indicators where applicable.

The overall circularity level is expressed as a percentage, obtained through weighted aggregation of the selected indicator scores. This allows a balanced assessment of Banco Alimentare's environmental, economic, and social performance. A disaggregated analysis by category is performed to identify strengths and areas for possible improvement. The adopted approach is systemic, considering multiple circularity aspects: efficient resource use, responsible waste management, innovation in business models, and collaboration along the value chain. This enables an objective evaluation of the system's effectiveness. Collaboration among businesses, third sector, and institutions is a strategic lever. Through territorial synergy, it is possible to build fairer, more sustainable, and efficient food systems (Maino, 2021).

5. Case study

This study aims to analyze the economic dynamics related to the donation of surpluses by companies to the Banco Alimentare of Catania. This organization operates not only in the province of Catania but covers the entire eastern Sicily region. The focus is on the positive effects in terms of cost reduction for companies and the development of sustainable practices. In 2024, the organization managed a total volume of approximately 7.922.763 kg of food. This represents a 25.1% decrease compared to 2023. The decline was due to changes in the operational context but did not compromise the effectiveness and quality of recovery and distribution activities. Supply channels come from various sources, with a predominance of FEAD and national funds. These provided 4.211.339 kg of food in 2024, marking a 44% decrease compared to the previous year (Garrone et al., 2023).

Agro-food companies contributed 1.335.510 kg of surpluses, down 14.85%, attributable to more accurate production planning and changes in donation policies. Collaboration with the Large-Scale Retail Trade (GDO) through the Siticibo Program recovered 820.712 kg of fresh and cooked food, focusing on nutritionally valuable products. Significant growth was reported in donations of fruit and vegetable products, which reached 401.185 kg in 2024, a 39.58% increase thanks to strengthened partnerships with the Agro Food Market of Sicily (MAAS) in Catania, where the organization is based, as well as with individual producers.

Recovery activities are supported by an advanced information system based on SAP ERP. This system ensures full traceability of incoming and outgoing food flows, monitoring expiration dates, quality, and food integrity. Operating procedures maintain the cold chain for fresh and frozen products, following HACCP food safety regulations. Food items with expired "Best Before Dates" are also handled in accordance with Gadda Law 166/2016 (Parlamento Italiano, 2016). This practice expands the quantity of food available for distribution, as foods past Best Before Dates are still safe for consumption if packaging remains intact and storage conditions are adequate. The volume of food recovered corresponds to estimated savings in the millions of euros, considering the commercial value and costs associated with production, transport, and disposal of unused food. Only in 2023, Banco Alimentare Sicilia Orientale ODV reduced CO_2 emissions by about 7.300 tons, with similar or improved figures expected for 2024. The logistical activities emitted only 512.5 kg of CO_2. Donation and redistribution activities are supported by well-established territorial networks involving over 350 partner organizations, including canteens, communities, and volunteer associations.

In summary, Banco Alimentare confirmed its ability to effectively manage food surpluses in 2024. It integrates technical, logistical, and relational skills. Careful monitoring of economic and environmental data, combined with an organizational approach based on transparency and partnerships, constitutes a replicable social circular economy model. This model generates sustainable value for both the community and the environment (Caglioti 2022).

6. Results and discussion

Banco Alimentare has developed a specific indicator to systematically assess the social, economic, and environmental impact of its activities. This indicator integrates parameters such as the quantity of food recovered, the economic value of corporate volunteering and the reduction of greenhouse gas emissions. Although the model does not formally follow international circularity standards like UNI/TS 11820 or ISO 59004 (2024), it reflects the principles of the circular economy, aiming to maximize resource efficiency and minimize waste. This tool enables transparent, multidimensional impact assessment, supporting strategic planning and communication with various stakeholders.

In 2024, the economic value of corporate volunteering linked to Banco's activities was estimated at around € 30.030 euros. This derives from being over 1.155 working hours contributed by company employees engaged in essential operational tasks related to sorting and distribution. Cost-benefit analysis showed a positive ratio of 1.22 between economic benefits and costs incurred by companies, confirming the social and economic sustainability of the implemented model. The data collected from the questionnaire given to "Banco Alimentare of Eastern Sicily" confirm the effectiveness of their model in reducing food waste and improving environmental impact. In 2024, they distributed over 10 million kilograms of food and saved more than 1,000 tons of CO_2 by recovering surplus food. The strong partnership with more than 50 agri-food companies and over 75 GDO stores supports their circular economic approach. Local projects like "Cuore Generoso" help recover fresh produce close to expiration at zero kilometers inside the MAAS center. The organization is also working on sustainability by installing a solar panel system, developed with ERG Italia and Crédit Agricole, and using electric vehicles to cut emissions. On the social side, the "Orange Day" education program raises awareness in schools about food waste and solidarity. Nearly 25 tons of seized fish were recovered in 2024 by following strict protocols to ensure food quality and safety. Despite these positive results, challenges remain around coordination, logistics and energy costs, and managing food expiration dates. The organization continues to address these through integrated sustainability strategies.

The Italian technical specification UNI/TS 11820:2022 introduces 71 key Environmental, Social and Governance (ESG) scalable indicators for evaluating the degree of circularity of individual businesses or clusters of organizations. These indicators are grouped into six categories: material resources and components, energy and water resources, waste and emissions, logistics, product and service, and human resources, assets, policies and sustainability. The formulation includes quantitative data, qualitative information and semi-quantitative data. Finally, UNI/TS provides a final formulation to calculate the overall Level of Circularity (LC) of an organization (Eq. 1):

$$LC = \frac{\sum P_c + \sum P_s + 0.5 \sum P_r}{n\, P_c + nP_s} \quad (1)$$

Table 1. Indicators results and description from UNI/TS 11820:2022 (Authors' elaboration)

Category	***Type***	***Indicator (UNI/TS 11820:2022)***	***Estimate for Banco Alimentare (2024)***	***Value***
1. Materials	specific	% of reclaimed material (vs. disposed)	100% (all managed flow is reclaimed and redistributed)	1
	specific	kg of reclaimed material vs. total managed	7,922,763 kg / 7,922,763 kg = 100%	1
2. Energy & Water	specific	% of energy from renewable sources	Solar panel system installed — estimated 5-10% of energy needs	0.1
3. Waste & Emissions	core	CO_2 reduction (t) from baseline (t/year)	~7,300 t of CO2 saved (2023, stable trend in 2024)	1
	core	CO**2** emissions from logistics (kg)	512.5 kg of CO2	1
4. Logistics	specific	% of electric vehicles out of total operational vehicles	Electric vehicles introduced — plausible estimate: 10%	0.1
	specific	Digital traceability (e.g., SAP ERP)	100% present on flows, expiration dates, and quality	1
5. Final Products/Services	rewarding	Average time food remains in distribution (days)	1	1
	specific	kg of fruit and vegetables reclaimed	401,185 kg (+39.6%)	0.396
6. Human Resources, Assets, & Policies	core	Corporate volunteering (hours and value)	1,155 hours → €30,030 (€26/hour)	1
	core	Number of partners involved	50+ agri-food companies, 75 large-scale retail points, 350 beneficiary organizations	1
	core	Control systems (HACCP, SAP ERP, Gadda Law)	100% in full use	1
	specific	Education/sustainability actions	"Orange Day" program active in schools	1
	specific	Local projects (inclusion, zero-km reclamation)	"Cuore Generoso" (at MAAS); 25 t of reclaimed fish	1
	rewarding	Replicable/transparent model (governance)	Replicable social circular economy model (Caglioti 2022)	1

Table 1 quantifies the value for each single indicator, specifying category, type (core, specific or rewarding), identifying number and unit.

The implementation of UNI/TS 11820:2022 provides that the Banco Alimentare Circularity Level in 2024 (LC) is 70.31%. More precisely, the circularity levels per indicator group correspond to the following values:

(a) 100.00% for material resources and components.
(b) 10.00% for energy and water resources.
(c) 100.00% for waste and emissions.
(d) 55.00% for logistics.
(e) 89.60% for products and/or services
(f) 100.00% for human resources, assets, policy, and sustainability.

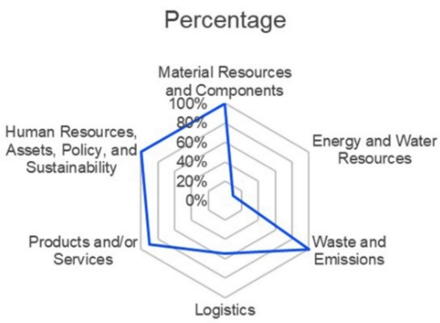

Fig. 1. Radar chart for each indicators' category from UNI/TS 11820:2022 (Authors' elaboration)

7. Concluding remarks

The study on the circularity level of Banco Alimentare, measured according to the UNI/TS 11820:2022 framework, reveals important insights into the operational and strategic role of third sector companies within the circular economy. Achieving a circularity level of 70.31% in 2024 is noteworthy, especially given that the UNI/TS 11820:2022 standard is new and not yet widely used as a benchmark in the sector. This high level of circularity demonstrates the company's deep commitment to sustainable practices and enhances its standing in a market that increasingly prioritizes environmental protection.

The analysis confirms the organization's crucial role in managing food surpluses sustainably, with significant social, economic, and environmental impacts. However, operational complexities and growing territorial coordination highlight the necessity for innovative management approaches. A key opportunity is the design of a territorial digital platform to monitor and manage surpluses, enhancing supply-demand matching and improving collaboration among businesses, nonprofits, and institutions. Such a modular and scalable platform could optimize logistics and ensure more transparent monitoring of food resources, reducing waste and strengthening Banco Alimentare as a cornerstone of the local solidarity economy.

The systematic adoption of the carbon footprint as a sustainability indicator allows quantification of the climate impact avoided through recovery and redistribution activities. Assimilated into a digital reporting system, this metric supports informed management aimed at emission reduction and promotes transparency and accountability. Integrating this digital platform with carbon footprint monitoring and UNI/TS 11820 (2024) regulatory indicators offers a standardized framework for measuring and improving circularity, enhancing the rigor of environmental and social impact assessments.

Technological innovation in surplus management and the use of advanced environmental indicators are strategic levers to boost Banco Alimentare's effectiveness and sustainability. Recent evidence shows that reducing food waste requires an integrated approach combining actions across the supply chain, supportive policies, and strengthened recovery networks like food banks that turn surpluses into valuable social and environmental resources.

References

Amicarelli V., Bux C., (2023), Users' perception of the circular economy monitoring indicators as proposed by the UNI/TS 11820:2022: evidence from an exploratory survey, *Environments*, **10**, 65, https://doi.org/10.3390/environments10040065

Berti F., Fidolini V., (2023), Pensare la precarietà alimentare in tempi di crisi. Prospettive e limiti d'intervento nel contesto contemporaneo, *Autonomie locali e servizi sociali*, **46**, 263–278.

Biondi F., (2025), Forme di protezione internazionale e complementare per fattori climatico-ambientali di migrazione, in *Migrazioni ambientali e crisi climatica – Speciale Le rotte del clima*, Vol. 1, 177–191.

Caglioti G., (2022), Le Food Banks nell'evoluzione delle politiche urbane del cibo: Banco Alimentare e la rete collaborativa costruita in Italia, *Rivista Italiana di Politiche Pubbliche*, **17**, 479–502.

Camoni D., (2023), La lotta contro lo spreco alimentare nel diritto comparato, *Rivista di Diritto Alimentare*, **17**, 5–23.

Cappelletti F., Papetti A., Rossi M., Germani M., (2022), Smart strategies for household food waste management, *Procedia Computer Science*, **200**, 887–895.

Consorzio Carpi, (2024), Aggiornamento UNI sulla circolarità: la UNI/TS 11820:2024 in una nuova veste, On line at: https://www.consorziocarpi.com/aggiornato-uni-circolarita/

Costantino L., (2024), Strumenti giuridici di prevenzione e contrasto dello spreco alimentare nell'esperienza giuridica italiana, *Rivista di diritto agrario*, **CIII**, 226–240.

CREA, (2024), Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria, (n.d.), *Osservatorio sugli sprechi alimentari*, CREA – Alimenti e Nutrizione, On line at: https://www.crea.gov.it/web/alimenti-e-nutrizione/-/osservatorio-sugli-sprechi-alimentari

European Commission, (2015), *The EU and the United Nations – Common goals for a sustainable future*, On line at: https://commission.europa.eu/strategy-and-policy/sustainable-development-goals/eu-and-united-nations-common-goals-sustainable-future_it

Fantin V., Sbaffoni S., Rinaldi C., De Marco E., Porta P.L., Cutaia L., (2024), Methodology and ICT tools to measure and communicate product circularity, *Environmental Engineering and Management Journal*, **23**, 1601–1614.

FAO, (2011), *Global food losses and food waste: Extent, causes and prevention*, On line at: https://www.fao.org/3/mb060e/mb060e00.htm

FAO, (2013), *Food Wastage Footprint: Impacts on natural resources*, On line at: https://www.fao.org/3/i3347e/i3347e.pdf

FAO, (2023), *Multiple shocks keep pushing world further away from development targets*, On line at: https://www.fao.org/newsroom/detail/FAO-SDG-UN-agriculture-hunger-targets-2023/en

Garrone P., Randellini N., Scotti G., Valentini G., (2023), *Indagine sulle eccedenze e sullo spreco alimentare in Italia: L'industria della trasformazione alimentare*, Food Sustainability Lab, Politecnico di Milano, Italy.

Heydari M., (2024), Cultivating sustainable global food supply chains: A multifaceted approach to mitigating food loss and waste for climate resilience, *Journal of Cleaner Production*, **442**, 141037, https://doi.org/10.1016/j.jclepro.2024.141037

Illich I., (1973), *Convivialità*, Mondadori, Milano, Italy.

ISO 59004, (2024), *Circular economy—Vocabulary, principles and guidance for implementation*, *ISO 59004:2024*, International Organization for Standardization On line at: https://circulareconomy.europa.eu/platform/en/knowledge/iso-590042024-circular-economy-vocabulary-principles-and-guidance-implementation

Lizzi R., (2022), Politiche urbane del cibo contro lo spreco e a sostegno delle donazioni alimentari: attori, meccanismi e fattori facilitanti della governance collaborativa nel caso italiano, *Rivista Italiana di Politiche Pubbliche*, **17**, 319–348.

Maino F., (2021), *Il ritorno dello Stato sociale? Mercato, Terzo Settore e comunità oltre la pandemia: Quinto rapporto sul secondo welfare*, Giappichelli Editore, Torino, Italy.

Maino F., Regonini G., Montanari M.G., Bandera L., (2020), *Il recupero e la distribuzione dei prodotti alimentari ai fini di solidarietà sociale*, Università degli Studi di Milano, On line at: https://air.unimi.it/bitstream/2434/797351/2/MV_n_21_RapportoFinale_RecuperoEccedenzeAlimentari_20ott2020.pdf

Matarazzo A., Costanzo M.R., Carpitano A., Zerbo A., Ingenito S., (2024), Indicators of circular economy in the Sicilian wine sector according to UNI/TS 11820:2022, In: *XXXII Congresso Nazionale di Scienze Merceologiche*, Lecce, 19–20 September 2024.

Parlamento Italiano, (2016), *Legge 19 agosto 2016, n. 166 – Disposizioni concernenti la donazione e la distribuzione di prodotti alimentari e farmaceutici a fini di solidarietà sociale e per la limitazione degli sprechi*, *Gazzetta Ufficiale della Repubblica Italiana*, Serie Generale, n. 202, 30 agosto 2016.

Pesenti L., Rovati G., (2015), *Food poverty, food bank. Aiuti alimentari e inclusione sociale*, Vita e Pensiero, Milano, 3–29.

Pirolo L., (2023), *Modelli di business contro lo spreco alimentare: il caso studio della piattaforma Too Good To Go*, MSc, Università Ca' Foscari di Venezia, Italy.

Quaglia S., Bartezzaghi G., (2025), *Linee guida per la pianificazione e lo sviluppo di Hub di Quartiere. Contro lo Spreco Alimentare*, Politecnico di Milano, Italy.

Rizzi P.F., (2024), L'evoluzione normativa della lotta contro lo spreco alimentare in Francia: il problema della qualità delle donazioni alimentari, *Rivista di diritto agrario*, **CIII**, 203–225.

Sassi M., Sassi A., (2018), *Understanding Food Insecurity*, Springer, Cham, Switzerland.

Segrè A., Falasconi L., (2011), *Il libro nero dello spreco in Italia: Il cibo*, Vol. 12, Edizioni Ambiente, Milano.

UNI/TS 11820, (2022), *Misurazione della circolarità: Metodi e indicatori per la misurazione dei processi circolari nelle organizzazioni, UNI/TS 11820:2022,* On line at: https://store.uni.com/uni-ts-11820-2022

UNI/TS 11820, (2024), *Misurazione della circolarità – Metodi ed indicatori per la misurazione dei processi circolari nelle organizzazioni*, *UNI/TS 11820:2024*On line at: https://www.uni.com/economia-circolare-la-uni-ts-118202024-in-una-nuova-veste/

UNEP, (2024), *Food Waste Index Report 2024,* United Nations Environment Programme, On line at: https://www.unep.org/resources/publication/food-waste-index-report-2024

Waste Watcher, (2025), *Waste Watcher 2025: Osservatorio internazionale su cibo e sostenibilità – Focus Italia*, Spazio Europa, Via Quattro Novembre 149, Roma, Italia.

Wezel A., Herren B.G., Kerr R.B., Gonçalves A.L.R., Sinclair F., (2020), Agroecological principles and elements and their implications for transitioning to sustainable food systems, *Agronomy for Sustainable Development*, **40**, 40, https://doi.org/10.1007/s13593-020-00646-z

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SYMBA: ADVANCING INDUSTRIAL SYMBIOSIS FOR A SUSTAINABLE, CIRCULAR AND BIO-BASED EUROPE*

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Abstract

SYMBA is a Horizon Europe project that aims to reduce environmental impacts on soil, water, and air by promoting Industrial Symbiosis practices across multiple sectors and regions. The project involves nine partners across five EU countries. The core objective is to develop a replicable Industrial Symbiosis methodology tailored to specific industrial contexts. This methodology will integrate and adapt established sustainability assessment frameworks, Life Cycle Assessment, Social Life Cycle Assessment, and Life Cycle Costing, to address the complexity of IS networks. Although Life Cycle Assessment is commonly used in Industrial Symbiosis studies, existing models often fail to capture multi-level interactions across actors and resource flows. Evidence from past Industrial Symbiosis networks indicates significant potential for environmental and economic benefits, including emission reductions of up to 31% and cost savings of up to 30%. SYMBA's approach begins with a structured literature review to extract methodological insights. This informs a regional analysis conducted across four demonstration sites, selected for their high Industrial Symbiosis potential. The analysis assesses readiness levels, existing practices, and sector-specific challenges, enabling adaptation of the methodology to each local context. The project also addresses policy barriers through collaboration with regional stakeholders, co-creating a Policy and Strategy Roadmap to guide Industrial Symbiosis deployment at scale. Outcomes will include actionable recommendations, best practices, and scalable business models. By promoting the circular use of resources and integration of secondary raw materials, SYMBA aims to strengthen Europe's bio-based economy and industrial resilience while demonstrating the real-world viability of industrial symbiosis.

Keywords: bioeconomy, circularity, industrial symbiosis, waste reuse

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1. Introduction

The industrial sector holds an inestimable value as a driving force of the European (EU) economy. According to Eurostat, the largest industries in Europe include food, beverages, tobacco, motor vehicles and other transport equipment and metals. However, as the European Environmental Agency (EEA) indicates, the EU industries continue to affect the environment, climate, and public health by exerting pressure through atmospheric the environment in the form of emissions to atmosphere and ecosystems, waste generation and resource consumption. Against this backdrop, the concepts of circular economy, Industry 4.0 and industrial symbiosis (IS) have emerged and are increasingly interconnected. Together, they aim to respond to global challenges in the most effective and sustainable way. Within this context, IS, as an integral component circular economy, envisions the creation of ecosystems in which energy and material flows are optimized, waste is minimized, and by-products repurposed to create added value (Frosch and Gallopoulos, 1989).

The SYMBA project builds on this vision by seeking to accelerate the adoption of IS across Europe. Its main objective is to develop of comprehensive guidelines, introduce innovative multi-criteria decision-making tools, and implement pilot applications in selected regions. By combining methodological rigor with real world experimentation, the project aims to deliver practical pathways for scaling IS across diverse industrial contexts.

2. Material and methods

2.1. Multi-Criteria Decision Analysis Methodology to evaluate IS solutions

SYMBA comprises multiple methodological phases, each designed to achieve a distinct objective. The prioritization and analysis of collected data were conducted using a combination of co-creation decision method and Multi-Criteria Decision Analysis (MCDA).

For the assessment of IS solutions, the study employed a weighted-sum MCDA integrating life cycle sustainability assessment (LCSA) indicators (Belton and Stewart, 2002;), while the mapping of IS regions was performed using a criteria-based Geographic Information System (GIS) analysis combining regional industrial data, material flow information from the SYMBA database, and stakeholder input from ICLEI’s network (Domenech et al., 2019).

2.2. The SYMBA Co-Creation Decision Method and Multi-criteria decision analysis

The Co-Creation Decision Method (CCDM) represents a participatory framework that actively integrates the diverse perspectives of stakeholders who contribute valuable to a service or product. This method facilitates collaborative development, evaluation, and selection of optimal solutions (Prahalad et al., 2004). In contrast to conventional top-down decision-making models, CCDM emphasizes shared ownership, inclusivity, and iterative feedback, thereby ensuring that the outcomes reflect the needs, expectations, and priorities of all involved actors. This approach is particularly advantageous in complex, multi-stakeholder contexts, such as public policy design, sustainable development initiatives, and innovation management where diverse and sometimes conflicting interests must be harmonized. In SYMBA, the CCDM was implemented twice by AIMPLAS and CETAQUA, utilizing different technological tools, including *Microsoft Outlook* and *Mentimeter*. The participants involved in the co-creation activities for the development of the CCMD include representatives from the consortium partners, as well as external stakeholders including 7 participants from industry, 7 participants from scientific community, 2 participants from government agencies, 1 participant from community and 3 listed as other. On the other hand, the MCDA acts as a key framework comprising both qualitative and quantitative methodologies designed to facilitate decision-making processes involving multiple, often competing criteria. This approach provides systematic support for resolving complex problems where stakeholders must balance conflicting objectives and reach compromise solutions (Belton et al., 2002).

In SYMBA, the IS solutions were systematically evaluated across five readiness-level criteria: Symbiosis, Environmental, Societal, Organizational, and Legal/Ethical readiness. Each criterion was assigned an individual score based on predefined metrics. Table 1 presents a comparative analysis of the outcomes from both implementation rounds, including the selected readiness levels (Criteria) and their corresponding percentage distributions.

Table 1. Average weightings for the criteria generated in the two rounds (internal and external) and final weighting

Criteria	***Internal weighting factor (%)***	***External weighting factor (%)***	***Final weighting factor (%)***
Symbiosis Readiness Levels (SymRL)	30	26.6	**28**
Environmental Readiness Levels (ERL)	25	18.4	**22**
Legal and ethical Readiness Level (LRL)	15	21.1	**18**
Organisational Readiness Level (ORL)	15	21.4	**18**
Societal Readiness Level (SRL)	15	11.6	**14**

When integrated with structured analytical tools such as MCDA, CCDM enhances the objectivity of the decision-making process by systematically evaluating and prioritizing criteria, while maintaining high levels of stakeholder engagement. The result is a comprehensive and context-sensitive methodology that effectively combines qualitative input with quantitative analysis.

2.3. Scalability and transferability of SYMBA

According to Bocken (2014), sustainable business models focus on the creation of new systems, which involves a wide range of stakeholders, instead of focusing on one single technology aspect. In order to support the implementation of sustainable business models, Bocken identified eight archetypes in which different sustainable models can be classified into depending on their objective: 1) maximize material and energy efficiency, 2) create value from waste, 3) substitute renewables and natural processes, 4) deliver functionality rather than ownership, 5) adopt a stewardship role, 6) encourage sufficiency, 7) re-purpose the business for society/environment, and 8) develop scale-up solutions. The business model canvas for SYMBA has been developed by the combination of three main elements:

- **Objective**: maximizing material and energy efficiency and/or creating value from waste
- **Baseline business model canvas**: Strategic Public-Private Innovation Network Business Model Canvas (SPIN BMC), developed by TNO, whose aim is to facilitate the building, scaling up and replicating of ecosystems of industrial symbiosis and circular economy (Fraccascia et al. 2019)
- **Potential governance models** (Schaltegger et al., 2012):
    - Model 1: Activities and responsibilities of members are based on a consortium agreement and benefits from the expertise of the members.
    - Model 3: Small group of people that constantly stimulates IS practices and attempts to discover unexploited IS opportunities.
    - Model 6: Coalition of several large private industrial companies that act as legal entities and have a shared interest in promoting the network’s success.

The SYMBA sustainability business model canvas for IS has been developed based on 9 building blocks: Key Partners, Key Activities, Key Resources, Value Proposition, Stakeholder Segment, Innovation Services, Impact and Sustainability metric, Cost-structure, Circular Innovation Portfolio. The SYMBA Business Model is scalable due to its modular block design, which integrates aspects common to different value chains (partners, activities, resources, innovation services, cost structure) while placing an emphasis on where sustainability and innovation can occur. This structure enables the replication across multiple organizations and sectors. In addition, transferability is ensured through the application of the SYMBA Methodology offering sector-specific guidelines – for textile, packaging, waste, wastewater and agrifood – that can be adapted and replicated in other industrial ecosystems. In this way, the model combines standardized modules with flexible methodological guidance, making it applicable across diverse contexts and a robust tool to foster circular economy transitions.

2.4. SYMBA Methodology/Guidelines

To promote the adoption of IS, SYMBA is developing methodological guidelines for applying Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (s-LCA) within IS systems. These guidelines are created through a step-by-step process that integrates evidence from existing literature with practical testing in demonstration regions.

The process begins by drawing on ongoing methodological debates and accumulated experience in applying LCA, LCC, and s-LCA to industrial symbiosis. A combination of manual reviews of key IS studies with an AI-supported large-scale scans is used to identify recent trends and reveal existing gaps. By synthesizing these insights, methodological approaches and modelling choices are consolidated into a preliminary set of guidelines. This draft is then shared with SYMBA demonstration regions, where feedback on local needs, capacities, and sector specific challenges is collected. The inclusion of regional perspectives ensures that the guidelines are not only scientifically robust but also practical and relevant to the realities of diverse industrial contexts. The iterative validation process increases the reliability of the framework and encourages stakeholder ownership. Once refined, the guidelines are tested through selected case studies, serving as living laboratories for real-world implementation. These applications allow the project team to adjust and strengthen the methodology, ensuring it is adaptable to varying industrial settings and scalable across different regions. The lessons learned will provide the final version of the guidelines, creating a reference that can be applied widely to enhance sustainability assessments.

Ultimately, the development of these guidelines represents more than technical exercise. It reflects SYMBA's commitment to fostering systemic change by enabling industries to understand the environmental, social, and economic implications of their collaborative practices. By providing clear, evidence based, and context sensitive tools, the project aims to accelerate the transition toward a more circular and resilient European economy, where resources are used efficiently, and industrial networks contribute to broader sustainability goals.

3. Case-studies

Candidate regions were identified through outreach to ICLEI and partner networks, as well as through a public call for expressions of interest. An initial pre-screen applied four criteria: bio-based potential, geographic diversity, willingness to develop local value chains, and stakeholder commitment. The shortlisted regions were validated together with project partners, after which four demonstration sites were selected. Geographic information systems were then used to map industrial clusters, resource streams, and potential synergies in each site. This selection process aligns with European evidence on where IS tends to emerge and scale, as described in SYMBA's public communication (Domenech et al., 2019).

3.1. Presentation of case studies

Four case studies were ultimately selected as high-potential regions for IS within the SYMBA project. The selection process was structured and participatory, combining systematic literature reviews with stakeholders' engagement to ensure both geographic diversity and strong bio-based potential. Based on criteria such as the presence of bio-based industries, opportunities for local value chain development, sectoral relevance, and commitment from regional actors the Metropolitan City of Milan (Italy), Murcia (Spain), Flanders (Belgium), and the island of Bornholm (Denmark) were chosen. Each offers a distinct context for testing SYMBA's IS methodology, highlighting diverse challenges, opportunities, and innovation pathways across Europe.

3.2. High potential IS regions identification

The identification of high potential IS regions in SYMBA followed a structured, multi-stage procedure designed to ensure both geographic diversity and the presence of enabling conditions for IS uptake. This process built on established European mapping approaches (Domenech et al., 2019) and adapted them to the project's bio-based focus and stakeholder-driven methodology.

3.2.1 Site selection criteria

ICLEI reached out to a pool of potential facilitators of IS and an open call for expressions of interest circulated through ICLEI's networks and SYMBA partner channels. Interested regions were screened against four pre-defined selection criteria:

1. **Bio-based potential** – availability of bio-based industries, agricultural and forestry activities, and related by-product streams suitable for symbiotic exchange.
2. **Geographic diversity** – representation of different EU macro-regions to test replicability under varying regulatory, infrastructural, and socio-economic contexts.
3. **Local value chain development potential** – evidence of existing industrial clusters or planned investments that could anchor symbiotic relationships.
4. **Stakeholder commitment** – demonstrated willingness of local authorities, companies, and other actors to participate in SYMBA activities.

The final selection of demonstration sites was validated collectively by project partners. This set reflects a balance of sectoral specialization, policy frameworks, and spatial characteristics, providing a robust basis for testing the scalability and transferability of the SYMBA methodology.

3.2.2. Sectoral and regional characteristics

- **CETENMA, Region of Murcia.** Focused on agri-food, biowaste and wastewater streams. Main barriers are regulatory complexity and funding access. Interest in regulatory support, financial incentives and digital matchmaking.
- **Gruppo CAP, Metropolitan City of Milan.** Advanced initiatives on PHA rich biomass for bioplastics, phosphorus rich biomass for fertilizers, biomethane for grid injection and cellulose recovery. Challenges include regulatory pathways, limited partners and logistics costs, with attention to End of Waste certification.
- **OVAM, Flanders.** Public authority developing a digital platform to map biomass supply and demand, clarify legislation and enable matchmaking. Obstacles include fragmented market knowledge, complex legislation and limited resources.
- **BOFA, Bornholm.** Early-stage context with priorities on plastics, food waste and textiles. Constraints include infrastructure and investment needs and precautionary approaches on treated wastewater. Mature composting for garden waste and participation in SYMSITES. The flagship idea is a multi-input multi-output biorefinery.

4. Results and discussion

Industrial Symbiosis remains only weakly embedded in European and national legislation. The Waste Framework Directive provides definitions for waste, by-products, and end-of-waste criteria, yet it does not establish a clear pathway for material exchanges among firms. As a result, many potentially reusable streams are still classified as waste, creating additional related to permitting and cross-border shipment requirements. Comparative evidence across Europe indicates that policy instruments, incentives, and permitting practices differ widely between country and region. A large European review mapped network types, resources exchanges, and common obstacles. It highlighted how economic incentives and legislative complexity directly influence the scale-up of IS, particularly through administrative challenges associated with the movement of secondary materials across burdens (Domenech et al., 2019).

Recent contributions underscore the absence of explicit IS strategies in most policy planning documents. This body of work calls for regulatory innovation to reduce legal uncertainty and lower transaction costs for firms, thereby creating a more favorable environment for industrial collaboration (Cudecka-Purina, 2025). Building on this evidence, four practical policy lines can be proposed. First, it is essential to clarify and harmonize the distinction between waste and by-products, while expanding end-of-waste criteria to include relevant bio-based streams. Second, tailored economic incentives such as reduced waste fees and targeted tax relief for verified exchanges. Third, the development of reliable information infrastructure and open data platforms is crucial for effective matchmaking between companies. Public resources such as SYMBA's searchable database and user-friendly interface illustrate how accessible tools can significantly lower search and coordination costs for both companies and administrations. Finally, industrial symbiosis should be integrated into regional development strategies and cohesion programs. Transparent and criteria-based region selection, as demonstrated in the cases of the Metropolitan City of Milan, Region of Murcia, Flanders, and Bornholm (Domenech et al., 2019; SYMBA, 2025).

The first step of the methodological work focused on a manual literature review of seminal studies applying LCA and LCC to industrial symbiosis. One of the main challenges concerns the definition of reference scenarios. Studies consistently compare IS against counterfactual cases such as stand-alone production or sector averages. While these reference systems are necessary to quantify benefits, they vary in ambition and design, often leading to uncertainty in results (Mattila et al., 2012; Aissani et al., 2019; Zhu, 2013). The choice of reference is therefore central to guideline development, as it determines the robustness of claims regarding avoided impacts and cost savings.

A second recurring issue is multifunctionality, which arises from the multiple outputs of symbiotic networks. Approaches include system expansion (substitution), allocation rules based on mass, energy, or economic value, and hybrid combinations. Although system expansion is generally preferred for capturing avoided burdens, data gaps frequently force the use of allocation (Kerdlap et al., 2020; Sandin and Peters, 2018). This underscores the need for flexibility in the guidelines, with explicit rules for determining when each method is most appropriate. Defining system boundaries also emerge as a key methodological decision. Broad boundaries that capture upstream inputs and downstream effects, such as transport, collection, waste treatment, are recommended to avoid problem shifting. However, such extensions often increase data requirements (Sandin and Peters, 2018; Sokka et al., 2010). Hybrid models that combine process-based LCA with Input-Output analysis are proposed as a solution to bridge data gaps and include off-site effects (Dong et al., 2017). Another critical gap is the integration of LCA and LCC. While environmental assessments are relatively mature, economic evaluations are often partial, focusing only on direct operational and investment costs. Shared infrastructure and avoided costs are rarely treated consistently across actors. Recent advances address this by developing matrix-based unified models such as UM3-LCE3-ISN, which allow the simultaneous treatment of environmental and cost flows (Kerdlap et al., 2020), or by combining Material Flow Cost Accounting (MFCA) with Cost-Benefit Analysis to capture hidden costs and value losses (Leiva et al., 2025).

Preliminary results from the s-LCA review reveal additional challenges and opportunities. Studies show that social dimensions are often underrepresented in industrial symbiosis assessments, with indicators concentrated mainly on job creation, occupational health, and community well-being. Few analyses systematically capture distributional effects, gender equity, or long-term societal impacts. Moreover, data availability is highly uneven, with most case studies relying on qualitative surveys or secondary reports rather than standardized indicators. These findings highlight the importance of integrating s-LCA into the SYMBA guidelines to ensure that social benefits and risks are evaluated on equal footing with environmental and economic dimensions. By developing clear criteria for selecting indicators and harmonizing them with LCA and LCC frameworks, SYMBA aims to advance a more comprehensive and balanced sustainability assessment of industrial symbiosis.

The mapping exercise identified more than 150 IS solutions implemented across Europe, classified into platforms, approaches, and methodologies. These solutions encompass a broad range of sectors, including wastewater, agri-food, textiles, packaging, and waste valorization, and reflect the diversity of strategies employed to foster circularity and symbiotic exchanges. Geographically, IS initiatives are concentrated in Northern and Western Europe, particularly in Denmark, Sweden, Finland, Germany, the Netherlands, Northern Italy, with emerging clusters in Spain and France. Self-organized networks are particularly prevalent in the Nordic region, while EU-funded methodologies and digital platforms dominate at the continental scale. The collected solutions were then systematically assessed using the MCDA framework. The final evaluation integrated perspectives from external stakeholders through surveys and co-creation workshops. The consolidated weighting factors assigned the highest importance to SymRL (28%), followed by ERL (22%), with ORL and LRL equally weighted (18%) and SRL ranked lowest (14%). This distribution reflects a consensus that technical and environmental feasibility are the most decisive factor for implementing IS.

5. Conclusions

This paper highlights how advancing industrial symbiosis represents a joint exercise between robust policy frameworks, methodological innovation, and the deployment of practical implementation tools. Through the SYMBA project, a comprehensive framework is being developed that combines evidence-based guidelines, a multi-criteria decision analysis (MCDA) tool, and real-world testing in diverse European demo regions. This integrated approach not only identifies barriers and opportunities but also provides concrete solutions for strengthening industrial cooperation across the textile, waste, wastewater, packaging, and agri-food sectors.

By bridging scientific methods and policy action, SYMBA creates a structured pathway that aligns regional practices with the broader objectives of the circular and bio-based economy. The co-creation of tools with stakeholders ensures that the developed methodologies are both scientifically sound and practically relevant, addressing the specific needs and constraints of local industrial ecosystems. This participatory dimension reinforces stakeholder ownership and facilitates long-term adoption beyond the project’s lifetime.

The project’s emphasis on scalability and transferability underlines its potential to serve as a reference model for future initiatives. Through harmonized guidelines on Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (s-LCA), SYMBA contributes to a more comprehensive understanding of the environmental, economic, and social impacts of symbiotic exchanges. The integration of these tools enables industries to quantify benefits, reduce uncertainties, and make informed decisions that balance performance with sustainability. In addition, the policy insights generated through SYMBA highlight the importance of reducing regulatory complexity, clarifying the status of secondary materials, and enabling open data infrastructures for matchmaking and transparency. Together, these advances form a coherent strategy for embedding industrial symbiosis into European industrial and environmental policies.

Ultimately, SYMBA demonstrates that industrial symbiosis is not merely a technical exercise but a systemic transformation that links innovation, governance, and collaboration. By pairing methodological rigor with practical implementation, the project paves the way for a new generation of circular industrial ecosystems, ones that optimize resource use, foster regional resilience, and accelerate Europe's transition toward a sustainable, climate-neutral, and inclusive economy.

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References

Aissani L., Le Féon S., Lacassagne A., Bahers J.-B., (2019), Life cycle assessment of industrial symbiosis: A critical review of relevant reference scenarios, *Journal of Industrial Ecology*, **23**, 972–985.

Belton V., Stewart T., (2002), *Multiple criteria decision analysis: An integrated approach*, Springer, Boston, MA, USA.

Bocken N.M.P., Short S.W., Rana P., Evans S., (2014), A literature and practice review to develop sustainable business model archetypes, *Journal of Cleaner Production*, **65**, 42–56.

Cudecka-Purina N., (2025), Legal barriers and policy gaps in industrial symbiosis: A pathway to regulatory innovation, *Environment. Technology. Resources. Proceedings of the International Scientific and Practical Conference*, **1**, 1–7, https://doi.org/10.17770/etr2025vol1.8663

Domenech T., Bleischwitz R., Doranova A., Panayotopoulos D., Roman L., (2019), Mapping industrial symbiosis development in Europe: Typologies of networks, characteristics, performance, and contribution to the circular economy, *Resources, Conservation and Recycling*, **141**, 76–98.

Dong L., Fujita T., Zhang H., Dai M., Fujii M., Ohnishi S., Geng Y., Liu Z., (2017), Highlighting regional eco-industrial development: Life cycle benefits of an urban industrial symbiosis and implications in China, *Ecological Modelling*, **361**, 164–176.

Fraccascia L., Giannoccaro I., Albino V., (2019), Business models for industrial symbiosis: A taxonomy focused on the form of governance, *Resources, Conservation and Recycling*, **146**, 114–126.

Frosch R.A., Gallopoulos N.E., (1989), Strategies for manufacturing, *Scientific American*, **261**, 144–152.

Kerdlap P., Low J.S.C., Tan D.Z.L., Yeo Z., Ramakrishna S., (2020), M3-IS-LCA: A methodology for multi-level life cycle environmental performance evaluation of industrial symbiosis networks, *Resources, Conservation and Recycling*, **161**, 104963, https://doi.org/10.1016/j.resconrec.2020.104963.

Leiva H., Julian I., Ventura L., Wallin E., Vendt M., Fornell R., Paniagua F.G., Ascaso S., Gomez-Perez M., (2025), Advancing sustainability through industrial symbiosis: A technoeconomic approach using material flow cost accounting and cost–benefit analysis, *Sustainability*, **17**, 2730, https://doi.org/10.3390/su17062730

Mattila T., Lehtoranta S., Sokka L., Melanen M., Nissinen A., (2012), Methodological aspects of applying life cycle assessment to industrial symbioses, *Journal of Industrial Ecology*, **16**, 51–60. https://doi.org/10.1111/j.1530-9290.2011.00443.x

Prahalad C.K., Ramaswamy V., (2004), Co-creation experiences: The next practice in value creation, *Journal of Interactive Marketing*, **18**, 5–14. https://doi.org/10.1002/dir.20015

Sandin G., Peters G.M., (2018), Environmental impact of textile reuse and recycling – A review, *Journal of Cleaner Production*, **184**, 353–365.

Schaltegger S., Lüdeke-Freund F., Hansen E.G., (2012), Business cases for sustainability: The role of business model innovation for corporate sustainability, *International Journal of Innovation and Sustainable Development*, **6**, 95–119.

Sokka L., Lehtoranta S., Nissinen A., Melanen M., (2010), Analyzing the environmental benefits of industrial symbiosis, *Journal of Industrial Ecology*, **15**, 137–155.

Zhu B., (2013), *Life cycle assessment and simplified life cycle costing on industrial symbiosis*, MSc Thesis, University of Linköping, Sweden.

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ReSicle: AN EXPERIMENTAL AND EDUCATIONAL CIRCULAR ECONOMY MODEL FOR THE INTEGRATED RECOVERY OF MATERIALS FROM END-OF-LIFE PHOTOVOLTAIC PANELS*

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Abstract

The ReSicle project showcases how secondary education can contribute to research and innovation in the context of ecological transition. Developed at the "Lorenzo Cobianchi" Institute in Verbania, it involved students from the Chemistry, Materials, and Biotechnology program in the development of a sustainable process for recovering valuable materials from end-of-life photovoltaic panels. An innovative, multi-step chemical procedure was implemented to recover silicon, aluminum, silver, and lead, avoiding the use of hazardous reagents such as hydrofluoric acid. The recovered materials were reused in further reactions, promoting a circular approach and reducing the environmental impact of the process. A key outcome was the conversion of recovered silicon into silica and subsequently into TEOS (tetraethoxysilane), a precursor for aerogels.
These were synthesized under mild conditions using TMCS (trimethylchlorosilane), resulting in materials with high porosity, low density, and excellent insulating and hydrophobic properties. The project also considered the valorization of by-products like hydrogen and nitrogen dioxide. Preliminary economic analysis indicates the process is potentially both sustainable and cost-effective. ReSicle also served as a hands-on educational model, actively involving students in all project phases, enhancing their scientific skills and fostering awareness of circular economy principles.

Keywords: circular economy, photovoltaic waste, material recovery, STEM education

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1. Introduction

The global transition towards renewable energy sources has seen a rapid and massive expansion of the photovoltaic sector. While this growth is fundamental for mitigating climate change, it also raises an emerging environmental issue: the management of end-of-life photovoltaic panels. With an average lifespan of 25-30 years, millions of tons of decommissioned panels are expected to become a significant electronic waste (e-waste) problem in the coming decades (Huang et al., 2017). The unsustainable management of this waste, which contains valuable materials like silicon, silver, and aluminum, but also potentially toxic substances, represents a challenge that requires the development of efficient recycling strategies that adhere to the principles of a circular economy.

Various methods exist for the recovery of materials from solar cells, including mechanical, thermal, and chemical processes (Punathil et al., 2021). Conventional chemical routes for the synthesis of silicon precursors, such as tetraethoxysilane (TEOS), often start from silicon tetrachloride ($SiCl_4$) and produce corrosive by-products like hydrochloric acid (Sánchez-Ramírez et al., 2018). Other research has focused on the direct synthesis of alkyl silicates from metallic silicon, but these often require complex reaction conditions (Gismalla, 2000). Therefore, research is oriented toward alternative processes that maximize the recovery of high-purity materials while minimizing environmental impact.

In this context, there is a growing need for innovative approaches to the integrated recovery of materials from decommissioned photovoltaic panels. A key area of interest is the development of chemical processes for silicon recovery that avoid the use of hazardous reagents and can also valorize other components, such as aluminum (Helmboldt et al., 2007). A less-explored synthetic route involves the conversion of recovered silicon into silicon dioxide (SiO_2), which can serve as a versatile precursor for the subsequent synthesis of high-value-added materials like TEOS (Putro et al., 2021). This approach not only provides a cleaner synthesis pathway but also allows for the reintegration of waste materials into the production cycle, embodying the principles of a circular economy.

TEOS obtained through such processes can be utilized for the synthesis of silica aerogels, nanostructured materials with remarkable properties, including extremely low density and high thermal insulation (Sarawde et al., 2007). The ability to produce these high-performance materials from recycled components demonstrates a powerful potential for creating new product value from waste streams.

Beyond the technical challenges, the effective management of e-waste also requires public engagement and education. Action-research models, particularly those conducted in educational settings, can serve as a powerful tool to engage students in real-world environmental challenges (Dege et al., 2014). By involving young minds in the entire research process - from experimental design to data analysis - such initiatives can inspire a new generation of scientists, engineers and citizens to think critically and creatively about sustainable resource management.

The ReSicle project aimed to design and validate a sustainable and educational model for the integrated recovery of valuable materials from end-of-life photovoltaic panels, following circular economy principles. The main goal was to develop an innovative chemical process capable of selectively recovering key materials such as silicon, aluminum, silver, and lead from decommissioned solar cells, while using less hazardous reagents to ensure both environmental and operational safety. Another objective was to purify the recovered silicon to a high degree of purity suitable for its conversion into silica and subsequently into tetraethoxysilane (TEOS), enabling the synthesis of aerogels, advanced nanostructured materials with important technological applications. The project also sought to demonstrate the potential reuse of recovered materials not only through isolation but by reintegrating them into new synthesis cycles to minimize waste and maximize resource efficiency. Additionally, the sustainable management of reaction by-products was pursued, including the capture and valorization of hydrogen as a clean energy source and the recycling of nitrogen dioxide into nitric acid for reuse within the process. Lastly, ReSicle aimed to integrate educational objectives by actively involving high school students in every phase of the research, from experimental design to analysis and scientific communication, fostering hands-on learning and raising awareness of sustainability challenges related to materials science and waste management.

2. Materials and methods

The entirety of the experimental work for the ReSicle project was conducted at the I.I.S. "L. Cobianchi", in its well-equipped chemistry laboratories. The core of this study was a single, representative solar cell sample, which served as the starting material for all subsequent material recovery and synthesis steps. The Scanning Electron Microscopy (SEM) analyses were performed at HI.Lab of OMCD TEK HUB.

2.1. Material recovery from photovoltaic panels

The methodology for material recovery was designed as a multi-stage, sequential chemical process to ensure the selective isolation of key components while avoiding the use of highly hazardous reagents. The process began with the targeted removal of the aluminum back layer. This was achieved by immersing the solar cell in a 10 M potassium hydroxide (KOH) solution, with the reaction vessel maintained at a constant temperature of 60°C for a duration of 5 minutes. Following this alkaline treatment, the remaining panel was thoroughly rinsed with distilled water to remove any traces of the basic solution. The aluminum-rich solution was then subjected to a controlled acidification with sulfuric acid (H_2SO_4), a step that resulted in the precipitation of aluminum hydroxide ($Al(OH)_3$). The precipitate was redissolved through careful heating of the solution, with subsequent slow cooling employed to promote controlled crystallization. The resulting solid, identified as potassium alum ($KAl(SO_4)_2 \cdot 12H_2O$), represents the successful recovery and purification of aluminum from the waste stream.

The subsequent phase of the recovery process focused on the separation of precious metals. The pre-treated panel was immersed in a 6 M nitric acid (HNO_3) solution, heated to 70 °C for 5 minutes, a process that effectively dissolved the silver and lead. The resulting metal-bearing solution was then treated with hydrochloric acid (HCl), which led to the precipitation of both lead chloride ($PbCl_2$) and silver chloride (AgCl). To achieve the crucial separation of these two precipitates, the solid mixture was reacted with a concentrated ammonium hydroxide (NH_4OH) solution. This step took advantage of the formation of a soluble silver diammine complex, $Ag(NH_3)^{2+}$, while leaving the $PbCl_2$ as an insoluble solid. The silver complex was then recovered from the solution and re-precipitated as AgCl through the addition of HCl.

The final and most critical step in the material recovery sequence was the isolation of the pure silicon. The panel, now devoid of its aluminum and noble metal layers, underwent a final chemical treatment with 85% phosphoric acid (H_3PO_4). The reaction was conducted at an elevated temperature of 120°C for 45 minutes to ensure the complete dissolution of the anti-reflective silicon nitride (Si_3N_4) coating, ultimately leaving behind the pure silicon wafer.

2.2. Analytical and spectroscopic characterization

To ensure the integrity and purity of the recovered materials, a comprehensive suite of analytical and spectroscopic techniques was employed. All analyses were performed in multiple replicates to guarantee replicability, with the reported values representing the average of the most consistent results. The concentration of aluminum in the recovered solutions was precisely determined using a complexometric titration, a classical analytical method employing a 0.050 M EDTA solution. This was followed by a back-titration with a known concentration of zinc sulfate

($ZnSO_4$) to quantify the unreacted EDTA, providing a highly accurate measure of the aluminum content. Silver content was similarly quantified using the Volhard method, a well-established volumetric precipitation titration technique. The concentration of lead was ascertained using Flame Atomic Absorption Spectrophotometry (FAAS) (instrument: Varian SpectrAA 220), a highly sensitive method based on the Beer-Lambert law, with a calibration curve constructed from a series of standard solutions. Finally, the morphological structure of the recovered silicon was examined using Scanning Electron Microscopy (SEM), while its elemental composition and purity were verified via Microwave Plasma-Atomic Emission Spectrometry (MP-AES) (instrument: MP-AES Agilent 4210).

2.3. Synthesis of TEOS and silica aerogels

The recovered silicon was first converted into a suitable precursor for TEOS synthesis. This was accomplished by dissolving the silicon in a 10 M NaOH solution under heat, followed by an acid precipitation step that yielded purified silica (SiO_2). This silica was then used as the starting material for the TEOS synthesis.

The reaction was performed in a single-neck flask containing 1.50 mmol of SiO_2, 8.00 g of ethanol, and a small quantity of potassium hydroxide (KOH) acting as a catalyst. The reaction mixture was stirred and heated in a paraffin bath for 6 hours at approximately 180°C. To drive the reaction to completion, a trap containing 3Å molecular sieves was attached to the flask to continuously adsorb water, a key by-product of the esterification reaction. The crude product was subsequently filtered to remove any unreacted solid silica, and the liquid filtrate was analyzed by Fourier-transform infrared (FT-IR) spectroscopy (instrument: Bruker Alpha II) (Fig. 1) and gas chromatography (GC) (instrument: CE Instruments GC 8000 TOP) (Fig. 2). The success of the synthesis was confirmed by comparing the resulting spectra and chromatograms to those of pure TEOS and ethanol. Simple distillation was then performed to separate the TEOS from the excess ethanol, yielding a purified product.

The purified TEOS served as the precursor for the synthesis of silica aerogels, utilizing a two-step, acid-base catalyzed sol-gel process followed by ambient pressure drying. The first step involved the acid-catalyzed hydrolysis of TEOS by mixing it with ethanol (EtOH) and a 0.01 M oxalic acid ($H_2C_2O_4$) solution.

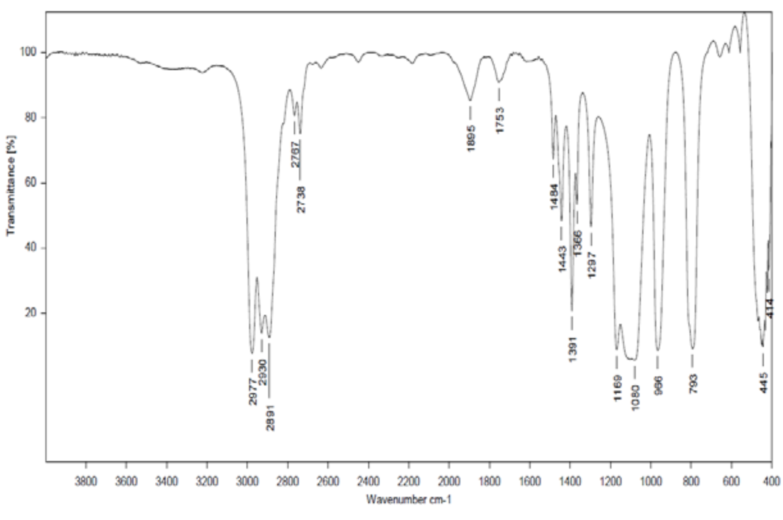

Fig.1. FT-IR spectrum of TEOS

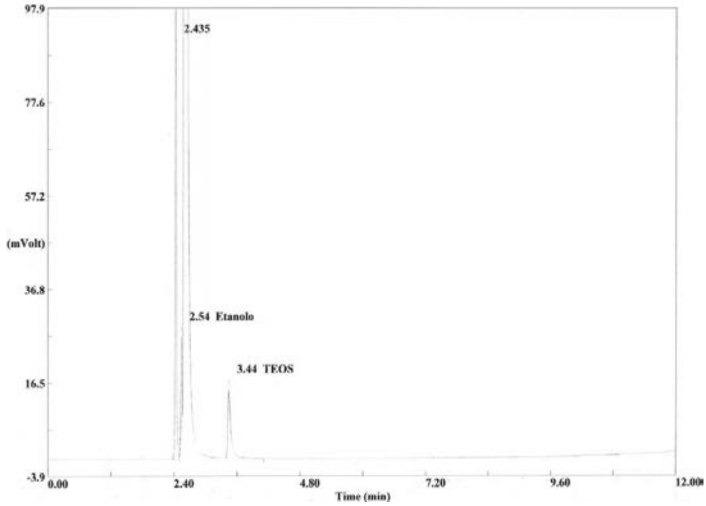

Fig. 2. Chromatogram of ethanol-TEOS mixture

After a controlled stirring period, the sol was allowed to age for approximately 24 hours. The second step involved the addition of a basic catalyst, 0.5 M ammonium hydroxide (NH_4OH), added dropwise to the acidic sol to initiate the condensation and gelation process. The molar ratios were controlled and maintained at TEOS:EtOH:$H_2C_2O_4$:NH_4OH = 1:6.9:3.5:2.2.

Following gelation, the alcogels were carefully removed from their molds and immersed in fresh ethanol for 6 hours. This solvent exchange was crucial for strengthening the gel network. To prepare the gels for surface modification, the ethanol was replaced with a non-polar solvent, n-hexane, for 12 hours. Surface modification was then carried out by immersing the alcogels in a hexane bath containing trimethylchlorosilane (TMCS), with a constant TEOS/TMCS molar ratio of 2:1. The final aerogel was obtained after a final washing with hexane, followed by slow evaporation of the solvent under a fume hood at room temperature.

2.4. Aerogel characterization and performance evaluation

The synthesized aerogels were extensively characterized to confirm their properties and evaluate their potential applications. The success of the surface modification with TMCS was verified by both SEM and FT-IR spectrophotometry, with the latter confirming the presence of characteristic Si−CH_3 and Si-O-Si bonds. The physical properties were also quantitatively determined: density was calculated by measuring the aerogel's mass with an analytical balance and its volume with a 10 mL burette filled with colored water. The unique nanometric structure was qualitatively confirmed by observing the Tyndall effect using a red laser. Hydrophobicity, a key property for many applications, was quantified by measuring the contact angle of water droplets on both the solid aerogel surface and on a sample of its powdered form.

The practical utility of the aerogels was assessed through two specific applications. First, the material's potential as a hydrophobic coating was tested by preparing an aerogel dispersion in ethanol and spraying it onto a glass surface. The resulting water repellency was quantified by measuring the contact angle of water on the treated glass. Second, the thermal insulation properties were evaluated by preparing two identical cement specimens, one of which was coated with a layer of the synthesized aerogel. Both specimens were then heated with a Bunsen burner flame for 5 minutes, and the temperature on the unheated side of each specimen was measured to determine the material's thermal conductivity. The results provided a direct comparison of the insulating performance of the aerogel.

3. Results and discussion

The ReSicle project successfully designed and validated a sustainable and integrated model for the recovery and valorization of valuable materials from end-of-life photovoltaic panels. The results demonstrate the technical feasibility of a sequential chemical process that is both efficient and environmentally conscious, aligning with the principles of a circular economy. The project also achieved significant educational outcomes, showcasing the power of action-research in a scholastic setting.

3.1. Integrated material recovery from photovoltaic panels

The multi-stage chemical process proved effective in selectively isolating key materials from the solar cell sample, avoiding the use of highly hazardous reagents like hydrofluoric acid. The initial alkaline treatment with KOH successfully removed the aluminum back layer. Subsequent treatment with HNO_3 and H_3PO_4 allowed for the selective recovery of silver, lead, and silicon while enabling the valorization of reaction by-products.

Quantitative analysis of the recovered materials from a 0.6160 g sample confirmed the efficiency of the process, yielding the following results:

Table 1. Determination of the metals and silicon present in the panel and their percentage composition

Element	*Analytical technique*	*Mass (g)*	*% in the sample*
Aluminum	Complexometric titration with EDTA	0.04967	8.07
Silver	Precipitation titration with KSCN	0.00724	1.18
Lead	FAAS spectrophotometry	0.00003	0.02
Silicon	Spectrometry MP-AES	0.48165	78.19

The high yield of recovered silicon (78.19%) is particularly notable, confirming the effectiveness of the selective removal steps. The purity of the recovered silicon was verified through advanced analytical techniques. Analysis via Scanning Electron Microscopy (SEM) and Microwave Plasma-Atomic Emission Spectrometry (MP-AES) confirmed the high purity of the recovered silicon, with values of 91.71% and 95.0% respectively (Fig. 3). This high purity is essential for its subsequent use as a precursor for advanced materials.

Fig. 3. Solar panel before (left) and after (right) purification

3.2. TEOS synthesis and aerogel preparation

The successful valorization of the recovered silicon was a pivotal achievement of the project, focusing on its conversion into tetraethoxysilane (TEOS), an essential precursor for advanced materials like silica aerogels. The research investigated two distinct synthetic pathways to optimize this conversion. The direct synthesis of TEOS from elemental silicon was explored, reacting the recovered silicon directly with ethanol under the established experimental conditions.

However, this method proved to be highly inefficient, resulting in a very low yield of approximately 10%. The primary reason for this inefficiency lies in the highly inert chemical nature of the recovered silicon, which presents a significant kinetic barrier to the direct esterification reaction.

To overcome this limitation, a more effective, two-step approach was developed. The recovered silicon was first converted into purified silica (SiO_2) through an alkaline dissolution followed by controlled acid precipitation. This purified silica, now a more reactive precursor, served as the starting material for the subsequent TEOS synthesis. This optimized route achieved a significantly higher yield of approximately 50%. The successful synthesis was rigorously confirmed through both Fourier-transform infrared (FT-IR) spectroscopy and gas chromatography (GC). The FT-IR spectrum of the synthesized product exhibited characteristic peaks corresponding to the Si-O-Si, C-O, and C-H bonds of the TEOS molecule. Concurrently, gas chromatography provided a high-resolution chromatogram that confirmed the purity of the synthesized TEOS by distinguishing it from unreacted ethanol and other by-products, thereby validating the scalability and efficiency of this synthetic route.

The purified TEOS was then utilized to prepare silica aerogels using a well-controlled, two-step, acid-base catalyzed sol-gel process followed by ambient pressure drying. The first step, acid-catalyzed hydrolysis, was initiated to break down the TEOS precursor into a network of silanol groups. This was followed by a base-catalyzed condensation and gelation phase, which promoted the formation of a three-dimensional Si-O-Si network. A critical step for the successful synthesis of stable aerogels was the careful solvent exchange and subsequent surface modification of the gel with trimethylchlorosilane (TMCS). This step was crucial to rendering the gel hydrophobic, preventing the collapse of its fragile, highly porous structure due to the capillary stress generated by the solvent's surface tension during the final drying phase. The success of this modification was confirmed by FT-IR spectroscopy (Fig. 3), which showed the presence of characteristic $Si-CH_3$ bonds, indicating the successful grafting of the hydrophobic groups onto the silica framework.

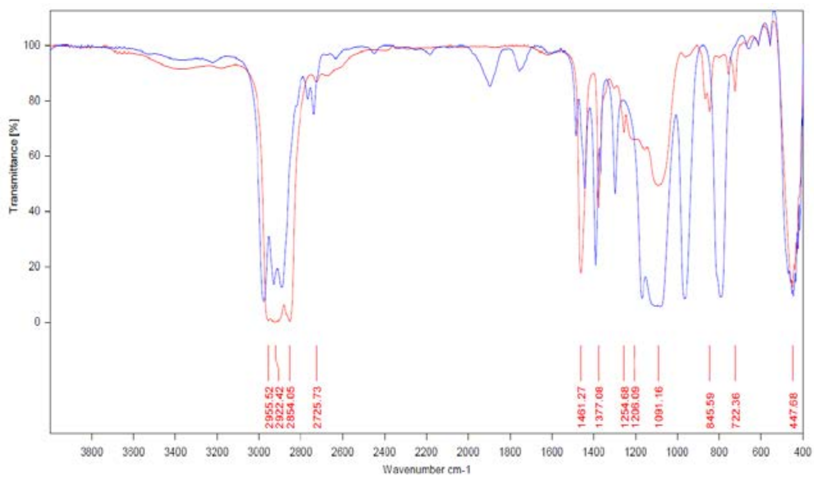

Fig. 4. Comparison of FT-IR spectra of aerogel (red) and TEOS (blue)

The final product (Fig. 5) was a white, lightweight solid with an exceptionally high porosity, visually confirmed by its characteristic transparency and low density. The measured density of 0.28 g/cm³ is a testament to the highly porous nature of the material. Furthermore, the aerogel demonstrated outstanding thermal insulation properties, that is not only a hallmark of a high-quality aerogel but also confirms its potential as a high-performance insulating material, directly competing with or even outperforming conventional insulation products.

Fig. 5. Aerogel product

The aerogel's nanometric particle dimensions were confirmed by observing the Tyndall effect (Fig. 6), which was demonstrated by pointing a red laser beam at the material.

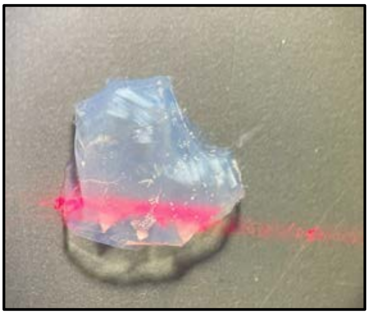

Fig. 6.

Tyndall effect on aerogel

Additionally, the material exhibited a high degree of hydrophobicity, which was verified by treating glass with an aerogel dispersion in ethanol. The material's hydrophobicity was further quantified by measuring the contact angle of water droplets on its surface, which was approximately 160°, indicating poor wettability and excellent water repellency (Fig. 7).

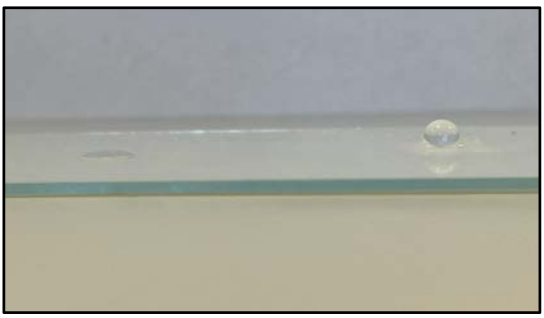

Fig. 7. Difference in wettability of an untreated (left) or aerogel-treated (right) glass surface

3.3. Economic and energetic considerations

A preliminary economic and energetic assessment was conducted to estimate the overall gain of the process, considering both operational costs (reagents, energy, equipment) and revenues from the sale of recovered products. This analysis was based on an approximate evaluation of mass, cost, and revenue balances, assuming the treatment of 1000 kg of end-of-life solar panels.

By producing this aerogel from recycled materials, it is possible to achieve a considerable reduction in raw material costs, while its superior insulating performance could translate into substantial energy savings. However, it's important to note that this is an initial evaluation, and a more detailed economic and energetic life cycle assessment is required to confirm these preliminary findings.

3.4. Educational outcomes and impact

Beyond the technical results, the ReSicle project served as an innovative educational model, successfully introducing high school students into a hands-on, research-based learning experience. Active participation in all phases of the project, from experimental design to data analysis and scientific communication, fostered the development of a wide range of competencies.

Students significantly enhanced their technical skills, gaining practical experience in advanced laboratory techniques, material synthesis, and the use of sophisticated analytical instruments. Just as importantly, the collaborative nature of the project cultivated crucial social skills, including teamwork, critical thinking, problem-solving, and effective communication.

The scientific merit and educational value of the project were recognized at a national and international level. The work was presented at the "I giovani e le scienze 2025" competition, which led to the project's accreditation for the prestigious Genius Olympiad in Rochester (NY - USA). At this international competition, the project received a Science Honorable Mention, a significant achievement that underscores the quality of the research and the dedication of the students involved. Additionally, at the "I giovani e le scienze" competition, the project was recognized by the Italian Chemical Society as a project of great value in the field of chemistry. These accomplishments not only validate the project's scientific approach but also highlight its success in inspiring and training the next generation of researchers and problem-solvers in the field of sustainable materials science.

4. Concluding remarks

The ReSicle project successfully designed and validated an innovative and integrated model for the valorization of end-of-life photovoltaic panels, offering a compelling example of a circular economy in action. The research demonstrated the technical feasibility of a sustainable chemical process that efficiently recovers valuable materials while avoiding the use of hazardous reagents. This process successfully yielded high-purity silicon, aluminum, and silver, showcasing a cleaner and more effective approach to electronic waste management.

A central achievement of this work was the successful reintegration of the recovered silicon into a new synthesis cycle. By first converting the recovered silicon into a more reactive silica intermediate, a remarkable TEOS synthesis yield of approximately 50% was achieved, a significant improvement with respect to the direct synthesis method. This purified TEOS served as the foundation for synthesizing high-performance silica aerogels, which exhibited exceptional physical properties, including a low density of 0.09 g/cm^3 and a thermal conductivity of only 0.016 W/mK. These results not only prove that waste materials can be transformed into high-value-added products but also demonstrate a powerful potential for creating new product value from discarded resources.

Beyond its technical success, the ReSicle project served as a powerful educational model. By actively engaging high school students in every phase of the research, the initiative cultivated essential technical and social skills, fostering critical thinking and a hands-on understanding of materials science and sustainability challenges. The project's recognition at the Genius Olympiad, where it received a Science Honorable Mention, validates its scientific rigor and highlights its broader impact in inspiring the next generation of scientists and engineers.

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References

Dege J., Wilke T., Pflugmacher A., Waitz T., (2014), Silica aerogels: Synthesis and experiments of a fascinating material for upper secondary school level, *New Perspectives in Science Education*, **3**, 1–6.

Gismalla H.H., (2000), *Direct synthesis of organic silicates*, MSc Thesis, University of Khartoum, Sudan.

Helmboldt O., Hudson L.K., Misra C., Wefers K., Heck W., Stark H., Danner M., Rösch N., (2007), Aluminium compounds, inorganic, in *Ullmann’s Encyclopedia of Industrial Chemistry*, Wiley-VCH, Weinheim.

Huang W.H., Shin W.J., Wang L., Sun W.C., Tao M., (2017), Strategy and technology to recycle wafer-silicon solar modules, *Solar Energy*, **144**, 22–31.

Putro W.S., Lee V.Y., Sato K., Choi J.-C., Fukaya N., (2021), From SiO_2 to alkoxysilanes for the synthesis of useful chemicals, *ACS Omega*, **6**, 35186–35195.

Punathil L., Mohanasundaram K., Tamilselavan K.S., Sathyamurthy R., Chamkha A.J., (2021), Recovery of pure silicon and other materials from disposed solar cells, *International Journal of Photoenergy*, **2021**, 5530213, https://doi.org/10.1155/2021/5530213

Sánchez-Ramírez E., Ramírez-Márquez C., Quiroz-Ramírez J.J., Contreras-Zarazúa G., Segovia-Hernández J.G., Cervantes-Jauregui J.A., (2018), Reactive distillation column design for tetraethoxysilane (TEOS) production: Economic and environmental aspects, *Industrial & Engineering Chemistry Research*, **57**, 5024–5034.

Sarawade P.B., Kim J.-K., Kim H.-K., Kim H.-T., (2007), High specific surface area TEOS-based aerogels with large pore volume prepared at ambient pressure, *Applied Surface Science*, **254**, 574–579.

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AN INDICATOR OF CIRCULARITY IN THE CONSTRUCTION SECTOR*

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Abstract

Circular economy is playing an increasingly central role in sustainability strategies, as it enables the reduction of non-renewable resource use, the minimization of waste, and the mitigation of environmental impacts associated with production and consumption. In this context, it becomes crucial to develop concrete tools to assess how circular a project truly is, thereby guiding more informed design and operational decisions. Among the various sectors under analysis, construction represents a strategic priority for the application of circular economy principles. It is a high-impact sector, responsible for a significant share of global energy consumption, waste generation, and greenhouse gas emissions. Therefore, the promotion of circular practices in construction directly addresses one of the main critical issues of environmental sustainability. However, the current literature still shows shortcomings in providing operational and specific metrics to measure circularity in the construction sector. Many of the existing indicators are too generic or fail to consider the peculiarities of the construction cycle. This study aims to contribute to the scientific discussion by presenting an applied case study that uses as a reference the UNI/TS 11820:2024 standard, recently updated to include indicators more suitable for the construction sector. The study evaluates the environmental, social, and governance circularity of two Sicilian companies operating in the construction sector. One company employs traditional methods, while the other operates in the field of green building and specializes in the construction of timber structures. The study analyzes whether circular economy can positively influence business performance by simplifying cost structures and enabling access to more competitive markets. The level of circularity (CL) will be assessed through a selective application of the indicators from UNI/TS 11820:2024, adapted to the construction context. Data were collected through energy audits, direct observations, financial statements, and ESG questionnaires. Despite the limited sample, the two companies show a growing orientation towards sustainable practices, particularly in energy efficiency, waste management, and the responsible use of water resources. The results confirm that circularity can represent not only an environmental advantage, but also a strategic, replicable, and measurable opportunity for innovation in the construction sector.

Keywords: circular economy, energy impacts, level of circularity, sustainable costruction, UNI/TS 11820:2024

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1. Introduction

Circular economy is now one of the most relevant strategic pillars in the development of sustainability policies and in the modification of production models in highly impactful sectors from an environmental point of view. It revolves around a set of principles aimed at resource and waste reduction, while at the same time elongating the life cycle of materials and products, and, in the process, creating more value for the environment, economy, and society. The construction sector is one of the priority areas for the application of circular approaches due to its contribution to the global energy consumption, waste generation, and the emission of greenhouse gases. The integration of practices such as reuse and recycling, modular construction, controlled resource use, and carbon footprint reduction have the potential to greatly improve the environmental and social performance of the entire life cycle of buildings and infrastructure.

There is still a growing interest in more sustainable construction models, however, the technical and regulatory literature points out a lack of specific metrics capable of measuring circularity in this sector with operational and standardized tools. The newly published technical specification, UNI/TS 11820:2024, in this context, offers a refined methodological framework along 71 indicators in the 'core', 'specific', and 'rewarding' categories to assess the circular performance of organizations and products. Using this tool to real case scenarios allows to grasp not only the quantification of Circularity Level (CL) but also scoring of the strengths and weaknesses, thereby greatly aiding investment and management decisions.

In this research, a comparative analysis of two companies working in the construction industry in Sicily, it taking different approaches to production and sustainability integration, will be done in order to evaluate and contrast their ESG's circularity performance using a tailored set of indicators developed from UNI/TS 11820:2024, adjusted to the construction context.

2. Methodology

In terms of methodology, the analysis is subdivided into three main steps: definition of boundaries and selection of relevant indicators, which is followed by data collection, verification, and validation of the data; and, finally, data processing that includes circularity level estimation and result visualization. In the first step, the indicators were based on the framework of reference UNI/TS 11820:2024, which was used to set the range of relevant indicators. Out of the initial 71 indicators, which were organized into six macro-categories, namely: material and components resources, energy and water resources, waste and emissions, product and service logistics, human resources and governance, and infrastructure, as well as the governance of the construction sector, only those with measurable relevance to construction were used.

All of the extracted "core" indicators were mandatory and, as the standards dictate, at least 50% of the "specific" indicators for each section covering "core" indicators must also be incorporated. "Rewarding" indicators were only used when there was supporting documentation or quantitative data available. Phase two focused on the acquisition of primary and secondary data relevant to the activities of the particular company. Primary data were gathered by means of on-site energy audits, which involved the collection of quantitative data regarding construction processes, the production stage and technology used on industrial construction sites, as well as secondary data obtained via technical interviews with managers and staff and completion of ESG" questionnaires. Secondary data was based on company documentation (such as financial statements, procurement data, reports for waste and environmental management, and environmental certifications) and data from measurements conducted by the companies themselves.

For the verification of flows of materials and their traceability, a mass balance approach was used to quantify the measurable and documented estimates of inputs, transformations, waste, and outputs. In the third phase, the Circularity Level (CL) was computed as proposed by the standard UNI/TS 11820:2024, which involves summing the scores of the core, specific, and rewarding indicators, each assigned a distinct weight. The analysis was guided by a circularity framework where each macro-category was computed to ascribe the level of circularity to the company and to also determine the areas of improvement and excellence on the company circularity overall. This provided a basis for developing comparative tables and radar charts which, in turn, aligned with the standard's outlined principles providing an overall and succinct summary of the results for the assessment. Such approach provided a means of combining standardized and regulatory assessments with the operational and supply chain specificities of the construction sector.

3. Case study: Comparison between two companies in the construction sector

This case study focuses on two companies working on the similar projects in Sicily to show two different approaches to the construction business. One is focused on green building while the other specializes in traditional construction. The first company ALFA constructs timber buildings using eco-friendly materials and employs modular construction and offsite fabrication while ensuring energy efficient construction. The second company BETA is involved in traditional construction and deals with the construction of timber buildings using reinforced concrete and other materials. While ALFA has a centralized management approach, BETA has a decentralized structure and focuses on public and private construction contracts with not much regard to efficient resource usage. Such differences in management approaches directly affect the application of the indicators specified in the IVU/TS 11820:2024. The outlined technical specifications consist of 71 indicators in three groups: core indicators which every organization has to fulfill; thematic indicators which must be achieved at least 50% for each thematic group; and awarding indicators which are optional for above and beyond action.

It's worth noting that some indicators cannot be calculated for both companies: some indicators are applicable to only one company, while for the other company those indicators must be considered as not being met. This difference is not a constraint, it simply illustrates how the standard is able to differentiate between more or less advanced circularity production models. For ALFA, the "Material Resources and Components" category has particular relevance. The company uses considerable amounts of FSC and PEFC certified wood, eco-bricks, and low-impact materials, and modular and disassemblable construction solutions. For this reason, the comparative assessment included indicators on the percentage of secondary or recycled materials, the share of sustainably certified materials, and the modularity and disassemblable degree of components. These indicators illustrate the contribution of green building to the reduction of environmental impacts throughout the life cycle. In contrast to BETA, there is a lack or limited availability of data and practices related to these very indicators, mostly due to the dominance of conventional materials and absence of targeted environmental certifications.

For this particular company, the focus was on capturing and applying core indicators of the energy consumed per unit of output, waste, and GHG processes which the standard defines and mandates as fundamental. These indicators are not only easier to compute; they are also more suited for identifying the gains that a 'traditional' company could achieve through the incremental implementation of the circular economy. The indicator that relates to the energy and water resources captured is applicable to both companies but with different outcomes. ALFA is integrated with production systems that use renewable sources such as photovoltaic systems and employs techniques to minimize water use in production. Therefore, ALFA can demonstrate a high performance level in the indicators of the share of renewable energy and water consumed per production cycle. BETA will determine the same indicators with values that approximate zero for renewable sources, and with a more coarse measure for water, demonstrating a sustainability gap. Likewise, in the waste and emissions category, both companies have submittal data, but differing in detail and accuracy.

In terms of adoption and tailoring of formalized waste management systems (MUD, traceability), ALFA integrates recovery and reuse of by-products while BETA confines itself to less detailed, compliant management, reflecting an intermediate level of adoption. This makes recovery of waste and greenhouse gas emission calculations fundamental for comparison. Overall, categories concerning logistics, product, and governance also show more heterogeneity. ALFA, with a short supply chain and local suppliers, reinforced core and specific indicators (with even some rewarding indicators) due to the environmental certifications for products and systems (ISO 9001, ISO 14001, CasaClima). BETA, on the other hand, has an organization with a site management oriented structure with personnel training directed primarily at safety and has no recognized environmental certifications. The selection of comparison indicators was therefore guided by two main aspects: from one hand, the necessity to include core indicators that provide direct and uniform comparison, and from other hand, the opportunity to include specific and rewarding indicators where one of the two companies fulfills the criteria, to illustrate the best practices and the level of innovation achieved. This choice allows the production of a balanced comparative framework, which does not excessively penalize less advanced companies but at the same time highlights the competitive advantage of companies that have invested in more sustainable processes and materials. The next section will present the results of the quantitative and qualitative comparison, showing how differences in production and organizational models translate into measurable circularity values.

4. Results and discussion

The application of UNI/TS 11820:2024 to the two case studies allowed the construction of a comparative indicator matrix, through which it was possible to measure and compare circularity performance. As previously mentioned, the selection included all “core” indicators, more than 50% of the “specific” indicators for each category, and a set of “rewarding” indicators chosen based on relevance and data availability. This approach ensured compliance with the methodological requirements of the standard while adapting to the analyzed construction context. Table 1 presents a summary of the results obtained for each selected indicator, with values expressed on a normalized scale from 0 to 1. A score of “1” corresponds to full compliance with the criterion, while a value of “0” indicates a lack of evidence or non-application. Intermediate values were assigned in cases of partial data or practices not fully consolidated.

In order to convey both qualitative and quantitative data in comparable figures, a normalization operation on a 0–1 scale has been implemented, which complies with the methodological guidelines of UNI/TS 11820. Each indicator has been judged not only from the perspective of its mere existence but also on the level of implementation to a certain extent. The highest score (1.0) was attributed in instances of total conformity and well-established documentation; as the regular utilization of secondary or eco-certified materials by ALFA was the reason that full points were achieved for those indicators concerned with raw materials. ALFA has very efficient practices for energy consumption per unit of output, where energy audits and prefabrication that is sustainable take place, however, due to the fact that the company has not reached full self-sufficiency yet, the maximum score was not given. The value of between 0.8 and 0.9 was assigned in such cases when the company showed that the application was well-established yet it was not complete. If some procedures related to energy and waste are in BETA, which meet standards, but at the same time, due to the lack of advanced monitoring or structured reduction strategies, the company, this is the way in which the indicators on energy and waste management for BETA could receive scores in the range between 0.5 and 0.7.

Table 1. Selected circularity indicators and normalized scores

Category	*Indicators*	*Type*	*ALFA*	*BETA*
Raw materials	% secondary/recycled materials	Core	1.0	0.0
Raw materials	% sustainably certified materials	Specific	1.0	0.0
Raw materials	Component modularity/disassemblability	rewarding	1.0	0.0
Raw materials	Component lifespan	Specific	0.9	0.6
Energy	Energy consumption for unit of output	Core	0.8	0.6
Energy	% energy from renewable sources	Core	1.0	0.0
Energy/water	Water consumption per production cycle	Specific	0.8	0.0
Waste	% recycled or reused waste	Core	0.9	0.6
Waste	Compliant waste management (MUD)	Specific	1.0	0.3
Emissions	CO_2 emissions for unit of output	Specific	0.8	0.5
Logistics	Short supply chain / Transport distance(km)	Rewarding	1.0	0.2
Product	Product certification	Core	1.0	0.0
Product	After-sales service	Specific	0.9	0.6
Product	Design for disassembly	Rewarding	1.0	0.0
Governance	Formalized ESG policies	Core	1.0	0.4
Governance	Sustainability/safety training	Specific	0.9	0.8
Governance	System certifications (ISO/EMAS)	Specific	1.0	0.0

Further, when the practice has existed only in a very limited way or as a mere legal compliance measure without a real management approach to circularity, the score was given in the range of 0.1–0.3. Besides, a 0.0 value was allowed only in cases in which there was no evidence at all or the indicator was not applicable. For instance, BETA is the holder of such indicators referring to FSC or PEFC certified materials, modular design, as well as the share of renewable energy, where the implementation is the least possible. The use of this interpretative scale paved the way for a straightforward comparison of the two companies.

It is not a subjective point, but rather, the way of expressing informational content which is systematic and logical as per the guidelines of the standard. The clear representation of circularity practices was made possible by this: On the one hand, a company like ALFA not only complies with multiple core and specific indicators but also excels in rewarding indicators due to the innovative design and material choice; on the other hand, BETA, a traditional company, obtains a lower score showing that it has especially material and governance issues, but still, it retains the possibility of progress that can be easily noticed in energy indicators and human resources training.On top of the reported scores, the circularity level was calculated according to the UNI/TS 11820:2024 formula.

- ALFA: Sum of scores = 16/17 indicators ≈ 94.1%
- BETA: Sum of scores ≈ 4.6/17 indicators ≈ 27.1%

There is a very large difference between the two companies: the first one gives the circularity level that is more than three times higher than the second, which means that they are significantly different in production and management models. The comparison at the category level allows one to see the advantages and disadvantages that the two companies have. ALFA takes the lead in areas such as materials, modular design, and certifications, which indicates the systematic implementation of eco-building standards and the use of a sustainability framework. Rewarding indicators, e.g., modularity and the design for disassembly, are the major elements that set this company apart, demonstrating that it has not only incorporated the circular flow in the production but also in design philosophy. Contrarily, BETA has the poorest results for almost all indicators. Only energy and human resources training have a positive trend where the company has started the journey of the best practices. Still, the lack of environmental certifications, and the predominant use of traditional materials, and combined with the absence of ESG formalized policies significantly limit the overall performance of the company. The disparity, thus, should not be seen as a cause of punishment of traditional companies but rather as a glimpse of the starting point and the extent of possible movement. The UNI/TS 11820 application helps to identify the degree of difference between the two groups, i.e., those that operate advanced models and the ones that are still in transition, and thus, it provides a strong basis for decision-making in investments, strategies, and innovation pathways.

5. Conclusions

The analysis conducted through the application of UNI/TS 11820:2024 made it possible to assess and compare the circularity level of two companies operating in the construction sector, representing different production models: one based on green building and the use of natural and certified materials, and the other rooted in traditional construction and more oriented toward managing conventional contracts. The results showed a significant gap, with a circularity level of 94.1% for ALFA and 27.1% for BETA. This outcome confirms that design choices, material management, and the adoption of environmental certifications are key factors in enhancing sustainability and circularity performance.

The comparison highlighted how green building, when supported by management and technical practices consistent with circular economy principles, can achieve high performance levels, above the industry average. Indicators such as the percentage of certified materials, component modularity, the presence of renewable energy, and system certifications played a key role in differentiating the two companies. Conversely, lower adoption of ESG policies, the absence of recycled and certified materials, and reliance on conventional energy sources substantially limited the performance of the company focused on conventional construction. However, the results should not be interpreted solely as a static comparison but also as an indication of potential areas for improvement. UNI/TS 11820 provides an operational roadmap that allows companies to identify priority areas for action.

In the case of BETA, the progressive introduction of secondary materials, process certification, and the establishment of formalized ESG policies represent concrete actions that could significantly increase circularity levels in the medium term. For ALFA, the future challenge is to consolidate its competitive advantage by further extending circular practices along the entire value chain, for example by strengthening industrial symbiosis strategies and expanding post-sale services focused on maintenance and reuse. From a broader perspective, this study demonstrates the applicability and effectiveness of UNI/TS 11820:2024 in the construction sector. Despite the sector's intrinsic complexity, characterized by an articulated supply chain and strong reliance on traditional materials, the standard allows for a quantitative, comparable, and communicable assessment to both internal and external stakeholders.

The possibility of summarizing results into a single circularity indicator, the CL, represents a useful tool both for companies, which can monitor their performance, and for public and private decision-makers, who need reliable metrics to guide policies, incentives, and investment strategies. Looking ahead, integrating UNI/TS 11820 with other regulations and the minimum environmental criteria required at the European level could further enhance its function, promoting convergence toward common standards for measuring sustainability. For the Italian and European construction sector, this would not only mean complying with regulatory and market requirements but also substantially contributing to the objectives of the European Green Deal and the decarbonization commitments for 2030 and 2050.

The comparison between the two case studies highlights that the transition to more sustainable construction models is not only an environmental necessity but also an opportunity for innovation, competitiveness, and resilience for companies in the sector. UNI/TS 11820:2024 proves to be an operational tool capable of measuring, enhancing, and guiding this change. Looking at it from a broader perspective, the study highlights that the UNI/TS 11820:2024 is a viable and effective standard that can be implemented in the construction industry. The standard allows for a quantitative, comparable, and communicable assessment to both internal and external stakeholders, notwithstanding the sector's inherent complexity, which is made up of an articulated supply chain and that is strongly reliant on traditional materials. The fact that results can be summarized in a single circularity indicator, the CL, turns out to be a handy instrument both for companies that can check their performance and for the public and private decision-makers who need trustworthy meters to direct policies, incentives, and investment strategies.

Thinking about the future, harmonizing UNI/TS 11820 with other directives and the minimum environmental criteria mandated at the European level could further extend its role, thus facilitating convergence toward common sustainability measurement standards. For the Italian and European construction sector, this, in turn, would translate not only into the fulfillment of regulatory and market requirements but also into the progress of the European Green Deal objectives and the decarbonization pledges for 2030 and 2050. To sum up, the linking between these two case studies reflects that the switch to more sustainable construction models is a necessity from the environmental perspective; however, it becomes an occasion for innovation, competitiveness, and the capacity of recovery by companies in the sector as well. UNI/TS 11820:2024 is a manifestation of an instrument that can operate, measure, and stimulate this transformation.

References

Amicarelli V., Primiceri M., Misino E., Bux C., (2023), An application of the UNI/TS 11820:2022 on the measurement of circularity in an electrical equipment manufacturing organization in Italy, *Journal of Cleaner Production*, **420**, 138522, https://doi.org/10.1016/j.jclepro.2023.138522

Ardente F., Mathieux F., (2014), Identification and assessment of product’s measures to improve resource efficiency: The case-study of an energy using product, *Journal of Cleaner Production*, **83**, 126–141.

Brunner P.H., Rechberger H., (2017), *Handbook of material flow analysis: For environmental, resource and waste engineers* (2nd ed.), CRC Press, Taylor & Francis Group, Boca Raton, London, New York.

BSI Group, (2017), *BS 8001 – Circular economy: Framework for implementing the principles of the circular economy in organizations – Guide*, British Standards Institution, London.

De Oliveira C.T., Oliveira G.G.A., (2023), What circular economy indicators really measure? An overview of circular economy principles and sustainable development goals, *Resources, Conservation and Recycling*, **190**, 106850, https://doi.org/10.1016/j.resconrec.2022.106850

De Pascale A., Arbolino R., Szopik-Depczyńska K., Limosani M., Ioppolo G., (2021), A systematic review for measuring circular economy: The 61 indicators, *Journal of Cleaner Production*, **281**, 124492, https://doi.org/10.1016/j.jclepro.2020.124492

Geisendorf S., Pietrulla F., (2018), The circular economy and circular economic concepts: A literature analysis and redefinition, *Thunderbird International Business Review*, **60**, 721–731.

Ghisellini P., Cialani C., Ulgiati S., (2016), A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems, *Journal of Cleaner Production*, **114**, 11–32.

Gleason Espíndola J.A., Cordova F., Casiano Flores C., (2018), The importance of urban rainwater harvesting in circular economy: The case of Guadalajara city, *Management Research Review*, **41**, 533–553.

Hughes R., (2017), The EU circular economy package—Life cycle thinking to life cycle law?, *Procedia CIRP*, **61**, 10–16. International Organization for Standardization, (n.d.), *ISO/CD 59004 – Circular economy: Terminology, principles and guidance for implementation*, On line at: https://www.iso.org/standard/80648.html

Jacobi N., Haas W., Wiedenhofer D., Mayer A., (2018), Providing an economy-wide monitoring framework for the circular economy in Austria: Status quo and challenges, *Resources, Conservation and Recycling*, **137**, 156–166.

Kirchherr J., Piscicelli L., (2019), Towards an education for the circular economy (ECE): Five teaching principles and a case study, *Resources, Conservation and Recycling*, **150**, 104406, https://doi.org/10.1016/j.resconrec.2019.104406

Kirchherr J., Reike D., Hekkert M., (2017), Conceptualizing the circular economy: An analysis of 114 definitions, *Resources, Conservation and Recycling*, **127**, 221–232.

Morea D., Fortunati S., Martiniello L., (2021), Circular economy and corporate social responsibility: Towards an integrated strategic approach in the multinational cosmetics industry, *Journal of Cleaner Production*, **315**, 128232, https://doi.org/10.1016/j.jclepro.2021.128232

Passaro P., Perchinunno P., Rotondo F., (2023), Statistical analysis of the circular economy for the intervention policies of the NRRP, *British Food Journal*, **125**, 3121–3140.

Poponi S., Arcese G., Pacchera F., Martucci O., (2022), Evaluating the transition to the circular economy in the agri-food sector: Selection of indicators, *Resources, Conservation and Recycling*, **176**, 105916, https://doi.org/10.1016/j.resconrec.2021.105916

Reich R.H., Vermeyen V., Alaerts L., Van Acker K., (2023), How to measure a circular economy: A holistic method compiling policy monitors, *Resources, Conservation and Recycling*, **188**, 106707, https://doi.org/10.1016/j.resconrec.2022.106707

Rossi E., Bertassini A.C., Ferreira C. dos S., Neves do Amaral W.A., Ometto A.R., (2020), Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electro-electronic cases, *Journal of Cleaner Production*, **247**, 119137, https://doi.org/10.1016/j.jclepro.2019.119137

Sani D., Picone S., Bianchini A., Fava F., Guarnieri P., Rossi J., (2021), An overview of the transition to a circular economy in Emilia-Romagna Region, Italy considering technological, legal–regulatory and financial points of view: A case study, *Sustainability*, **13**, 596, https://doi.org/10.3390/su13020596

Sassanelli C., Rosa P., Rocca R., Terzi S., (2019), Circular economy performance assessment methods: A systematic literature review, *Journal of Cleaner Production*, **229**, 440–453.

Scrucca F., Ingrao C., Barberio G., Matarazzo A., Lagioia G., (2023), On the role of sustainable buildings in achieving the 2030 UN sustainable development goals, *Environmental Impact Assessment Review*, **100**, 107011, https://doi.org/10.1016/j.eiar.2023.107011

Suarez-Eiroa B., Fernandez E., Mendez-Martínez G., Soto-Onate D., (2018), Operational principles of circular economy for sustainable development: Linking theory and practice, *Journal of Cleaner Production*, **214**, 952–961.

UNI – Ente Italiano di Normazione, (2022), *UNI/TS 11820:2022 – Misurazione della circolarità: Metodi e indicatori per la misurazione dei processi circolari nelle organizzazioni*, On line at: https://store.uni.com/uni-ts-11820-2022

UNI – Ente Italiano di Normazione, (2024), *UNI/TS 11820:2024 – Misurazione della circolarità: Metodi ed indicatori per la misurazione dei processi circolari nelle organizzazioni*, On line at: https://www.uni.com/economia-circolare-la-uni-ts-118202024-in-una-nuova-veste/

Veleva V., Bodkin G., (2018), Corporate–entrepreneur collaborations to advance a circular economy, *Journal of Cleaner Production*, **188**, 20–37.

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AN INTEGRATED PERSPECTIVE FROM TERRITORIAL VULNERABILITY IN THE CONTEXT OF THE EU ZERO DEFORESTATION REGULATION*

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Abstract

This study integrates territorial vulnerability to climate change with the challenges posed by the EU Zero Deforestation Regulation 2023/1115 (EUDR) for Italian agro-industrial supply chains, particularly timber. The EUDR requires operators to implement due diligence and geolocation of origin plots to combat "embedded deforestation". Italy, as the third-largest European importer of products linked to deforestation and dependent on imports for 80% of its wood supply, faces critical trade-offs between competitiveness and sustainability. The Municipality of Grosseto (Tuscany, Italy) was selected as a case study due to its strategic position and diverse ecosystems, including coastal dune systems, back-dune wetlands, Mediterranean scrub, and diversified agricultural systems. Territorial vulnerability was assessed using the Relative Indices Triangle (RIT), which integrates exposure, sensitivity, and adaptive capacity. Results show a moderate Relative Exposure Index (REI = 25.45%), a high Relative Sensitivity Index (RSI = 36.97%), and a good Relative Adaptive Capacity Index (RACI = 37.58%), classifying Grosseto as "Zone A" (medium exposure, high sensitivity, sufficient adaptive capacity). These findings show that climate vulnerability affects supply chain stability and traceability, creating risks of sourcing from degraded ecosystems, central to EUDR compliance. Rising temperatures (+0.17°C/year) and irregular precipitation have already reduced agricultural productivity by 15% and degraded forests. Linking vulnerability assessment with regulatory requirements, RIT analysis can support climate adaptation and EUDR implementation. Targeted interventions (i.e., efficient water management, crop diversification, and energy retrofitting of rural infrastructure) mitigate climate impacts, strengthen resilience, and reduce dependence on imported materials of uncertain origin. Territorial analysis thus serves both as a diagnostic tool and a strategic means to align Italian agro-industrial supply chains with EUDR sustainability goals.

Keywords: climate adaptation, supply chain traceability, territorial vulnerability, timber industry

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1. Introduction

Recent studies on Mediterranean territorial vulnerability assessments adopt integrated spatial and temporal methodologies. For instance, Solans et al. (2022) present a comprehensive framework for climate adaptation planning in Mediterranean basins, emphasizing the crucial role of vulnerability assessments to inform adaptive strategies. Complementing this, Vogel et al. (2021) highlight the importance of subregional scale analyses to capture seasonal and spatial heterogeneity in ecosystem vulnerability, while Lazoglou et al. (2024) identify key climate change hotspots. Although originally developed for environmental adaptation, these insights are equally decisive for forest supply chains: droughts, wildfires, and soil degradation directly affect the availability of local timber, increasing risks of supply disruption and undermining compliance with legality and traceability requirements set by the EU Zero Deforestation Regulation 2023/1115 (EUDR).

In contrast, the literature that integrates the implications of the EUDR with territorial vulnerability methodologies remains limited. While existing assessment frameworks are robust, they do not yet explicitly connect environmental and climatic pressures with supply chain risks. This reveals a significant research gap in linking territorial vulnerability approaches with zero-deforestation compliance, to support resilient and legally robust timber supply chains across Europe.

In Italy, evidence on timber import dependency is still scarce, but studies on the resilience of domestic supply chains offer useful insights. Negro et al. (2021), analyzing the sector's response to the 2018 Vaia windstorm and the Programme for the Endorsement of Forest Certification (PEFC) Fair Supply Chain Project, show how environmental vulnerabilities can rapidly translate into market disruptions, increasing reliance on imports. This connection between ecological fragility and supply chain weakness is now even more critical under EU rules: declining availability of national timber, if unmanaged, may force reliance on high-risk imports from deforestation-prone regions, exposing operators to EUDR non-compliance.

At the same time, technological solutions are emerging to strengthen traceability and resilience. Blockchain and big data analytics for forest monitoring (Bennett, 2024; Taylor et al., 2020), Radio-Frequency Identification (RFID) systems and sustainable transport innovations (Pichler et al., 2022; Elias, 2024), as well as decentralized tamper-proof platforms (Brau et al., 2023), not only enable legality and sustainability checks, but also allow stakeholders to monitor how local environmental vulnerabilities translate into market and compliance risks. The integration of such digital tools with advanced territorial vulnerability methods (Solans et al., 2022; Lazoglou et al., 2024) opens the way to an integrated framework in which climate and territorial data directly feed traceability systems, enabling early detection of supply disruptions and ensuring alignment with EU regulations.

In this regard, the selection of case studies becomes critical. Re et al. (2023) analyze the Ligurian coast based on hydro-geomorphological vulnerability, while Pace et al. (2023) apply spatially explicit transition matrices to map land degradation at the provincial level. Both approaches demonstrate how local variability is decisive not only for climate adaptation strategies but also for supply chain resilience: a more vulnerable territory is simultaneously a fragile node within the timber supply network.

Building on this, the present study aims to bridge the gap between territorial vulnerability assessments and regulatory compliance requirements, applying this approach to the Mediterranean context with a focus on timber supply chains.

The Municipality of Grosseto (Tuscany, central Italy) was selected as a case study for its strategic location and growing exposure to climate risks such as droughts, wildfires, and biodiversity loss. The environmental heterogeneity of the area – ranging from coastal dunes and Mediterranean scrublands to forested hills and alluvial plains – makes it a particularly relevant setting to test integrated approaches. In this context, environmental vulnerabilities do not only pose adaptation challenges. They also directly affect the stability of local and national timber supply chains: wildfires and forest degradation reduce resource availability, forcing greater reliance on imports and raising risks of EUDR non-compliance. As such, Grosseto represents a regional laboratory where climate vulnerability analysis, digital traceability tools, and EU regulatory requirements can be combined, demonstrating how targeted adaptation measures (fire prevention, water management, resilient forest governance) can reduce both climate and market risks, while ensuring timber supply chains that are transparent, sustainable, and fully aligned with EU policies.

2. Materials and methods

The Municipality of Grosseto spans from the Tyrrhenian coast to the first inland hill systems, covering approximately 4,700 square kilometers and presenting a remarkable environmental mosaic. Coastal dunes, back-dune wetlands, and Mediterranean scrublands merge with holm oak and cork oak woodlands in the hills, while the Ombrone and Bruna river plains host riparian corridors and a mix of intensive and traditional agricultural landscapes. This combination of geomorphological settings and land covers supports high habitat diversity, making Grosseto a representative example of a Mediterranean coastal–inland transition system.

The area is further enriched by the Maremma Regional Park (≈9,000 ha) and the Ramsar-listed Diaccia Botrona wetland, both of which enhance its conservation value and offer a living laboratory for climate adaptation research. The territory retains a rich agroforestry heritage: anthropogenic stone-pine coastal belts, mixed holm-oak stands, and traditional vineyards/olive groves supply ecosystem services and sustain local economies. Precision-agriculture trials and multifunctional agroforestry systems are being introduced to diversify production and reinforce resilience.

To systematically evaluate territorial vulnerability by accounting for both environmental and socio-economic factors, this study adopts the Relative Indices Triangle (RIT) method, originally developed by Liu et al. (2013). This barycentric approach provides an intuitive and integrated representation of the three core dimensions of territorial risk, defined as the potential adverse consequences of climate-related hazards in a given area (Birkmann, 2006; IPCC, 2022).

Mathematically, risk is conceptualized as Eq. (1):

$$Risk = Hazard \times Vulnerability \qquad (1)$$

In this context:

- Hazard refers to the probability and severity of climate-related events such as heatwaves, floods, and droughts;
- Vulnerability is a composite of three interrelated components: Exposure, Sensitivity, and Adaptive Capacity.

Using the RIT method, a set of indicators was selected and aggregated into three normalized indices:

- The Exposure Index (EI) includes climatic hazard indicators such as annual temperature anomalies, precipitation deficits, heatwave frequency, and coastal flooding, based on data from the Tuscany Regional Hydrological Service (SIR Toscana, 2023), the LaMMA Consortium (2023, a regional environmental monitoring and modeling center), and Copernicus ERA5 datasets 2024.

- The Sensitivity Index (SI) integrates biophysical and demographic dimensions. Key variables include crop-specific water needs, loss of soil organic matter, percentage of population over 75 years old, and density of critical infrastructure in coastal zones.
- The Adaptive Capacity Index (ACI) reflects the system's ability to respond to climate threats. Indicators include per capita Gross Domestic Product (GDP), certified forest areas under Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC) schemes, broadband coverage (used as a proxy for digital readiness), and the presence of Sustainable Energy and Climate Action Plans (SECAPs), which reflect institutional preparedness.

All indicators were normalized using the min–max scaling method, yielding values between 0 (least favorable) and 1 (most favorable), as shown in Equation (2):

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{2}$$

Each composite index was calculated using a weighted arithmetic mean, with the relative importance of each indicator determined based on its territorial relevance and expert consultation. Finally, the indices were transformed into relative measures — the Relative Exposure Index (REI), Relative Sensitivity Index (RSI), and Relative Adaptive Capacity Index (RACI) — which represent the percentage contribution of each component to overall vulnerability, as described in Eqs. (3)–(5):

$$REI = \frac{EI}{EI + SI + ACI} \times 100; \tag{3}$$

$$RSI = \frac{SI}{EI + SI + ACI} \times 100; \tag{4}$$

$$RACI = \frac{ACI}{EI + SI + ACI} \times 100 \tag{5}$$

These relative indices allow for a comparative and spatially explicit analysis of vulnerability components, supporting decision-makers in identifying areas where adaptation efforts should be prioritized. The final visualization of territorial vulnerability within the RIT framework is achieved through an equilateral triangle plot, where each vertex represents one of the three Relative Indices (REI, RSI, and RACI). Each territory is positioned within the triangle based on the relative contribution of these indices, enabling a spatially intuitive classification of vulnerability profiles. The triangle is subdivided into distinct vulnerability zones by angular bisectors, which serve as threshold boundaries. These zones are defined as follows:

- Zone A: Characterized by low exposure (REI $< 33\%$), high sensitivity (RSI $> 33\%$), and moderate to high adaptive capacity (RACI $\geq 33\%$). Territories in this zone are sensitive to climate impacts but benefit from a relatively strong capacity to respond and adapt.
- Zone B: Defined by high exposure (REI $\geq 33\%$), moderate to high sensitivity (RSI $\geq 33\%$), and low adaptive capacity (RACI $< 33\%$). This configuration reflects areas facing heightened vulnerability, primarily due to the intensity of climatic hazards combined with limited institutional or socio-economic resilience.

- Zone C: Encompasses areas with moderate exposure (REI < 33%), high sensitivity (RSI ≥ 33%), and limited adaptive capacity (RACI < 33%). These territories are particularly at risk, as vulnerability stems from intrinsic fragility and insufficient adaptive mechanisms, rather than direct hazard pressure.

This graphical classification enables rapid interpretation of complex multidimensional data and supports the prioritization of adaptation strategies in spatial planning and policy development. Data collection adhered to regional institutional protocols, utilizing hourly records (2013–2024) from the Ponte Tura climate station (located 13 m above sea level), which were then aggregated to daily and annual scales. Additional variables: wind gusts, solar radiation, Potential Evapotranspiration (PET), and self-calibrating Palmer Drought Severity Index (sc-PDSI), were derived from LaMMA datasets, providing high-resolution meteorological and environmental information. Statistical validation included Mann-Kendall trend tests ($p<0.05$) and Sen's slope estimation (Mann, 1945).

Socio-economic and land-use data from ISTAT (2023), the Chamber of Commerce, and Regional Land-Use Maps were harmonized for indicator integration. All processing was done in Python 3.11.4, while triangular plots were produced using ggtern in R 4.3.2. Custom scripts ensured consistency in trend analysis, variable calculation (e.g., temperature, PET), and graphical output. Scripts are available upon request.

Finally, the methodology was validated through four stakeholder workshops and consultations with technical staff from the Municipality of Grosseto, ensuring scientific rigor and operational relevance. This comprehensive framework offers a robust, spatially explicit vulnerability assessment tool, essential for climate planning and compliance with emerging regulations such as the EU Zero Deforestation Regulation (EUDR) (Negro et al., 2021; Bennett, 2024). RIT outputs were embedded in the Municipality's SECAP as the synthesis platform that aggregates diagnostics and stakeholder input and co-prioritizes measures, creating a direct pipeline from analysis to policy and EUDR-relevant actions (SECAP GR, 2025; Marchi et al., 2024).

5. Results and discussion

Long-term data from the Ponte Tura meteorological station (2013–2024) show a statistically significant warming trend of +0.17 °C per year in mean air temperature (Fig. 1), as also reported in Zocco et al. (2025) and the SECAP of the Municipality of Grosseto (2025). This study builds on previous analyses by providing extended temperature projections up to 2030, offering new insight into near-future climate dynamics in the area. This is accompanied by rising temperature extremes, prolonged summer droughts, and increasing rainfall irregularity. Over the same period, relative humidity declined by approximately 10% (Fig. 2a), contributing to intensified evapotranspiration (Fig. 2b) and worsening drought stress (Zocco et al., 2025; SECAP GR, 2025).

These changes in climate, together with more frequent heatwaves and stronger winds, significantly increase wildfire risk in the territory (SECAP GR, 2025). Between 2017 and 2022, fire frequency has risen, affecting forests, Mediterranean scrubland, and both cultivated and abandoned agricultural land where shrubs can easily dry out (Fig. 3a and Fig. 3b). Wildfires currently pose a high risk and are expected to intensify further in the short to medium term (SECAP GR, 2025). Their impacts include damage to ecosystems, threats to public safety, and losses in agriculture and forestry. Notably, there has also been a 10% decline in summer tourist arrivals in the last three years, linked to heatwaves and fires in the forested surroundings of Grosseto (SECAP GR, 2025).

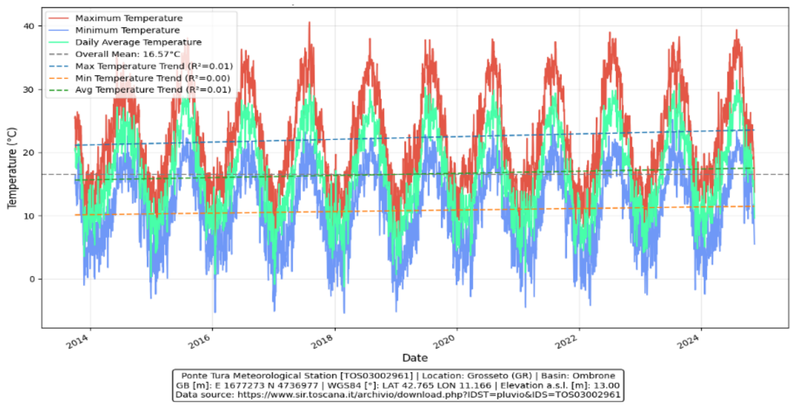
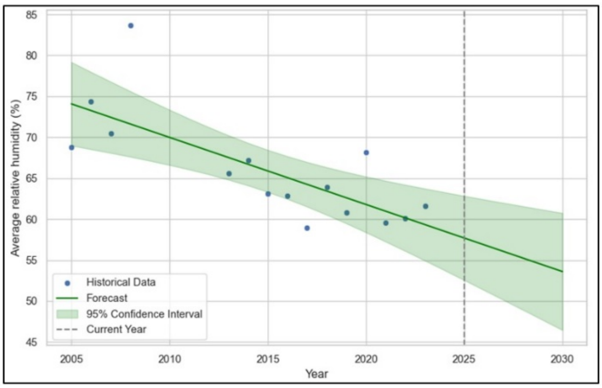


Fig. 1. Temperature trend at the Ponte Tura station (Grosseto). Authors' elaboration (SECAP GR, 2025).



(a)

(b)

Fig. 2. (a) Historical (2004-2024) and projection with confidence intervals of the relative humidity. **(b)** Potential Evapotranspiration (PET) calculated using historical temperature, humidity, solar radiation, and wind data provided by the LaMMA Consortium
Source: Authors' elaboration (SECAP GR, 2025).

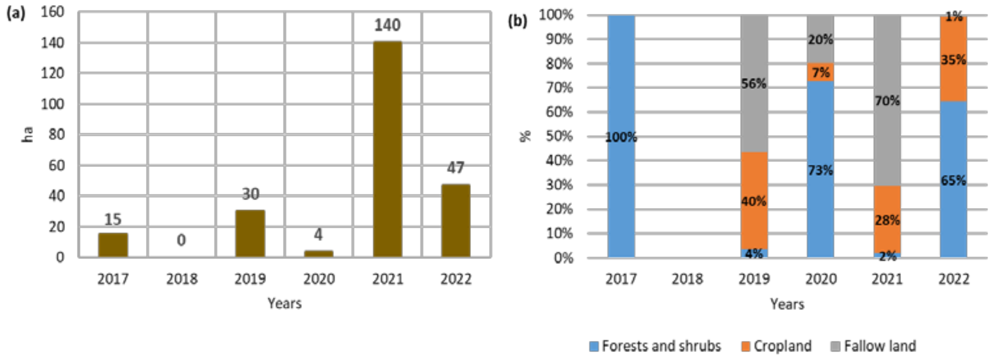


Fig. 3. (a) Trend of wildfires in the Municipality of Grosseto: total area affected, in hectares (ha). **(b)** Percentage distribution of wildfires by land cover type (woodlands and shrubs, cropland, and fallow land) in the Municipality of Grosseto. Source: Analysis based on Forest Fire Prevention (Antincendi Boschivi, AIB) data (2017–2022), SECAP GR (2025).

At the territorial scale, wildfires contribute to AFOLU emissions both by releasing biogenic CO_2 (Lasslop et al., 2016) and by reducing forest cover, which lowers the ecosystem's carbon sequestration capacity (Marchi et al., 2023, 2024; Sporchia et al., 2023, 2024). Although total annual precipitation (~650 mm) remains near historical levels, it is now concentrated in short, intense autumn events, increasing the risk of both drought and hydrogeological hazards. At the same time, declining relative humidity (~10%), reduced cloud cover (~8%), and rising solar radiation (~15% over the past two decades) intensify evapotranspiration and exacerbate drought stress. Stronger and more frequent wind gusts accelerate fire spread, threatening tourists, residents, and the coastal infrastructure typical of these areas. Wildfires, especially common along the coast, cause severe damage to homes, facilities, and natural landscapes, jeopardizing community safety and local economies.

The application of the Relative Indices Triangle (RIT) methodology (Fig. 4), as detailed by Zocco et al. (2025), quantifies this scenario, yielding a Relative Exposure Index (REI) of 25.45%. This value indicates that, although direct climatic pressures are notable, exposure alone is not the main driver of vulnerability. The Relative Sensitivity Index (RSI) of 36.97% reveals a high susceptibility to these pressures, stemming from the territory's socio-economic and biophysical characteristics. Key sensitivity factors include the high-water demand of local crops, an elevated demographic aging index (178.9), and the significant proportion (15.2%) of the population living in hydrogeologically vulnerable areas (Zocco et al., 2025). In contrast, the Relative Adaptive Capacity Index (RACI) of 37.58% suggests a moderate-to-high capacity to cope, supported by proactive governance, as evidenced by the SECAP (2025), and a stable regional economy.

Based on these values, Grosseto falls within 'Zone A' of the RIT, corresponding to areas where sensitivity is relatively high, adaptive capacity is moderate-to-high, and climatic exposure is moderate. This suggests that the territory's vulnerability is primarily driven by its intrinsic socio-economic and biophysical characteristics rather than by extreme climatic pressures (Zocco et al., 2025), a pattern supported by tangible ecosystem impacts such as a 15% decline in agricultural productivity for key crops over the past five years, directly linked to increased water scarcity, heat stress, and the growing frequency of wildfires (Bruno et al., 2023). These fires, particularly prevalent in coastal forested areas, exacerbate damage to both natural and built environments, aligning with the SECAP risk assessment, which identifies agriculture, forestry, and wildfire management as highly vulnerable sectors (SECAP GR, 2025).

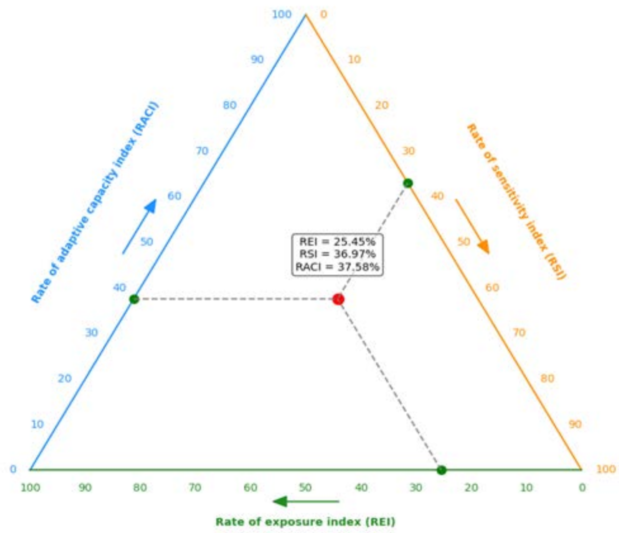


Fig. 4. Positioning of the Municipality of Grosseto within the Relative Indices Triangle (REI = 25.45%, RSI = 36.97%, RACI = 37.58%). The red point indicates the municipality's position within 'Zone A'.

For the Italian timber industry, which relies on imports for approximately 80% of its needs, the climate-driven degradation of domestic forests, exacerbated by increasing wildfire frequency and severity,further amplifies the regulatory risks associated with the EU Zero Deforestation Regulation (EUDR). The strict due diligence required by the EUDR poses a significant compliance challenge, particularly for SMEs in territories like Grosseto and other areas characterized by similar vulnerabilities and socio-environmental conditions, which may lack the resources to trace complex international supply chains. This territorial vulnerability could intensify import dependency, increasing the risk of non-compliance and potential market exclusion.

To address these interconnected challenges, a multi-faceted adaptation strategy is essential. Integrating advanced technologies, such as blockchain, IoT, and AI-powered remote sensing, can enhance supply chain transparency and traceability, thereby facilitating EUDR compliance. Alongside this, adaptive measures including advanced water management, crop diversification towards more drought-resistant species, and retrofitting rural infrastructure are critical to bolster local resilience. Crucially, strengthening local and regional timber networks will enhance supply chain resilience, reducing dependency on imports and aligning with the strategic objectives of the SECAP. These efforts collectively contribute to increasing the overall adaptive capacity of the territory and its economic sectors in the face of ongoing climatic pressures.

6. Concluding remarks

The Province of Grosseto exemplifies a territory where high socio-ecological sensitivity, rather than extreme climatic exposure, drives vulnerability. This study, using an integrated climate analysis and the Relative Indices Triangle (RIT) framework, highlights that vulnerability arises mainly from the balance between sensitivity and adaptive capacity. Ecosystem impacts, including a 15% decline in agricultural productivity over five years due to water scarcity, heat stress, and wildfires, support these findings and align with SECAP's identification of agriculture, forestry, and wildfire management as vulnerable sectors.

For the Italian timber industry, dependent on imports for around 80% of its needs, the climate-related degradation of domestic forests, worsened by increased wildfires, heightens regulatory risks tied to the EU Zero Deforestation Regulation (EUDR). Strict due diligence under the EUDR poses challenges, especially for SMEs in Grosseto and similar territories, which may struggle to trace complex supply chains. Increasing vulnerability is likely to force greater reliance on imports, thereby raising the risk of non-compliance and market exclusion.

Effective adaptation requires reducing ecosystem sensitivity through sustainable land management and improving supply chain transparency with technologies like blockchain, IoT, and AI-powered remote sensing. Upgrading rural infrastructure and strengthening local timber networks also enhances resilience. Embedding these strategies within policy frameworks such as SECAP is crucial for a sustainable, compliant agro-industrial future. Collaboration among stakeholders and continuous monitoring are key to keeping adaptation measures effective amid a changing climate and regulations.

Given Grosseto's complex combination of landscapes and socio-ecological characteristics, this study serves as a methodological example to inspire similar assessments in other national and international territories with comparable conditions. Its integrated approach and policy recommendations can guide efforts to enhance resilience elsewhere.

The SECAP provides the institutional vehicle to translate this integrated vulnerability–traceability framework into policy, coordinating measures that simultaneously lower climate risk and strengthen legality/deforestation-free assurance in timber flows. Beyond data analysis, embedding results in the SECAP adds strategic value by weaving them into a coherent territorial policy architecture that supports EUDR compliance and local forest-sector resilience.

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References

Bennett L., (2024), The role of blockchain technology in enhancing supply chain transparency in Italy, *Preprints*, https://doi.org/10.20944/preprints202405.1405.v1

Birkmann J., (2006), *Measuring Vulnerability to Natural Hazards: Towards Disaster-Resilient Societies*, UNU-EHS, Bonn, Germany.

Brau J., Gardner J., DeCampos H., Gardner K., (2023), Blockchain in supply chain management: A feature-function framework for future research, *Supply Chain Management: An International Journal*, **29**, 27–49.

Bruno M., Marchi M., Ermini N., Niccolucci V., Pulselli F.M., (2023), Life cycle assessment and cost–benefit analysis as combined economic–environmental assessment tools: Application to an anaerobic digestion plant, *Energies*, **16**, 3686, https://doi.org/10.3390/en16093686

Copernicus ERA5 datasets, (2024), ERA5 hourly data on single levels from 1940 to present, On line at: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels

Elias M., (2024), Timber traceability and sustainable transportation management: A review of technologies and procedures, *Series II – Forestry • Wood Industry • Agricultural Food Engineering*, 11–52, https://doi.org/10.31926/but.fwiafe.2024.17.66.1.2

ISTAT, (2023), *Statistiche demografiche del comune di Grosseto*, Istituto Nazionale di Statistica, Rome, On line at: https://esploradati.istat.it/databrowser

LaMMA Consortium, (2024), Sistema Informativo Regionale (SIR) – Rete Climatica Toscana [dataset], On line at: https://www.lamma.toscana.it

Lasslop G., Brovkin V., Reick C.H., Bathiany S., Kloster S., (2016), Multiple stable states of tree cover in a global land surface model due to a fire–vegetation feedback, *Geophysical Research Letters*, **43**, 6324–6331.

Lazoglou G., Papadopoulos-Zachos A., Georgiades P., Zittis G., Velikou K., Manios E., **et al.**, (2024), Identification of climate change hotspots in the Mediterranean, *Scientific Reports*, **14**, https://doi.org/10.1038/s41598-024-80139-1

Liu X., Wang Y., Peng J., Braimoh A.K., Yin H., (2013), Assessing vulnerability to drought based on exposure, sensitivity and adaptive capacity: A case study in middle Inner Mongolia, *Chinese Geographical Science*, **23**, 13–25.

Mann H.B., (1945), Nonparametric tests against trend, *Econometrica*, **13**, 245–259.

Marchi M., Capezzuoli F., Fantozzi P.L., Maccanti M., Pulselli R.M., Pulselli F.M., Marchettini N., (2023), GHG action zone identification at the local level: Emissions inventory and spatial distribution as methodologies for policies and plans, *Journal of Cleaner Production*, **386**, 135783, https://doi.org/10.1016/j.jclepro.2022.135783

Marchi M., Nocentini E., Tropea F., Tonielli A., Marchettini N., Pulselli F.M., (2024), The Sustainable Energy and Climate Action Plan (SECAP) design and development: The case study of the Municipality of Grosseto (Italy), *60th ISOCARP World Planning Congress*, On line at: https://riyadh2025.isocarp.org

Negro F., Espinoza O., Brunori A., Cremonini C., Zanuttini R., (2021), Professionals' feedback on the PEFC fair supply chain project activated in Italy after the "Vaia" windstorm, *Forests*, **12**, 946, https://doi.org/10.3390/f12070946

Pace L., Imbrenda V., Lanfredi M., Cudlín P., Simoniello T., Salvati L., **et al.**, (2023), Delineating the intrinsic, long-term path of land degradation: A spatially explicit transition matrix for Italy, 1960–2010, *International Journal of Environmental Research and Public Health*, **20**, 2402, https://doi.org/10.3390/ijerph20032402

Pichler G., Sandak J., Picchi G., Kastner M., Graifenberg D., Stampfer K., **et al.**, (2022), Timber tracking in a mountain forest supply chain: A case study to analyze functionality, bottlenecks, risks, and costs, *Forests*, **13**, 1373, https://doi.org/10.3390/f13091373

Re A., Minola L., Pezzoli A., (2023), Climate scenarios for coastal flood vulnerability assessments: A case study for the Ligurian coastal region, *Climate*, **11**, 56, https://doi.org/10.3390/cli11030056

SECAP GR, (2025), *Piano d'Azione per l'Energia Sostenibile e il Clima (PAESC) – Aggiornamento 2025*, Municipality of Grosseto, On line at: https://www.comune.napoli.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/35107

Solans A., Macian-Sorribes H., Martínez-Capel F., Pulido-Velázquez M., (2022), Vulnerability assessment for climate adaptation planning in a Mediterranean basin, *Hydrological Sciences Journal*, **69**, 21–45.

Sporchia F., Marchi M., Nocentini E., Marchettini N., Pulselli F.M., (2023), Sub-national scale initiatives for climate change mitigation: Refining the approach to increase the effectiveness of the Covenant of Mayors, *Sustainability*, **15**, 125, https://doi.org/10.3390/su15010125

Sporchia F., Marchi M., Petraglia A., Marchettini N., Pulselli F.M., (2024), The pandemic effect on GHG emission variation at the sub-national level and translation into policy opportunities, *Journal of Environmental Management*, **349**, 119539, https://doi.org/10.1016/j.jenvman.2023.119539

Taylor R., Davis C., Brandt J., Parker M., Stäuble T., Ameen Z., (2020), The rise of big data and supporting technologies in keeping watch on the world's forests, *International Forestry Review*, **22**, 129–141.

Vogel J., Paton E., Aich V., (2021), Seasonal ecosystem vulnerability to climatic anomalies in the Mediterranean, *Biogeosciences*, **18**, 5903–5927.

Zocco M., Pulselli F.M., Marchi M., (2025), *Vulnerabilità territoriale e cambiamenti climatici: proiezioni, impatti e mitigazione nel Comune di Grosseto*, Tesi di Laurea, Università di Siena, Italy

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Books:
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Handbook, (1951), *Handbook of Chemical Engineer*, vol. II, (in Romanian), Technical Press, Bucharest, Romania.

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Star K., (2008), *Environmental risk assessment generated by natural hazards*, MSc Thesis, Institute of Hazard Research, Town, Country.

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JRC European Commission, (2011), *Supporting Environmentally Sound Decisions for Construction and Demolition (C&D) Waste Management*, A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA), On line at: http://lct.jrc.ec.europa.eu/pdf-directory/ReqNo-JRC65850-LB-NA-24916-EN-N.pdf.

EC Directive, (2010), Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (Integrated Pollution Prevention and Control), *Official Journal of the European Union*, **L334**, 17-119.

EC, (2014), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Towards a Circular Economy: A zero waste programme for Europe, European Commission, On line at: http://ec.europa.eu/environment/circular-economy/

Law 152 (2006), Legislative Decree No. 152 of the 03 April 2006, Environmental Regulations, *Official Journal*, No. 88 of the 14 April 2006 – Ordinary Supplement No. 96.

GD, (2004), Governmental Decision no. 1076/2004 surnamed SEA Governmental Decision, regarding the procedure for strategic environmental impact assessment for plans or programs, published in Romanian Official Monitor, part I, no. 707 from 5th of August, 2004.

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