Premi di Tesi di Laurea ENEA-CONAI 2024 e 2025
Atti delle tesi presentate

ENEA-CONAI Master Thesis Awards 2024 and 2025
Proceedings of the selected thesis

Master Thesis on Circular Economy and Sustainability

Second Edition

Edited by
Erika Mancuso, Laura Cutaia, Tiziana Beltrani, Sabrina Moro Iacopini and Chiara Morbidini

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Summary

Introduzione

La pubblicazione scientifica, giunta alla seconda edizione, si propone di dare un contributo alla ricerca e all'innovazione nell'ambito dell'economia circolare, con particolare riferimento al mondo del packaging e alla filiera della gestione e del riciclo dei materiali di imballaggio ma non solo, ampliando la panoramica anche ad altri settori come l'agroalimentare, il tessile, il recupero di batterie al litio, ecc.

Il volume evidenzia la diversità di approccio degli articoli di tesi riportati al suo interno, suddividendoli in argomenti più emergenti, come l'intelligenza artificiale ed anche più tradizionali, come l'eco-design e l'information & training.

Il tema dell'economia circolare è così esplorato da tanti punti di vista, a testimonianza del fatto che la multi-disciplinarietà nel campo della sostenibilità è ormai un valore imprescindibile, una realtà ampiamente trattata e trasversale a più settori accademici.

Questa iniziativa congiunta di Enea e Conai si muove, peraltro, all'interno di un quadro regolatorio e di policy europee che guarda sempre più a un mercato europeo competitivo, oltre che compatto, nell'affrontare le sfide dello sviluppo sostenibile da qui ai prossimi 15 anni. Partendo dalla necessità di progettare packaging sempre più sostenibili, riciclabili e riutilizzabili, prevista in tutta Europa dal PPWR.

L'apporto di nuove idee e progetti fornito dalle tesi di laurea, inoltre, va sicuramente nella direzione di sostenere la crescita nonché l'attuazione di processi di decarbonizzazione e circolarità industriale, stimolando nuove conoscenze e informazioni per lo sviluppo di tecnologie low carbon, come prefigurato dal Net Zero Industry Act e dal Clean Industry Act.

A conferma di ciò, riportiamo le parole del fisico Guido Tonelli pronunciate in un discorso pubblico*: "*C'è un tipo di attività nascosta*" spiega lo scienziato "*di sicuro c'è un giovane in questo momento in qualche laboratorio che non conosciamo, che sta facendo ricerca, che sta trovando nuove idee, che apparentemente sembrano inutili che invece possono rivelarsi una soluzione ai problemi del nostro tempo*". Di questa attività nascosta dobbiamo essere consapevoli, dice ancora il fisico. (*Evento di presentazione del Report di Sostenibilità Conai 2024)

Questo è lo scopo con cui portiamo avanti il progetto, con l'intenzione di mettere in luce l'attività intellettuale e di ricerca delle giovani menti che hanno studiato nell'Università italiana.

E con l'ulteriore auspicio di dare impulso alla creazione di un ponte tra Università e mondo del lavoro.

Simona Fontana, Direttore Generale CONAI

Claudia Brunori, Direttore Dipartimento Sostenibilità Enea

Introduction

The scientific publication, now in its second edition, aims to contribute to research and innovation in the field of circular economy, with particular focus on the packaging sector and the supply chain for the management and recycling of packaging materials, but not exclusively. It also broadens the scope to include other sectors such as agri-food, textiles, lithium battery recovery, and more.

The volume highlights the diversity of approaches found in the thesis articles it contains, categorizing them into more emerging topics—such as artificial intelligence—and more traditional ones, such as eco-design and information & training.

The theme of the circular economy is thus explored from multiple perspectives, demonstrating that multidisciplinarity in the field of sustainability has become an essential value, a widely discussed reality that spans across various academic sectors.

This joint initiative by ENEA and CONAI also operates within a regulatory and policy framework shaped by European directives, which increasingly aim toward a competitive and cohesive European market in addressing the challenges of sustainable development over the next 15 years. It starts from the need to design increasingly sustainable, recyclable, and reusable packaging, as required across Europe by the PPWR.

Moreover, the contribution of new ideas and projects provided by university theses clearly supports the growth and implementation of decarbonization and industrial circularity processes, fostering new knowledge and information for the development of low-carbon technologies, as envisioned by the Net Zero Industry Act and the Clean Industry Act.

To confirm this, we quote physicist Guido Tonelli, who stated in a public speech*: “There is a kind of hidden activity,” the scientist explains, “surely, somewhere right now, there is a young person in a laboratory we don’t know, doing research, coming up with new ideas that may seem useless at first but could turn out to be solutions to the problems of our time.” We must be aware of this hidden activity, the physicist adds. (*Presentation event of the CONAI 2024 Sustainability Report)

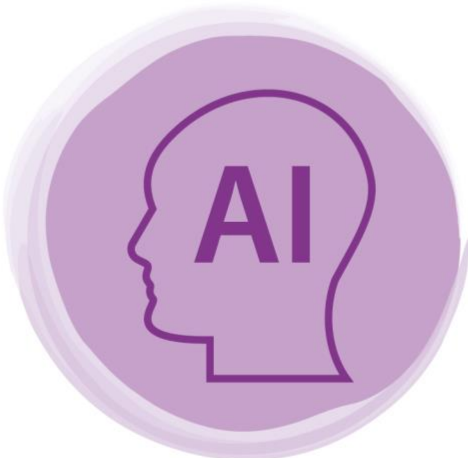
This is the purpose behind the project: to shed light on the intellectual and research activities of young minds who have studied in Italian universities.

And with the further hope of encouraging the creation of a bridge between academia and the professional world.

Simona Fontana, General Director of CONAI.

Claudia Brunori, Director of Department for Sustainability, ENEA.

ARTIFICIAL INTELLIGENCE



The Role of Artificial Intelligence in Supporting Circular Economy Models: A Case Study on IBM

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Abstract

This study explores the crucial role of artificial intelligence (AI) as a transformative driver toward a circular economy (CE) model. It analyzes the historical evolution of AI [1], the European regulatory framework, and its intersection with the key principles of CE. The analysis demonstrates how AI, particularly through technologies like machine learning, can optimize resource management, reduce waste, and promote more sustainable business models. Using the IBM case study [2], the paper highlights practical applications that improve corporate efficiency and sustainability. The findings underscore AI's strategic role in fostering sustainable development, while also acknowledging the ethical and environmental challenges associated with its use.

Keywords: Artificial Intelligence, Circular Economy, Sustainability, IBM, Machine Learning

Introduction

The contemporary era is characterized by a dual, transformative shift: a technological revolution led by the rapid development of artificial intelligence (AI), and an ecological transition that calls for a fundamental rethinking of production, consumption, and resource management. The traditional linear economic model—commonly summarized as "take-make-dispose"—has proven increasingly unsustainable. Its reliance on finite resources, combined with the acceleration of environmental degradation and climate change, has made it clear that new models are urgently needed. In response, the concept of a circular economy (CE) has emerged, offering a regenerative framework aimed at closing resource loops, eliminating waste, and maximizing the value of materials through reuse, recycling, and restoration. At the same time, AI has established itself as one of the most disruptive forces of the modern era, providing tools for unprecedented efficiency, predictive capability, and decision-making across sectors. This paper is situated at the intersection of these two transformations, investigating how AI can act not merely as a technological instrument but as a strategic enabler of the circular economy.

The foundation of this analysis begins with a seminal question posed by Alan Turing in 1950: "Can machines think?" [7] While this may seem self-evident today, in an era where AI is already embedded in everyday life, Turing's question initiated decades of research, debate, and experimentation. The evolution of AI [1] has been a complex journey, moving from early symbolic reasoning systems to the era of Machine Learning and Deep Learning, fueled by the explosion of Big Data and advanced computational power. This progression demonstrates that AI is far more than an automation tool: it is a capacity-enhancing partner capable of addressing systemic challenges, including those inherent in transitioning toward sustainable economic models.

This thesis is structured into three chapters designed to provide a comprehensive, multidisciplinary perspective. The first chapter traces the historical development of AI, from its philosophical origins to modern innovations, examining both technical distinctions, such as weak versus strong AI, and the evolving regulatory and ethical frameworks that shape its use. The second chapter focuses on the circular economy, analyzing its environmental, economic, and social implications. It explores its guiding principles, major regulatory initiatives such as the EU Circular Economy Action Plan [9], and the ways in which AI can serve as a powerful lever to scale sustainability practices across industries. Finally, the third chapter presents a detailed case study of IBM, a global leader in information technology, demonstrating practical applications of AI in corporate sustainability. This includes optimizing resource management, predictive maintenance, and intelligent supply chain practices, as well as showcasing strategic collaborations with companies and institutions that highlight tangible results.

Ultimately, this paper aims to demonstrate that the convergence of AI and the circular economy is not merely theoretical but actionable. By leveraging AI thoughtfully, humanity has the opportunity to redefine economic growth, making it both resilient and environmentally responsible. This study emphasizes that technology alone is insufficient; success depends on governance, ethical oversight, and collaboration among academics, companies, and policymakers. In doing so, it seeks to provide a forward-looking vision of a future in which AI and sustainability are deeply intertwined, driving progress toward a more balanced, circular, and resilient global economy.

Methods

This paper adopts a predominantly qualitative and descriptive research approach, focused on exploring and gaining an in-depth understanding of the intersection between artificial intelligence (AI) and the circular economy (CE). The research is based on a literature review that integrates historical, scientific, regulatory, and corporate case study sources to build a solid and coherent analytical framework.

The methodology is structured in three main phases, each of which contributes synergistically to answering the research question.

Historical and Conceptual Analysis [2]: The first phase consists of a meticulous historical and theoretical reconstruction of the two main fields of study. For artificial intelligence, the analysis begins with Alan Turing's pioneering question ("Can machines think?”) [7] in the 1950s, tracing an evolution that spans early successes and subsequent "AI winters." This phase includes an analysis of the theories and experiments that led to the development of key concepts such as Machine Learning and Deep Learning, which are fundamental for modern applications. Concurrently, for the circular economy, its conceptual origins, key principles of regeneration and reuse, and the relevant regulatory framework, with a focus on the European context[2], are analyzed. This approach ensures that the research is firmly anchored to the historical and legal definitions and contexts of both disciplines, providing the necessary theoretical foundation for the subsequent analysis.

Case Study [4]: The second phase applies a single case study approach to deeply examine the practical implementation of the theory. The case of IBM was selected for its global relevance in the IT sector and its explicit commitment to integrating AI solutions to support sustainability and the circular economy. The analysis focuses on corporate strategies, innovative partnerships (such as those with Tommy Hilfiger and the Hera Group), and the use of specific technologies like IBM Watson. This methodological approach allows the paper to move beyond mere theoretical analysis to a concrete exemplification, demonstrating how AI-based solutions can be applied to optimize production processes, reduce waste, and improve large-scale resource management.

Critical and Prospective Analysis[8]: The third and final phase of the work consists of a critical analysis of the findings and a discussion of future implications. Based on the evidence collected, the potential impact and the still-open challenges related to the integration of AI and sustainability are discussed. This includes evaluating critical aspects such as the energy consumption of AI systems, ethical issues related to their management, and the importance of human oversight. It concludes with a prospective vision on the role of AI in shaping a more resilient future, suggesting directions for future research and for corporate and public policies.

The combined use of these research methods, which moves from theory to practice and from a historical perspective to a prospective vision, allows for a comprehensive, contextualized, and detailed understanding of the phenomenon, supporting the paper's main thesis with both theoretical and practical evidence.

Findings

The analysis conducted in this paper has highlighted a series of significant findings regarding the impact of artificial intelligence (AI) on the circular economy[1][8]. The evidence emerging from the literature review and the IBM case study confirms that AI is not just a simple technological tool, but a powerful catalyst for the transition towards a more sustainable and regenerative economic model.

The main findings can be summarized as follows[1][8].

AI as a Driver for Optimization and Prediction: AI technologies, particularly Machine Learning and Deep Learning, have been identified as fundamental for optimizing processes along the entire value chain. Unlike traditional systems, which rely on static data, AI can analyze enormous volumes of data in real-time to predict demand, optimize logistical routes, and improve material management. This predictive capability translates into a significant reduction in waste and greater efficiency in resource use, aligning with the core principles of the circular economy. A concrete example is the optimization of product life cycles, which AI makes possible through constant monitoring and predictive maintenance, extending the useful life of goods and reducing the need for new production. This aspect is crucial for reducing dependence on new raw materials.

Practical Application in the Corporate Sector [1][4][7]: The IBM case study provided a concrete illustration of how these theoretical principles are applied in the corporate world. Collaborations with strategic partners such as Tommy Hilfiger and the Hera Group demonstrate that AI is used to overcome the practical challenges of sustainability, from material traceability to the intelligent recycling of electronic waste. These findings highlight that the integration of AI solutions not only improves environmental performance but also strengthens a company's competitiveness, reputation, and innovation, creating a strategic market advantage. IBM's approach shows that AI solutions can be scalable and adaptable to different industrial sectors and that investing in AI for sustainability is a forward-thinking business choice.

Synergy between Innovation and Sustainability: The findings demonstrate that AI can facilitate the implementation of new circular business models, such as "product-as-a-service" or reverse logistics, which have long been considered difficult to scale. This supports the thesis that technological innovation and environmental responsibility are not in conflict but can be closely interconnected to create shared value.

Challenges and Implications [2]: Despite the numerous benefits, the analysis also highlighted the challenges associated with adopting AI in a circular economy context. Issues such as the high energy consumption of artificial intelligence systems, the need for ethical regulations (like the EU's AI Act), and the management of data privacy remain crucial for ensuring responsible technological development and ethical implementation.

Discussion/Conclusion

This paper sought to answer the question of whether artificial intelligence can have an impact on the circular economy. The first chapter introduced artificial intelligence starting from its roots in the 1950s, when the scholar Alan Turing asked whether "can machines think?" [7]. At the time, there was not yet the knowledge we have today to scientifically and theoretically analyze this question, the answer to which, although seemingly obvious, can hide a more profound argument.

Thanks to the spread of technology, AI has become an almost everyday phenomenon, seen as a new "invention" of the 21st century, a setting for great innovations and giant leaps forward. This has led to people getting used to it, especially Generation Z[9]1, who, being the first digital natives, have seen the various phases of development and are no longer surprised.

Machines alone are unable to do anything without human intervention. However, once programmed, also thanks to machine learning which allows them automatic learning through certain algorithms inserted by humans, they are able to perform many functions that often surpass the human brain in speed, precision, and detail calculation. Humans, however, are fundamental, because thanks to their studies they are able to create ever more innovative discoveries and make them available to others, who can choose to draw inspiration from them to imitate or improve the technology, thus fueling the cycle of knowledge.

Even if one day machines will be able to think 100%, only time will tell; currently, there is always a need for the technical and intellectual support of scholars, because AIs often have errors. This technology has great potential and can be of help in many sectors, such as healthcare, which gained a lot of relevance after the COVID-19 pandemic. Some institutions showed severe shortcomings or difficulties in managing crises, and this triggered various movements for updating and training (particularly at Harvard) [3] to prepare healthcare management personnel to use AI in their work to make it more efficient. The fact that such an important university provides an ad hoc course demonstrates the potential, importance, and advantages that this technology can offer.

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Can artificial intelligence support companies in implementing sustainable innovation strategies? Evidence from agri-food companies

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Abstract

In the face of global challenges such as climate change, resource scarcity, and population growth, sustainable innovation has become a priority for the agri-food industry. In this context, Artificial Intelligence (AI) offers new opportunities to support the transition toward more sustainable and circular business models. This study proposes a framework that connects strategies, practices, and AI technologies to support decision-making processes. Through a systematic literature review, six groups of strategies and twenty-four AI-enabled practices were identified. A survey conducted among agri-food companies assessed the perceived relevance of these practices, with and without AI support, using the TOPSIS multi-criteria decision-making method.

Keywords: AI, Sustainability, SLR, TOPSIS, Innovation strategy assessment

Introduction

Innovation has long been a key driver of business competitiveness [1], but current global challenges, including climate change [2], the scarcity of natural resources [3], [4] and population growth [5] require a fundamental rethinking of the approaches adopted by companies. Although the agri-food industry is central to the global economy [6], it significantly contributes to environmental impact [2], calling for a shift toward more sustainable practices. In this context, Sustainable Innovation Strategies (SISs) play a strategic role by embedding sustainability into business models, balancing economic growth, environmental protection, and social equity in line with the Triple Bottom Line paradigm [7]. However, Small and Medium-sized Enterprises (SMEs) face barriers in adopting Sustainable Innovation Practices (SIP), due to costs, limited skills, and short-term vision [1]. Digital technologies, particularly AI and Big Data (BD), are emerging as key enablers of sustainability, though they raise ethical concerns related to data governance [8]. Despite growing interest in this field, the literature still lacks a systematic framework that connects AI-supported SISs with SIPs. This study aims to address this gap by proposing a framework designed to assist agri-food companies in identifying the most effective strategies and practices to support their sustainable transition.

The sustainable innovation in agri-food industry

Innovation is a strategic driver of economic growth, especially in an increasingly competitive and uncertain global context. In recent decades, the Schumpeterian concept of innovation has evolved toward sustainability, promoting solutions aimed at reducing environmental impact throughout the entire product life cycle. This approach is also known as eco-innovation [1]. The agri-food industry, particularly relevant in developing countries, is a complex value chain facing critical challenges related to food production, distribution, and consumption [6], [9]. Among these, climate change poses a growing threat, affecting crop yields and the spread of pests and diseases. At the same time, the sector is responsible for about one-third of global CO_2 emissions [2] and contributes to biodiversity loss [8], [9]. Demographic pressure, with a projected global population of 9.7 billion by 2050, is expected to increase food demand by 80% by 2100 [5]. This raises concerns about the system's capacity to ensure safe, accessible, and nutritious food [4], [10], exacerbated by rising food prices and public health implications [9]. To address these challenges, the 2030 Agenda promotes the transformation of agri-food systems through sustainable innovation [11]. Such innovation should occur across three dimensions: i) technical, through improved agricultural practices and waste reduction; ii) organizational, by fostering collaboration along the supply chain; and iii) systemic, by developing new products, technologies, and markets. This transition requires coordinated efforts by institutions, businesses, and farmers, supported by effective public policies [12].

The AI technologies in agri-food industry

The agri-food industry is undergoing a process of digital transformation, which is essential to address current challenges. Industry 4.0 technologies play a key role in making the supply chain more efficient and resilient. Tools such as BD, Internet of Things (IoT), Advanced Automation and Robotics (AA/AR), Simulation, and Additive Manufacturing (AM) enable: i) real-time monitoring of environmental and energy conditions; ii) analysis of large volumes of data to support decision-making; iii) automation of operations, reducing costs and time; iv) simulation of scenarios to optimize yield and resource use; v) innovation of processes through customized and sustainable solutions [6], [13]. AI represents an emerging frontier, with transformative potential for both agricultural and industrial practices [10]. It enables: i) intelligent crop monitoring; ii) weed detection; iii) efficient management of irrigation and fertilizers; iv) quality and food safety control; v) traceability; vi) optimization of production processes [14]. However, the adoption of AI also presents ethical and social challenges, including privacy protection, data security, high energy consumption, and the generation of electronic waste. Nevertheless, AI is emerging as a crucial catalyst for sustainable innovation in the sector.

Methods

The study methodology is structured in two phases: a qualitative and a qualitative-quantitative phase (Figure 1). To address the research questions (Figure 1), a Systematic Literature Review (SLR) was conducted, applying the PRISMA guidelines to define inclusion and exclusion criteria. Two queries (Figure 1) were formulated to select: i) a sample aimed at identifying emerging SIPs and SISs regardless of the sector; ii) a sample focused on AI-supported SIPs within the agri-food domain. Content analysis enabled the mapping of SIPs, SISs, and the role of AI, which were synthesized into the proposed framework (Figure 3). Additionally, a focus group identified the main decision-making criteria used by companies in selecting SIPs. The second phase involved administering a questionnaire to two agri-food SMEs and one multinational corporation, in order to assess the perceived relevance of SISs and SIPs under two different scenarios: with and without explicit reference to AI. Two structured questionnaires were used, differing in the presence of the AI component. The data were analyzed using the TOPSIS multi-criteria decision-making method, which ranks alternatives based on their distance from the ideal solution [15], resulting in two rankings of the most relevant SIPs (Figure 1).

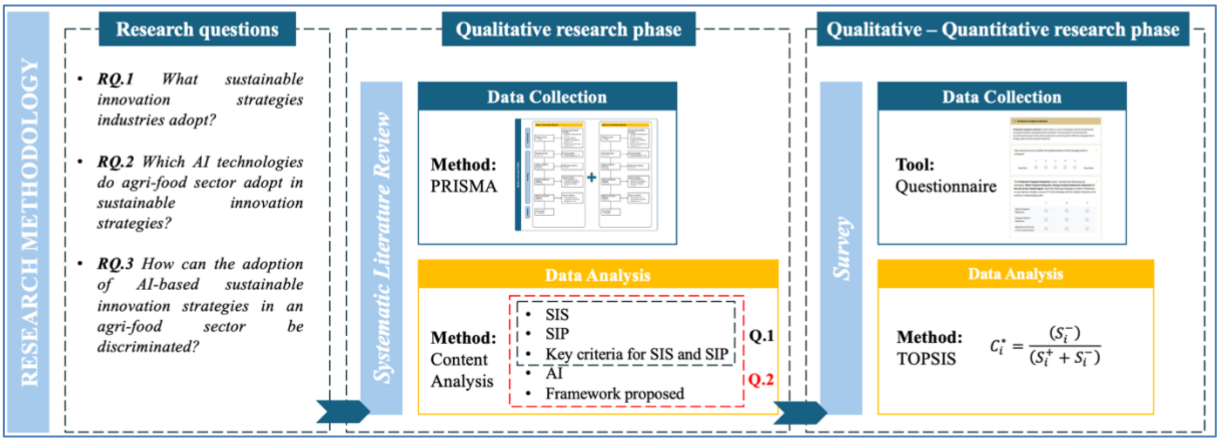

Figure 1_ Research methodology overview

Findings

The content analysis highlighted strategies adopted by companies across various sectors (agri-food, healthcare, education, energy, chemical, technology, and services) to integrate sustainability into their business models. Using an inductive approach, the results were organized into six first-level SIS clusters, divided into sixteen second-level clusters (Figure 2). The first cluster, Production Footprint Reduction, includes SIS aimed at reducing the environmental impact of companies' production activities. In particular, the analysis identified SIP focused on reducing the use of non-natural inputs (such as fertilizers) [8], as well as practices aimed at lowering the use of resources like water [1], energy [14], and CO_2 emissions [16]. The Adoption of Circular Approaches cluster includes SIP aimed at minimizing waste and maximizing resource reuse, thus extending the lifecycle of materials and products [1], [3]. No AI-based applications were identified within this cluster. The third cluster, Sustainable Enhancement of Territory, encompasses practices that promote responsible use of local resources to protect biodiversity and reduce environmental impact, alongside practices involving communities to strengthen rural economies and spread sustainable development models [2], [6]. The Sustainable Management cluster comprises practices aimed at promoting employee well-being, proactive governance on sustainability issues, and more efficient management to improve business performance from a sustainability perspective [16]. The Improvement of Food Quality and Safety cluster, mainly emerging from the agri-food industry, includes practices to ensure quality, hygiene, and traceability throughout the entire food supply chain [14]. Other practices focus on sustainable packaging [10]. The final cluster, Customer and Partner Relationship Care, gathers practices aimed at understanding and satisfying the needs of customers and other stakeholders [5], alongside environmental practices such as selecting sustainable suppliers to reduce the impact of the procurement phase. Considering exclusively the results related to the agri-food industry and supported using AI, the second-level SIS are reduced to nine clusters belonging to five of the six first-level clusters. (Figure 2).

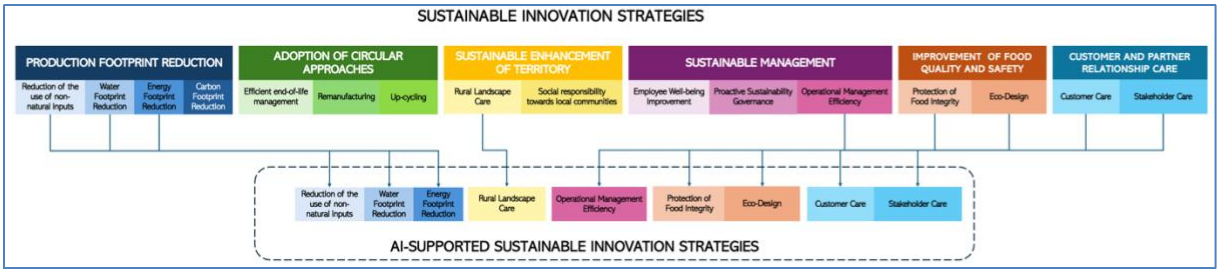

Figure 2_Presentation of SISs with a particular focus on AI-supported SISs in the agri-food industry

These findings enabled the development of a framework that connects SIS and SIP to AI and Industry 4.0 technologies, where applicable in support of AI (Figure 3). The framework serves as a decision-making tool, allowing companies to select the most suitable AI technologies based on the sustainability goals they aim to achieve or, conversely, to identify feasible practices starting from the available technologies.

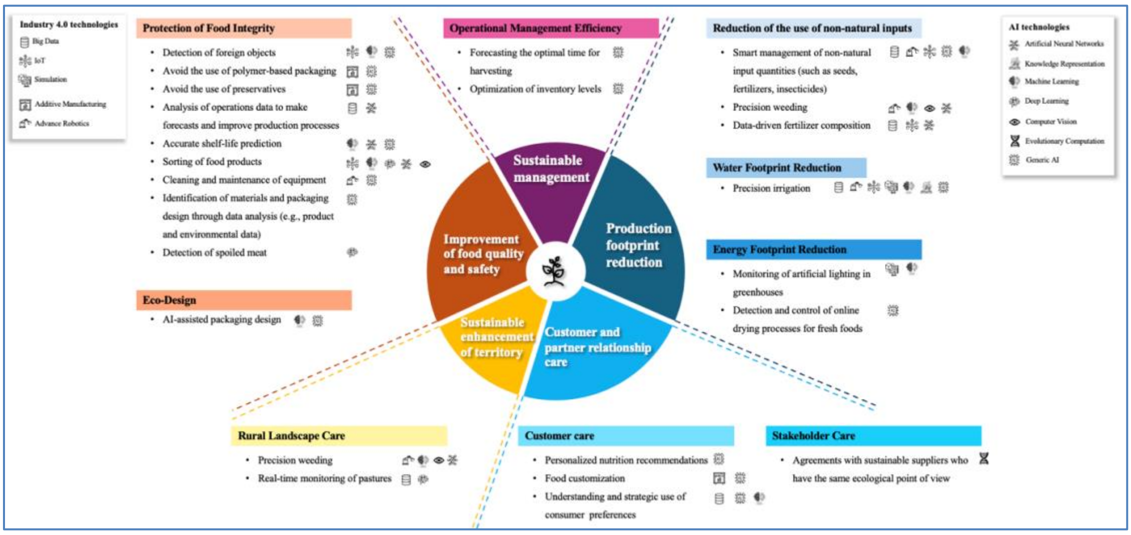

Figure 3_Proposed framework linking SISs and SIPs to related AI and Industry 4.0 technologies within agri-food industry

The literature review, validated through a focus group, led to the identification of seven criteria that influence companies' selection of practices. These include: cost of investment, perceived benefit, awareness, police compliance, ease of implementation, impact of innovation, and sense of legitimacy. These criteria were used to design a questionnaire administered to two agri-food SMEs and one multinational company. The practices were evaluated using a Likert scale in two scenarios: with and without explicit reference to AI. The analysis, conducted using the TOPSIS method, produced two rankings of the most relevant practices, revealing differences in the perception of sustainable practices depending on whether AI is involved. Specifically, with the introduction of AI, practices related to Customer Care, Operational Management Efficiency, and Reduction of Water Footprint gain more relevance. Conversely, in the absence of AI, practices focused on Protection of Food Integrity and Rural Landscape Care become central. Figure 4 presents the five most relevant practices.

SISs and SIPs ranking (No AI)	
Energy Footprint Reduction	Detection and control of online drying process for fresh foods
Rural Landscape Care	Precision weeding
Energy Footprint Reduction	Monitoring of artificial lighting in greenhouses
Rural Landscape Care	Real-time monitoring of pastures
Protection of Food Integrity	Detection of foreign objects

SISs and SIPs ranking (AI-based)	
Customer Care	Detection and control of online drying process for fresh foods
Customer Care	Precision weeding
Energy Footprint Reduction	Monitoring of artificial lighting in greenhouses
Water Footprint Reduction	Real-time monitoring of pastures
Operational Management Efficiency	Detection of foreign objects

Figure 4_The five most relevant sustainable practices perceived by companies, with and without AI support, identified using the TOPSIS method.

Discussions

Research confirms growing awareness of integrating sustainability into business strategies across industrial sectors. Many strategies rely more on traditional practices than technologies, suggesting that many sustainable actions are replicable and not necessarily tied to digital tools. Additionally, some sector-specific innovations appear to be adaptable to the agri-food context. AI, often integrated with BB, IoT, and ML, emerges as a key component in SIS. The results can be discussed on three levels of implementation: i) operational; ii) organizational; iii) supply chain. The comparison of the rankings obtained through the TOPSIS method highlights an increased relevance of practices related to operational efficiency and customer care, with the latter being particularly emphasized. Two out of three practices in this area rank among the most relevant, indicating a strong business interest in market needs. Conversely, practices aimed at reducing non-natural inputs lose importance with the introduction of AI, likely due to the high cost of enabling technologies such as sensors and drones.

Conclusions

The study proposes a framework that links AI to SIPs, addressing a gap in the literature on the integration between sustainability and digital technologies. Through a taxonomy structured into six first-level and fourteen second-level clusters, twenty-four AI-supported SIPs were identified. The TOPSIS analysis enabled their ranking based on perceived relevance, both with and without explicit reference to AI, in the agri-food context. The study presents several limitations: the absence of a standard taxonomy for AI technologies, a methodology not grounded in established theoretical models, limited literature coverage, sensitivity of the TOPSIS method to weighting, and a small sample of SMEs. Future developments include: defining a more detailed AI taxonomy, expanding the literature review, adopting structured theoretical approaches, integrating robust weighting methods (e.g., AHP), and extending the sample.

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METHODOLOGIES FOR SUSTAINABILITY AND CIRCULARITY ASSESSMENT

Comparative Life Cycle Assessment of stationary containers for MSW separate collection

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Abstract

Containers for the collection of municipal solid waste (MSW) play a critical role in the circular economy but are often overlooked in sustainability assessments. This study presents a comparative Life Cycle Assessment (LCA) of two types of 3200-liter stationary containers for separate waste collection: high-density polyethylene (HDPE) and steel. Using the ReCiPe 2016 (H) and IPCC 2021 GWP100 methods, the analysis highlights significantly lower environmental impacts for HDPE containers, especially in terms of human health damage. The obtained results emphasize the importance of recycled materials in reducing greenhouse gas emissions and resource depletion. Increasing the percentage of recycled HDPE further decreases the environmental footprint, reinforcing the benefits of circular economy practices. The study aims to guide stakeholders and policymakers in making informed decisions about sustainable materials and design strategies in waste management systems.

Keywords: Circular economy; Steel; HDPE; Life Cycle Assessment; Environmental sustainability; MSW

Introduction

In the context of municipal solid waste (MSW) management, stationary containers serve as a critical operational interface between citizens and the waste collection system. Despite their central role in the waste collection chain, their environmental impacts across the life cycle have received limited attention in the literature [1]. This study addresses this gap by conducting a comparative Life Cycle Assessment (LCA) of 3,200-liter stationary waste containers made of high-density polyethylene (HDPE) and of steel.

The main aim is to quantify and compare the environmental impacts of the two container types across their entire life cycle, from raw material extraction to end-of-life disposal, in accordance with the ISO 14040 [2] and 14044 standards [3]. The analysis incorporates multiple scenarios that consider varying shares of recycled materials and different transport distances. The ultimate goal is to identify more sustainable design choices and support environmentally informed decision-making in both product development and public policy, in alignment with circular economy principles.

Methods

The LCA [4] was conducted using SimaPro 9.6 software, based on data from scientific literature, manufacturers' websites and publicly available technical documentation. Additional datasets were retrieved from the Ecoinvent 3.8 database integrated in

SimaPro. The assessment followed the APOS (Allocation at the Point of Substitution) system model, provided by the Ecoinvent database. The data and modelling framework were implemented in SimaPro using a modular structure. To ensure a consistent comparison between the two materials, the functional unit selected for this study is a 3,200-liter waste container. Based on this modelling approach, several assumptions were necessary to ensure clarity and consistency in the analysis: the containers were modelled as mono-material products made entirely of HDPE or steel, while small components such as screws, hinges and wheels were excluded from the model as they represent less than 5% of the total weight. The system boundaries include raw material extraction, material processing, container manufacturing, transport to the point of use and end-of-life treatment, while the use and reuse phases were excluded from the scope. The model was built using a modular approach in SimaPro, where each life cycle phase, i.e. production/assembly, life cycle and end of life, was modelled as a separate subsystem to improve traceability and transparency. To capture the influence of logistics, the model included the transport of the final product, considering two realistic distance scenarios (100 km and 500 km) to assess the sensitivity of transport emissions, also taking into account differences in container weight. At the end of life, containers were assumed to be subjected to a combination of recycling (70%), landfill (15%) and incineration (15%). The end-of-life phase was modelled using material-specific recycling processes for HDPE and steel, incorporating both recycling efficiency and substitution potential. The avoided impact was calculated as the product of the recycling efficiency (A) and the substitution ratio (B), resulting in values of 0.90 for steel and 0.73 for HDPE (Table 1). Residual material not recovered through recycling was treated as waste and sent to landfill or incineration.

Table 1. Impacts avoided for steel and HDPE [adapter from 5]

Material to be recycled	*Recycling efficiency (A)*	*Substitution ratio (B)*	*Avoided impact (A*B)*
Steel	0,90	1,00	0,90
HDPE	0,90	0,81	0,73

Findings

The Life Cycle Impact Assessment (LCIA) phase plays a pivotal role in the LCA process, as it enables the quantification and interpretation of the potential environmental consequences associated with the life cycle of the waste containers under analysis [6], [7]. For this purpose, two internationally recognized methods were adopted: the global ReCiPe 2016 method and the “single-issue” IPCC 100y 2021 method. To establish a baseline, the initial comparison focuses on steel and HDPE containers produced with 50% recycled content, both subjected to a transportation distance of 500 km. This condition represents the baseline scenario (Scenario S0) of the study, as it reflects the current production practices commonly adopted by companies in the sector [8]. To explore the influence of key factors, the analysis was expanded to include alternative scenarios that varied transportation distance and the percentage of recycled content used in production. This approach allowed for the assessment of how these variables affect environmental performance and helped identify potential strategies for impact mitigation. To this end, three additional scenarios were modelled, combining variations in recycled content and transportation distance: 100% recycled content with a 500 km transport distance (Scenario S1), 50% recycled content with a 100 km transport distance (Scenario S2), and 100% recycled content with a 100 km transport distance (Scenario S3) (Table 2). The comparative analysis of these scenarios allows for the evaluation of the role of material circularity and logistical optimization in reducing environmental impacts, contributing to a more sustainable strategy for the production of urban waste containers.

Table 2. Different scenarios contemplated in the sensitivity analysis.

Different scenarios	*Recycled content used (%)*	*Transportation distance (km)*
Scenario 0	50	500
Scenario 1	100	500
Scenario 2	50	100
Scenario 3	100	100

Following the application of the IPCC 100y 2021 Single Issue [9] approach to Scenario 0 (Figure 1), in terms of the contribution to global warming from fossil fuel use (GWP100 - fossil), both containers show similar impacts, with the HDPE container recording a slightly lower value (408.88 kg CO2 eq) than the steel container (420.82 kg CO2 eq). This suggests that the environmental behaviour of the two materials, over their entire life cycle, in terms of global warming is substantially similar. The HDPE container has a slightly lower carbon footprint than its steel counterpart in terms of fossil resource use. However, it has higher impacts in relation to biogenic emissions and land use change.

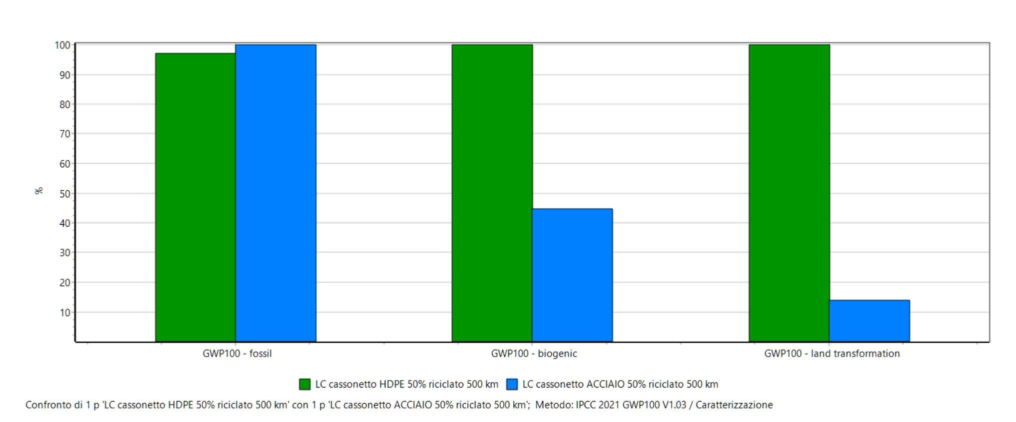

Figure 1_IPCC Method 2021 GWP100 / Characterization, comparison between HDPE and steel container with 50% recycled raw material transported 500 km.

Although the IPCC method provides insight into global warming impacts, it does not capture the full spectrum of environmental effects. For this reason, the assessment conducted with the ReCiPe 2016 Midpoint (H) method [10] offers a more comprehensive perspective, covering 18 different impact categories, of which climate change is just one. As illustrated in Figure 2, HDPE containers show lower impacts than steel containers in 14 out of the 18 categories analysed. These findings suggest that HDPE may be the more environmentally favourable option when considering aggregated damage categories and the overall single score

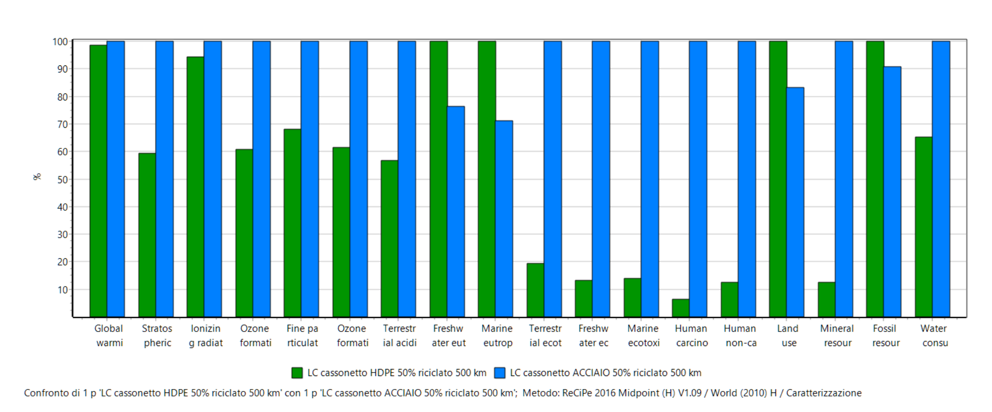

Figure 2_ReCiPe 2016 Midpoint (H) comparison between HDPE and steel containers with 50% recycled raw material transported 500 km.

Building upon the midpoint analysis, the endpoint method was applied to integrate results across damage categories. The overall comparison between all the scenarios analysed is presented in Figure 3, through the application of the ReCiPe 2016 Endpoint (H), which allows for a detailed and integrated view of the environmental impacts, allowing a comparative evaluation of the different container configurations, both as a function of the materials used and the transport distance.

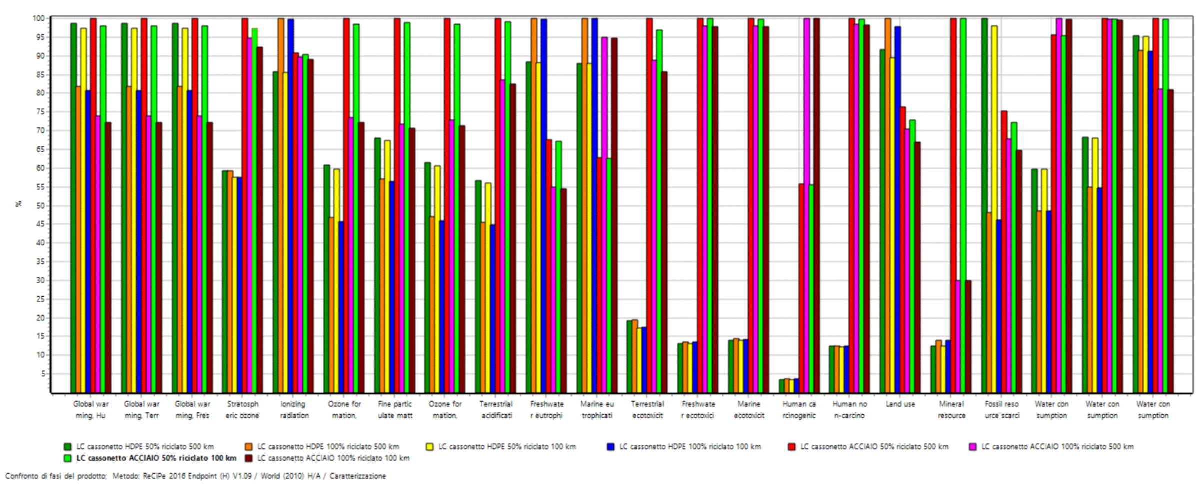

Figure 3_ReCiPe 2016 Endpoint (H)/Characterization, comparison between the four scenarios

The analysis highlights that the highest environmental impacts are found for the 100% recycled steel container transported for 500 km, which records the highest values in several categories, including Global warming - Human health (2.95E-04 DALY), Human carcinogenic toxicity (2.70E-03 DALY), Water consumption (1.09E-05 DALY) and Mineral resource scarcity (3.03 USD2013). On the contrary, the most sustainable configuration is the 100% recycled HDPE container transported for 100 km, with the lowest environmental impacts in most categories, such as Fine particulate matter formation (2.57E-04 DALY), Terrestrial acidification (1.62E-07 species.yr), Water consumption (5.27E-06 DALY) and Fossil resource scarcity (19.58 USD2013).

Discussion/Conclusions

The analysis conducted has shown that, although in certain scenarios the environmental performance of plastic and metal waste containers may appear similar, in most cases the HDPE container exhibits a lower environmental impact compared to the steel one. This advantage can be attributed to several factors, including the lower weight and the reduced energy consumption associated with the transformation processes. With regard to transportation, although the weight of steel is approximately 50% higher than that of plastic, its contribution to the overall environmental impacts was not found to be decisive in overturning the general conclusions of the study. An additional aspect analysed in this study concerns potential strategies for environmental improvement through the use of recycled materials. The sensitivity analysis showed that increasing the share of recycled content in the production of waste containers leads to a significant reduction in environmental impacts, highlighting the key role of recycling in enhancing product sustainability. This aspect becomes even more relevant in the context of a circular economy, where the valorisation of waste materials becomes an essential strategy for reducing the environmental footprint of the sector. In the light of these results, the importance of adopting a design approach aimed at reducing environmental impacts through a conscious selection of materials and manufacturing technologies clearly emerges. Future research could further explore this topic by assessing, for example, the influence of container lifespan and maintenance costs on overall sustainability, or by investigating new design solutions that integrate innovative materials and advanced technologies to reduce environmental impact. In this way, it will be possible to develop increasingly efficient and sustainable waste management strategies, in line with the objectives of ecological transition and carbon emission reduction.

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Recycling of critical raw materials in lithium-ion batteries: material flow analysis and economic analysis of the Italian industry

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Abstract

The circular economy promotes material reuse and recycling, driving major investments in Italy and Europe. The European Green Deal and Italy's National Recovery and Resilience Plan support this transition, particularly for critical raw materials (CRMs), essential yet economically risky for Europe. The European Commission's CRM Act, incorporated into Italy's legal framework, emphasizes CRM supply diversification. Lithium-ion batteries (LIBs), crucial for renewable energy and sustainable mobility, are a key focus. This study employs Material Flow Analysis (MFA) to evaluate CRM recycling potential in LIBs in Italy, analysing the economic feasibility of recycling processes. Different scenarios explore how CRM prices and energy costs affect profitability of the recycling of the vehicles registered in 2022 in Italy. Results suggest a primarily profitable recycling industry, with demand rising from 2030 to 2035. The study underscores the need for robust recycling infrastructure to ensure economic and environmental sustainability, enhancing CRM recovery in Italy.

Keywords: Critical raw materials (CRMs), Lithium-ion batteries (LIBs), Material flow analysis (MFA), economic analysis, Circular economy, scenario analysis

Introduction

The circular economy is a system planned for reusing and recycling materials in different production cycles, reducing wastes [1] and providing economic, environmental and social benefits [2]. Both Europe and single countries are investing on circular economy, drawing up plans to adopt it widely. On the one hand, Europe has issued two plans [3] [4] that outline concrete actions to foster sustainable economic growth based on the framework of the European Green Deal and Clear Industrial Deal [5] [6]. On the other hand, in 2022, Italy adopted its "National Strategy for the Circular Economy" through the National Recovery and Resilience Plan [7]. One of the sectors where circularity can have a significant role is the field of critical raw materials (CRMs), a list of materials that are considered critical for economic importance and supply risks, representing a weakness in Europe [8]. To manage properly these CRMs and the challenges related to them, the European Commission drafted the CRM Act, that contains metrics, clear targets and parameters for supply diversification, both from internal extraction and recycling [9]. The main guidelines provided by the CRM act were then adopted by Italy in the law decree of June 2024 [10]. Italy had already established its own permanent technical committee on critical raw materials in 2021 to ensure effective coordination and dialogue among stakeholders on the production and supply of these essential resources [11].

The EU, in order to reach the goals of decarbonisation and digitalisation, identified five strategical sectors [9]. One of the most important technologies among these sectors are the lithium-ion batteries (LIBs), thanks to their electrochemical performance and energy density. They are adopted in several solutions, such as electronic devices or in the automotive industry. Their combinations of materials generates categories, different in terms of costs, safety and performance. In the electronic devices, LCO batteries (lithium cobalt oxide) are the most diffused because of their characteristics [12], while in the automotive sector different solutions are adopted, such as lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC) or lithium nickel cobalt aluminium oxide (NCA). Nowadays, most of the activities related to the industry of LIBs is located in Asia, thus is necessary to identify potential recovery processes of CRMs, as their availability within Europe would enable the insourcing of LIBs components procurement.

The most adopted technologies to recycle LIBs are pyrometallurgy and hydrometallurgy. On the one hand, pyrometallurgy aims to recycle metallic compounds through high temperatures, purifying materials in physical and chemical transformations [13]. It is the most widely used and mature technology, thanks to high efficiency and low requirements in terms of equipment. However, the output is an alloy that requires subsequent treatments to recover purer metals and lithium [14]. In addition, it is energy intensive, so its economic convenience depends on the price of metals such as cobalt or copper. On the other hand, hydrometallurgy aims to extract metals through aqueous solutions. Compared to pyrometallurgy, this technology is less energy intensive and allows to recover higher percentages of metals, but it’s less adopted, may produce toxic gasses from inorganic acids [15] and generates large amounts of wastewater, that needs to be treated to not affect the environment significantly [14].

The literature has shown that material flow analysis (MFA) is a solid and widespread methodology for analysing recycling processes. It is a “systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material.” [16]. The studies available in the literature are primarily conducted in China and Europe, either from a continental perspective or with a single-country focus. The emphasis on Asia is linked to China’s key role in the development of the LIB industry [17], while the European interest aligns with the importance assigned to the green transition in political and industrial policy for the near future [9].

The objective of this study is to analyse the potential economic benefits of recycling CRMs contained in the LIBs of the car fleet in Italy, followed by an economic assessment of variable costs and revenues associated with the quantities of inputs and outputs involved. The economic analysis is further strengthened by different scenarios that modify key cost and revenue factors to assess the resilience of the results in response to variations in the main elements of the analysis.

Methodology

This study investigates the recycling potential of critical raw materials (CRMs) from lithium-ion batteries (LIBs) in Italy, combining a material flow analysis (MFA) and an economic assessment. The MFA ensures mass balance and represents material flows via Sankey diagrams. The main input—end-of-life LIBs—was estimated from the 49,536 electric vehicles registered in Italy in 2022, multiplied by an average battery mass of 576.38 kg, yielding a total input of 28,551 tons.

The recycling process integrates pyrometallurgical and hydrometallurgical techniques. LIBs are discharged for safety and residual energy recovery, then disassembled to enhance material purity. Pyrometallurgy produces an alloy (nickel, cobalt, copper) and slag (lithium, manganese, iron), while residual flue dust and off-gas are discarded. Both the alloy and slag are further treated via hydrometallurgy to extract compounds such as lithium carbonate, cobalt sulfate, and manganese sulfate. Process parameters were derived primarily from Blomeke et al. (2022) [18]. Wastewater data were estimated and distributed across outputs based on reasonable assumptions.

The economic analysis quantifies revenues and costs for each process step, using inflation-adjusted unit values. Revenue is based on market prices for recovered materials, while costs cover chemicals, energy, landfill fees, and wastewater treatment. Wastewater management costs were computed using Italian public utility fee structures [19], incorporating fixed and variable components based on pollutant concentrations and volumes.

Scenario analyses were performed by varying CRM prices (±10%, ±15%) and energy costs (±80%), assessing impacts on profitability. Scenarios were categorized as simple (one parameter) or complex (multiple parameters), especially combining energy and wastewater costs due to their influence on total expenditures.

Lastly, future recycling demand (2030–2035) was projected based on EV production forecasts and LIB life cycles, highlighting the strategic relevance of domestic CRM recovery in supporting Italy’s circular economy.

Findings

The Material Flow Analysis (MFA) revealed that the pyrometallurgical stage produces a high amount of slag, underlining the importance of subsequent hydrometallurgical treatment to enhance critical raw material (CRM) recovery. The hydrometallurgical processes are characterized by substantial consumption of sulfuric acid and sodium hydroxide, and the generation of approximately 100,000 tons of wastewater—four times the mass of spent batteries processed.

Recovery rates of CRMs from the original battery composition were as follows: lithium carbonate (63%), cobalt sulfate (93%), nickel sulfate (94%), manganese sulfate (93%), and aluminium (92%). These values align with the recovery performance reported by Blomeke et al. (2022), reflecting the model's methodological consistency.

The base economic model shows that wastewater treatment comprises over 70% of total costs due to the hydrometallurgical process, with sodium hydroxide being the most cost-intensive input. CRMs account for 75% of total revenues, underscoring their economic relevance. At full capacity (28,551 tons of LIBs), the estimated profit per battery is approximately €300, equating to 7% of revenue.

Compared to Bruno and Fiore (2023) [20], this study reports significantly higher revenues (€4,495/t vs. €1,242/t) and costs (€3,992/t vs. €230/t). Differences consist in considered materials and exclusion of wastewater costs in the prior study. Moreover, CRM prices—particularly for lithium—vary widely across the studies.

Scenario analysis confirms that CRM prices are the most influential parameter: a ±15% fluctuation results in a ±12.84% change in revenues. Variations in energy prices alone yield marginal effects (±1.28%) but become substantial (up to 12.2%) when wastewater costs are affected. The only unprofitable case occurs with a 15% drop in CRM prices. Excluding logically inconsistent extremes, the most beneficial results yield profits of €349.87–€335.38 per battery, while the worsts return €244.63–€239.12.

Lastly, future demand projections (2030–2035) suggest significant growth in material flows and revenues, rising from €130 million in 2030 to €1.4 billion in 2035, assuming stable inflation and increasing EV market penetration.

Discussion/Conclusion

This study assesses the feasibility of establishing a lithium-ion battery (LIB) recycling industry in Italy, focusing on the recovery of critical raw materials (CRMs). By integrating Material Flow Analysis (MFA) with economic modeling, the research provides quantitative insights into material availability and evaluates profitability across multiple scenarios. Results show that LIB recycling is generally economically viable. Unfavorable outcomes are mainly linked to unlikely drops in CRM prices or to unrealistic scenario assumptions. The projected increase in recycling demand between 2030 and 2035—aligned with the EU's zero-emission vehicle targets—emphasizes the urgency of strategic infrastructure planning.

The study advances existing research by quantifying CRM flows specific to Italy, an area often explored only at the European or global scale. The integration of MFA with economic analysis introduces a novel approach to identifying profitability drivers. On the managerial and policy level, the findings highlight Italy's potential to lead in the

European LIB recycling sector, contingent on appropriate policy support to enable investment and long-term returns.

However, the study acknowledges key limitations. The annual resolution of MFA constrains water use estimates, critical for hydrometallurgical processes. Incorporating construction and operational cost data, along with financial metrics like Net Present Value (NPV) would enhance economic assessment. Lastly, a Life Cycle Assessment (LCA) would complement the findings by quantifying environmental benefits, reinforcing the study's contribution to circular economy discourse.

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ECO-DESIGN

Mediterranean: Development of a Material Based on Opuntia and Algae According to the Principles of Material Driven Design.

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Abstract

Starting from the environmental criticalities affecting the Sicilian territory, the project focuses on issues such as the invasiveness of the prickly pear and the management of Posidonia and seaweed accumulations. From these challenges comes the idea of developing a bioplastic obtained from the territory's waste. The project proposes an innovative, tested and prototyped neo-material, exploring its possible uses both at the product level and as a sustainable alternative for the entire production chain. The work demonstrates how the observation of nature and its principles can guide towards sustainable and effective solutions, enhancing the landscape and land resources.

Keywords: Material Driven Design, Nature, Experience, Sicily, New Materials, Bioplastic

Introduction

The mass of human-made products has surpassed the global living biomass (both estimated at around 1.1 teratonnes in 2020 [1]), highlighting the need for a critical redefinition of our relationship with materials and the environment. Although the concept of sustainable design has evolved to encompass ecological, social, and economic aspects [2], its interpretation and application remain ambiguous and lack consensus [3]. Traditionally, sustainable design has focused on eco-friendly materials, energy optimization, and waste reduction, but today's challenges demand a paradigm shift: reinventing processes and production systems in harmony with their context, moving beyond mere impact minimization. In this context, the definition of "sustainable material" is often vague [4], referring to bio-based materials that are not necessarily biodegradable. It is essential to prioritize solutions that combine both attributes, integrating seamlessly into natural post-consumption cycles.

Environmental issues today are not limited to pollution or the accumulation of artificial waste but also include indirect effects of human-induced climatic and environmental transformations. Examples include the increasingly frequent and unmanageable accumulation of Posidonia and marine algae, exacerbated by intensifying storm surges, leading to high disposal costs and negative environmental impacts (loss of CO_2 absorption potential, emissions) [5]; or the invasive spread of Opuntia, which in certain areas of the Sicilian region threatens biodiversity and generates control costs [6][7].

Faced with these challenges, this thesis employs Material Driven Design (MDD) [8] to develop an innovative and sustainable neo-material [9]. The development process, documented from theory to practical experimentation based on material tinkering [10], includes the evaluation of mechanical properties through tensile and compression tests. Various applications and product concepts are explored, which, by incorporating the aesthetics of waste [11], promote conscious consumption and valorize overlooked resources. The research culminates in a reflection on sustainability and education in design, proposing scenarios such as the Mediterranean Kit (a DIY kit for creating the biomaterial) and models based on workshops or industrial collaborations. This work demonstrates how material-based design and responsible innovation can drive a paradigm shift toward a future where sustainable materials and circular economy practices are the norm.

Methods

The material development was carried out through a rigorous methodological approach guided by Material Driven Design (MDD), which positions the material as the starting point to stimulate design imagination and define objectives prior to product conception. For the development of the neo-material, the MDD phases were enriched and integrated with the principles of DIY Materials [10][12]. This approach enabled the designer to act directly as experimenter and producer, focusing on the creation of the material rather than its selection.

The experimentation began with material tinkering, defining a base compound consisting of agar, glycerin, and water—selected for their bioplastic compatibility and their capacity to act as a flexible and biodegradable polymer matrix. Through iterative experimental cycles, proportional variations of the ingredients and the addition of local resources were introduced to enhance the value of territorial raw materials and improve performance. Specifically: mucilage and fibers from Opuntia ficus-indica improved the elasticity, strength, and biodegradability of the biopolymer, while powders derived from marine algae and Posidonia oceanica (fibers and polysaccharides) increased structural strength.

This process led to the definition of two base formulations: A1 and A2, which were subjected to further evaluations regarding the behavior of the compounds in relation to thickness, additives, and drying/maturation techniques. During the technical characterization phase of the biomaterial, mechanical tests — specifically tensile and compression tests — were conducted. In parallel, a study was carried out for experiential characterization and monitoring of the biodegradation process.

Findings

The characterisation of the neo-material provided essential data on its mechanical properties and potential for innovative applications, evaluated through compression and tensile tests.

Compression Test

The compression test was performed using a Galdabini SUN 20 universal testing machine (maximum load: 200 kN). The test was conducted under displacement control at 3 mm/min on a total of 6 samples. Significant variability was observed in the maximum strength (Figure 1), with samples 2 and 4 showing the highest values (445.729 N and 447.235 N), highlighting a notable capacity for recovery and resilience, although with internal damage at the elastic limit.

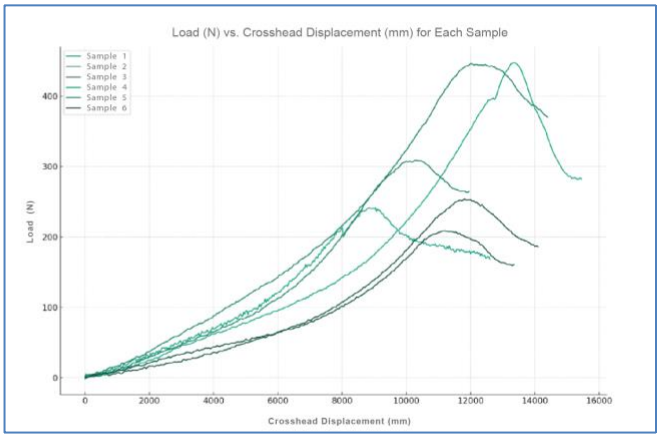

Figure 1_Load–displacement curves from the six tested samples.

Tensile Test

The tensile test was carried out with an MTS Insight 50 universal testing machine equipped with a 100 N load cell. The test was performed in force control mode, with a constant increment of 0.01 N/s, on a total of 28 samples (14 for formulation A1 and 14 for formulation A2). Results for Bioplastic Film A1 showed: average Peak Load of 11.124 N; average Peak Stress of 0.989 MPa; average Strain at Break of 48.365%; average Young's Modulus of 2.156 MPa. For Bioplastic Film A2, values recorded were: Peak Load 20.464 N, Peak Stress 1.102 MPa, Strain at Break 80.356%, and Young's Modulus 1.760 MPa (Figure 2).

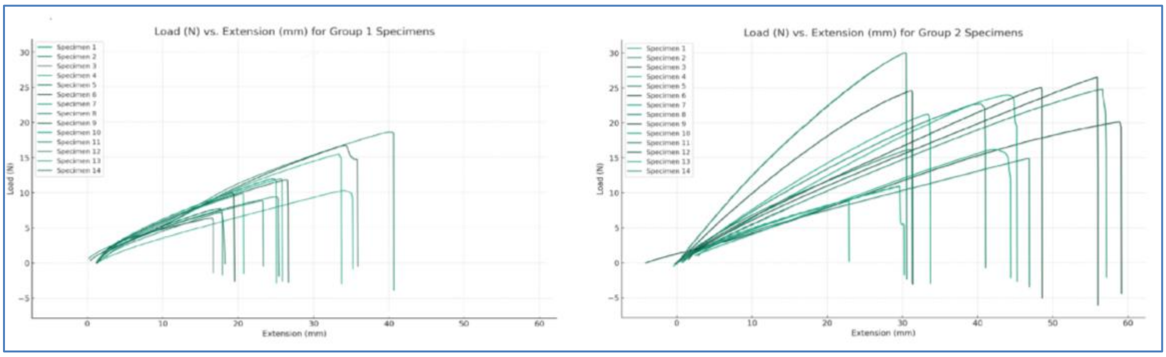

Figure 2_Load–extension curves for Group 1 (A1 - left) and Group 2 (A2 - right).

Comparing the two formulations, Group A2 demonstrated superior mechanical performance compared to Group A1, with an average increase of 83.95% in peak load and 66.14% in strain at break, indicating higher strength and elasticity.

Comparison Results

For result comparison, data from Hernández et al. [13], which investigates the tensile mechanical properties of agar- and glycerol-based biopolymer films, were analyzed.

Compared to the reference Agar/Glycerol, A1 and A2 showed competitive performance: the tensile strength of both exceeded the minimum value, and the elasticity of A2 was comparable to the maximum. A1 and A2 tend to be stiffer than Agar/Glycerol. A comparison with commercial plastics such as: Thermoplastic Styrenic Elastomers (TPS), Acrylonitrile Butadiene Styrene (ABS), Polypropylene (PP), revealed that A1 and A2 formulations exhibit comparable tensile properties, with a Young's modulus more similar to Agar/Glycerol, indicating greater flexibility but lower structural rigidity (Table 2).

Table 1. Tensile Performance: Bioplastic Formulations (A1, A2) and Select Commercial Polymers

Material	**Young's Modulus (GPa)**	**Tensile Strength (MPa)**	**Elongation at Break (%)**
LDPE	min 0.2 - max 0.4	min 10 - max 30	min 100 - max 900
ABS	min 2.1 - max 2.3	min 27 - max 55	min 3.5 - max 50
TPS Thermoplastic starch	min 1 - max 3	min 3- max 50	min 100- max 1000

PP	min 1.1 - max 1.7	min 25 - max 35	min 100 - max 600
Agar/Glycerol	min 0.00003 - max 0.013	min 0.11 - max 39.11	min 3.92 - max 115.80
A1	min 0.001 - max 0.002	min 0.425 - max 1.24	min 35.81 - max 77.03
A2	min 0.001 - max 0.003	min 0.586 - max 1.59	min 45.03 - max 115.77

Although they do not reach the maximum elongation at break values of some reference polymers, they demonstrate good ductility. These biomaterials prove ideal for niche applications requiring flexibility and moderate tensile strength.

Practical applications and application scenarios

The exploration of biomaterial applications has highlighted its distinctive characteristics for the development of innovative and sustainable concepts. Each product is designed to embody sustainable production principles (resource efficiency, waste minimisation, recyclability). Visual and tactile storytelling (texture, colour, shape) is essential to communicate the story of the material and promote conscious consumption, embracing the aesthetics of waste [11]. The realisation of tangible prototypes has demonstrated the versatility of the biomaterial in areas such as children's gadgets, packaging, fashion, furniture and lighting. Three main scenarios were outlined:

Scenario 1: Self-production with Kits, which promotes a paradigm shift in design and materiality, enabling users to create DIY biomaterials and encouraging ethical responsibility.

Scenario 2: The “Mediterranea” shop Concept, which emphasizes the material’s contextual sustainability, promoting conscious consumption and connection with local culture and resources.

Scenario 3: Industrialization for Collaborations, envisioning industrial biomaterial production, fostering synergies with designers and brands focused on sustainability to explore new frontiers in design.

These scenarios illustrate the diversification offered by the biomaterial, opening a wide niche market [14], addressing specific needs through sustainable products, and fostering responsible, personalized consumption. Within the self-production scenario, the Mediterranean Kit was developed: an experimental device allowing users to produce and test biomaterials based on Opuntia and algae, promoting access to sustainable production practices and serving as a personal laboratory for material design.

Conclusion

This biomaterial based on algae, marine plants and Opuntia ficus-indica, created to promote the sustainable use of local resources, has demonstrated promising mechanical properties, particularly the A2 formulation, which proves competitive with benchmark materials such as Agar/Glycerol and suitable for applications requiring flexibility and moderate tensile strength. This highlights the potential to transcend the ambivalence often associated with the term "sustainable," by advancing toward tangible solutions that are both bio-based and biodegradable, capable of integrating harmoniously into post-consumption natural cycles.

The value of this work goes beyond the mere creation of a new material. Indeed, it reflects on how the current transition to a circular economy, although promising, often clashes with implementation by economic actors who do not always prioritise the environment or society. The project, which embraces the aesthetics of waste and aims at a more conscious consumption, suggests an alternative path. The product concepts and three application scenarios - from self-production to craft workshop and industrial collaboration - illustrate a design model that not only minimises impacts, but regenerates production systems in harmony with the context.

Notably, the Mediterranean Kit emerges as a key catalyst for broader transformation in how we conceptualize and engage with materials and design. It embodies the principles of experiential learning and "do-it-yourself" practices, which are fundamental to design education. As emphasized by Mette Bak-Andersen [3], a deep understanding and hands-on engagement with materials is crucial for developing more sustainable and informed design practices. Similarly, the concept of "DIY Materials" underscores how do-it-yourself approaches can evolve into powerful educational tools for experimentation and innovation, fostering intuitive and practical material knowledge. The integration of DIY kits in education — following the example of initiatives such as Precious Plastic [15] for plastic recycling — represents an effective strategy to raise awareness and promote sustainable production practices.

This approach prepares future designers to meet the challenges of sustainability with innovative and conscious solutions, encouraging independence, creativity, critical thinking and collaboration [16]. The research emphasises how design deeply rooted in materiality and responsible innovation can indeed drive a paradigm shift, laying the foundations for a future in which sustainable materials and the circular economy are the norm, and the designer increasingly emerges as experimenter and producer.

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Improvising Architecture: a Jazz-Inspired Design Method for Reused Materials

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Abstract

This research theorizes and experimentally applies a design methodology based on improvisational processes drawn from musical theory and jazz practice. It explores the analogy between compositional and improvisational dynamics in music and design, through a phenomenological approach focused on the acts of designing and making. The study investigates the historical and theoretical affinities between music and architecture, emphasizing the roles of compositional structure and real-time creativity. It further examines the aesthetics of reuse, analyzing how jazz musicians employ diagrams and structural anchors to guide "ad libitum" performances. These methods are transposed into architectural and design practices using diagrammatic tools and flexible design strategies. A practical case study—the design and construction of the Holy See pavilion at the XVIII Venice Biennale using reuse materials—illustrates the application of these improvised methods in a real-world context.

Keywords: Music, Architecture, Design, Improvisation, Reuse, Jazz, Diagram

Introduction

In today's world, marked by environmental emergencies, resource scarcity, and growing social instability, architecture is increasingly required to respond with flexibility and creativity to complex and unpredictable situations [1]. The reuse of building materials in architectural and exhibition design offers a potential solution to both economic and environmental challenges [2], while also enriching the cultural significance of design, a counterbalance to the crisis of the contemporary urban form [3].

However, these reuse practices, still largely experimental, often suffer from a lack of systematization and indexing, which limits their practical application [4]. In this context, improvisation is no longer seen as an exception or a secondary design mode, but rather as a conscious and structured approach capable of generating effective solutions in uncertain conditions [5].

Inspired by the language of jazz music, particularly its ability to use flexible frameworks to guide improvisation, balancing compositional rigor with expressive freedom [6], this research aims to build a theoretical and practical bridge between music and architecture. The goal is to identify diagrammatic models and design tools that can translate the principles of musical improvisation into operative strategies for spatial design, with a specific focus on reuse, regeneration, and the transformation of existing structures.

The study begins with a historical and theoretical analysis of the relationships between music and architecture, two disciplines often considered closely related due to their shared compositional nature [7], their relationship with time, and their capacity to shape space [8]. Three main categories of practical analogies between the two disciplines have been identified: the ambivalent metaphorical link (use of a shared vocabulary), the analytical comparison of languages (presence of similar formal structures), and the reciprocal functional performance (active collaboration between the two disciplines) [9]. Through this theoretical framework, the work seeks to establish a design methodology that, while inspired by musical concepts, is grounded in a critical and operative process capable of addressing the needs of contemporary architecture.

Methods

This research focuses on describing the compositional processes common to both music and architecture, leading to the definition of the concept of improvisation in both disciplines. Specifically, the intention is to highlight how composition and improvisation are not opposites, but rather two poles that complement each other in the design process. Composition is seen as the act of crystallizing form, a process of selection, drawing, and representation [10]. Improvisation, on the other hand, although lacking canonical notation, is based on flexible frameworks that allow for controlled creative expression, as seen in the jazz genre [11].

This study adopts a comparative and interdisciplinary approach to explore the methodological affinities between musical compositional processes and architectural/design processes. The analysis is structured into three main directions: composition as writing, improvisation as a structured practice, and the reuse of materials as a creative strategy.

The first part explores the notion of composition as a foundational activity common to music, architecture and other arts. Following Luigi Ghirri's interpretation, composition is understood as the selection and definition of a representative framing scheme, through which we can add or subtract elements to the whole [12]. In architecture, Vittorio Gregotti identifies drawing as a crucial compositional tool, capable of anticipating design possibilities before their material realization [13]. In music, the role of notation is examined as an operational system for the transmission and realization of a work, including historical examples alternative to Western score notation such as Japanese, Greek, and European medieval writings [14].

The second theme focuses on considering improvisation not as opposed to composition but as its complementary pole. Two emblematic cases from the 20th century are analyzed: John Cage, the father of aleatoric music, removes the will of the composer and performer in favor of chance [15]; and John Coltrane, who, during the 1960s, helped formalize jazz improvisation as a theoretical language [16]. Jazz is examined in its historical and technical function, as a musical system that integrates improvisational practices and complex diagrammatic structures [17]. The importance of context and technical preparation is emphasized, showing how improvisation becomes a conscious design practice [18].

Finally, the third methodological focus is dedicated to the theme of reuse and reassembly, a key concept in both contemporary musical and architectural composition. The research analyzes the creative use of pre-existing materials, musical or architectural, as an intentional and culturally significant practice. In architecture, historical examples of creative reuse of materials, both distant and more recent, are highlighted. A prominent example is the Greco-Roman practice of "spolia", which involved using precious materials from previous buildings and sculptures to construct new works [19]. Another significant case concerns the reuse of debris from buildings destroyed during World War II, such as in Germany for the Notkirchen project by Otto Bartning, where the remains of damaged structures were used to create emergency churches [20].

In music, the reworking of pre-existing sonic materials, reintroduced into new semantic and formal structures, is a defining practice of jazz. This practice, like architectural design methods, draws particularly from the cultural heritage of American "songs", reassembling the content of the repertoire and infusing new energy and vitality into each interpretation [21].

The overall methodological approach aims to highlight operational analogies between disciplines that might seem distant, valuing non-canonical practices as tools for design and critical reflection.

Findings

The diagrammatic patterns used in jazz music to produce improvisational performances can also be a useful tool for design disciplines. They help to systematize a process that, by nature, avoids rigid compositional structures but still requires guidance, an 'outline' to find concrete expression.

Starting from the idea that both musical improvisation and design need a balance between freedom and structure, the study identifies three diagrammatic models: model, repertoire, and translation. Each of them is shown with case studies where they are used individually, but the research also suggests a more complete vision, where these models can be seen as three phases of one single process with the goal of creating a project based on improvisation.

The model is inspired by systems like the Coltrane Circle, which is a reference used by the musician to build an improvisation around a group of chords [22]. In a similar way, the architect Stan Allen used diagrammatic devices in his project for the ZAL area in Barcelona, where variations of the model come from ecological theories [23]. The repertoire shows the importance of reusing existing material, like in jazz with the songs found in “real books” [24], and also in architecture with the collage technique, used by architects like Meier or Miralles [25]. The translation model talks about how to transform diagrams directly into built forms, like Kazuyo Sejima from the SANAA studio does, creating architecture that keeps flexibility and connection to the context [26].

To support these theoretical models, the research includes a reportage about an internship experience at the architecture studio Albori from Milano, during the design and building of the Holy See Pavilion for the XVIII Mostra Internazionale di Architettura di Venezia, by Fondazione La Biennale di Venezia [27]. In this project, a flexible and adaptive method was used, especially useful when time and resources are limited, that is in reuse design. The project drawings show a real application of the improvisation method formerly described, specifically for a project by the architecture studio NOWA: Bosco Colto Campus in Caltagirone, Sicily (Figure 1).

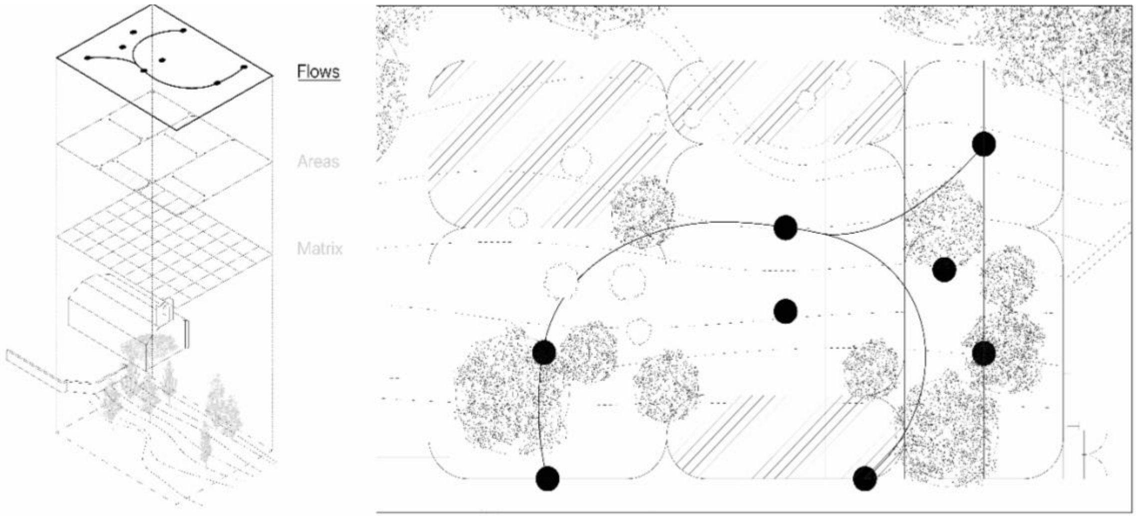

Figure 1_Diagram and drawing for the scenario "Laboratorio" designed for Bosco Colto Campus 2024.

The workshop is part of a cultural program to bring new life to the small town of Santo Pietro in Sicily [28]. The project, designed through the application of the three different diagrammatic schemes of "model", "repertoire" and "translation", proposes two different uses of the same space: one is a shared garden with universities and local associations; the other is a space for design and construction workshops for students and teachers during summertime. These examples show how diagram-based methods can be a good solution in complex and open design situations.

Discussion / Conclusion

The jazz method for reuse projects is proposed as an alternative model to the rigid, traditional compositional process, suited to manage the complexity and unpredictability of contemporary contexts. Its strength lies in the ability to enhance what already exists, accepting and integrating materials, ideas, and constraints as resources rather than obstacles.

However, applying this method still faces significant challenges, such as lack of regulations, high costs, and a shortage of specific technical training [29]. The practice of reuse, although sustainable and innovative, is often limited to isolated experiments. Therefore, a cultural and systemic change is needed to make these approaches structural and not just episodic.

Finally, the work highlights how a design methodology inspired by jazz can provide a useful, systemic, and creative framework, capable of adapting to the specifics of the place, time, and people involved in the project. It's a way of thinking about the project not just as a product, but as a performance, where rigor and freedom coexist.

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ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

CONSORZIO NAZIONALE IMBALLAGGI

Enhancing Product Design for Disassembly: A Study Utilizing Computer-Aided Design (CAD) Software and the DeSE Tool

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Abstract

The study analyzes the disassembly complexity, environmental footprint, and recyclability of a speed reducer gearbox and gas knob assembly by using Solid Edge CAD (Computer-Aided Design) software and the DeSE (Design for Sustainability and Environment) tool. The gearbox had high disassembly complexity (Icom) due to interference fits and the high number of fasteners, whereas the gas knob had reduced complexity, increasing maintainability. Redesign alternatives to the gearbox replaced interference fits with spline connections and eliminated 50% of the fasteners, decreasing disassembly complexity by 32%. Redesigning the gas knob minimally increased ease of disassembly. Environmental impact analysis showed that the gearbox's primary emissions stemmed from its energy-intensive use phase (99.96% of total CO_2 emissions based on an EoL strategy of incineration and a medium-voltage gearbox), while the gas knob's impact was initiated by material extraction and manufacturing. Both products had high recyclability values (Rcyc: 0.85 gearbox, 0.84 gas knob). The limitations included physical disassembly difficulty for the gearbox, requiring a hydraulic press, and challenges in mechanical component material identification. This study emphasizes the importance of Design for Disassembly (DfD) and Design for Recycling (DfR) in enhancing sustainability, fostering a culture of maintenance, and facilitating circular economy integration in mechanical design.

Keywords: Disassembly Complexity (Icom), Design for Disassembly (DfD), Design for Recycling (DfR), Design for Sustainability and Environment (DeSE), Circular Economy, Life Cycle Assessment (LCA)

Introduction

The engineering sector is increasingly in need of products that can be easily disassembled and recycled [4], [6]. Design for Disassembly (DfD) has become a key strategy for effective maintenance, repair, as well as end-of-life processing [2], [3]. Life Cycle Assessment (LCA), as an all-encompassing tool for environmental implication analysis across a complete product lifecycle, is valuable because it enables more sustainable decisions in product design, going beyond traditional performance indicators [5]. Sundin and Björkman emphasize that DfD is essential for developing products with ease of disassembly, recyclability, and reusability within production networks [3].

Maintenance inefficiency causes 30% of production downtimes, which costs U.S. operations an estimated $222 billion annually [1]. Complex mechanical systems like gearboxes require significant time and tools for repair, lowering productivity and increasing costs. Unplanned downtime, costing up to $260,000 per hour, affects 82% of companies, highlighting the need for DfD to enhance maintenance efficiency and reduce operational expenses [2].

Design decisions greatly affect environmental and economic outcomes since about 70% of lifecycle costs are determined at the design phase [10]. Excessive use of fasteners, mixed usage of materials, and complex part geometries impair disassembly and recycling activities. Improvements in disassembly efficiency can potentially boost recycling by up to 50%, thereby reducing waste and emissions [6]. Considering the gas knob's intricate multi-material design and the gearbox's interference fits combined with numerous fasteners, disassembly becomes very difficult.

Disassembly is a crucial design factor that impacts the ease of component recovery. Ijomah's research quantifies disassembly complexity based on geometry, materials, and joining methods, demonstrating that well-designed separation can enhance material recovery by 40–50% [3]. Moreover, effective DfD practices can extend product life by 40–60% and cut material waste by up to 35%, emphasising the importance of material homogeneity and retention [3].

Methods

The methodology is initiated with the study of the physical parts of the original products and the subsequent generation of virtual 3D models. The models are then studied using DeSE software to consider the important factors like disassembly complexity and scope for recyclability. This is done iteratively in a way that DfD principles are applied while quantitatively and qualitatively enhancing the design with improved environmental performance.

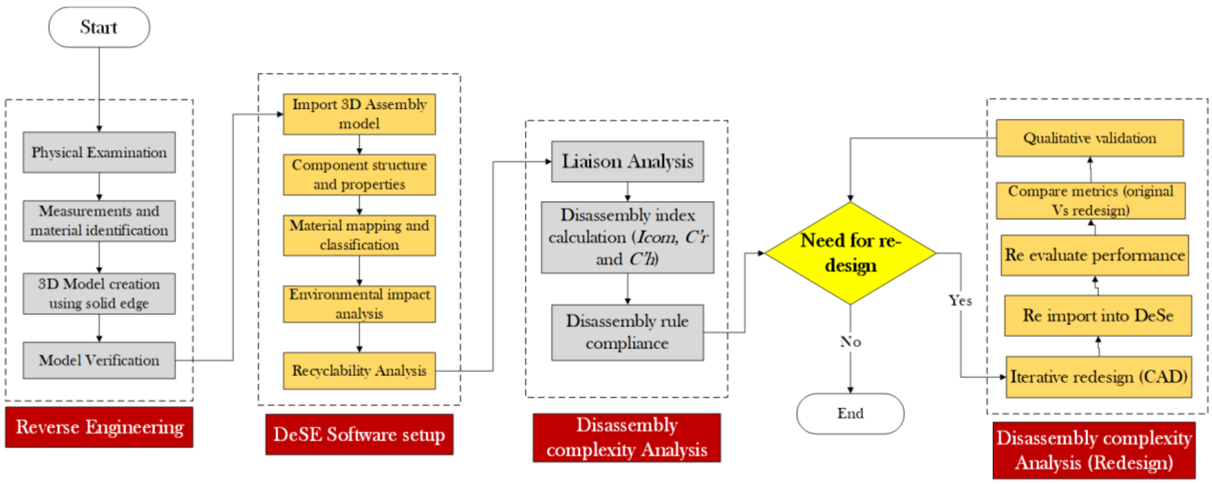

Figure 5_Methodology Framework for DfD

Findings

The overall **complexity index (*Icom*)** is calculated as: I'com= $\frac{C'h + Cr}{2}$ (Eq. 1),

Where: *C'h*– Handling complexity, and *C'r*– Removal complexity.

Measurable physical characteristics and operational elements make up the framework of the Handling Complexity (Ch) and Removal Complexity (Cr) indexes. Size, thickness, and mass make up Ch, which indicates how easy a part may be worked with, whereas fastener properties, tool needs, and unfastening effort make up Cr. To create a single index, each component is rated and then averaged or summed. By highlighting parts that could be difficult to handle or remove, this index helps designers evaluate disassembly difficulty and enhance serviceability [9].

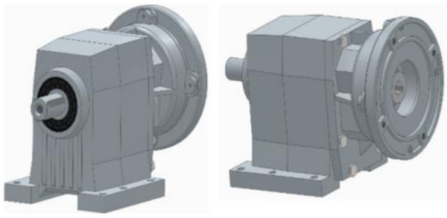

Figure 6_Gearbox Assembly modelling on Solid Edge 2024

Table 1. Gear Box Assembly Icom Results

Disassembly Index	Value
Total	**14.6**
Min	**0.28**
Max	**1.9**
Mean	**0.66**

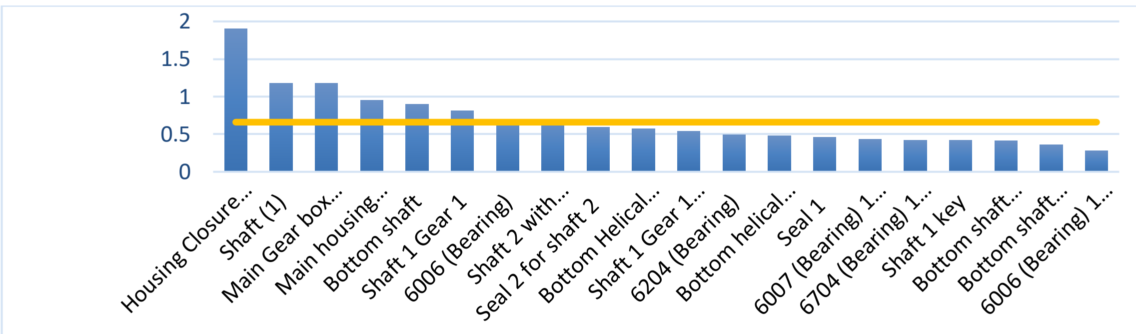

Figure 7_Gearbox Disassembly Index Calculation and Results

The initial gearbox design included a strong interference fit for connecting the shaft, gear, and key (Figure 4). It was redesigned as shown in Figure 5 by replacing the traditional key-shaft-gear assembly with a spline mechanism that links shaft and gear.

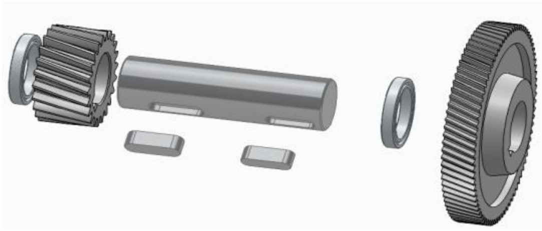

Figure 8_Disassembling the bottom Shaft Assembly

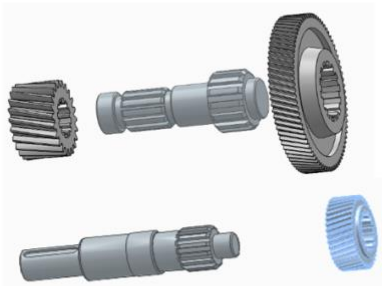

Figure 9_Redesigned Bottom shaft Assembly

For the main gearbox housing with a high complexity index, the original 10 hex bolts are reduced to 5 in the redesign, with a snap-fit mechanism added to simplify and speed up assembly and disassembly.

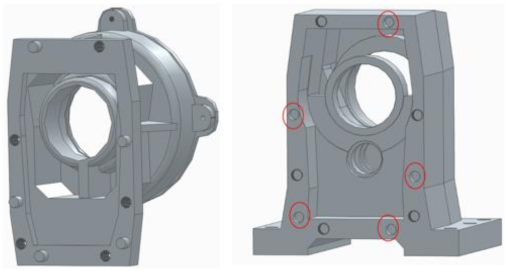

Figure 10_Redesigned gearbox housing

The gearbox redesign has improved disassembly efficiency, with the overall disassembly index (Icom) reduced to 9.88 and an average of 0.55, indicating easier disassembly. Peak Icom values dropped from 1.06 to a more balanced distribution. Key improvements include the housing with a hexagonal rib—now using fewer fasteners and a snap-fit—and the base housing, redesigned to reduce high-fit interference and lower disassembly effort.

Table 2. Redesigned Gear Box Assembly Icom Results

Disassembly Index	Value
Total	9.88
Min	0.37
Max	1.06
Mean	0.55

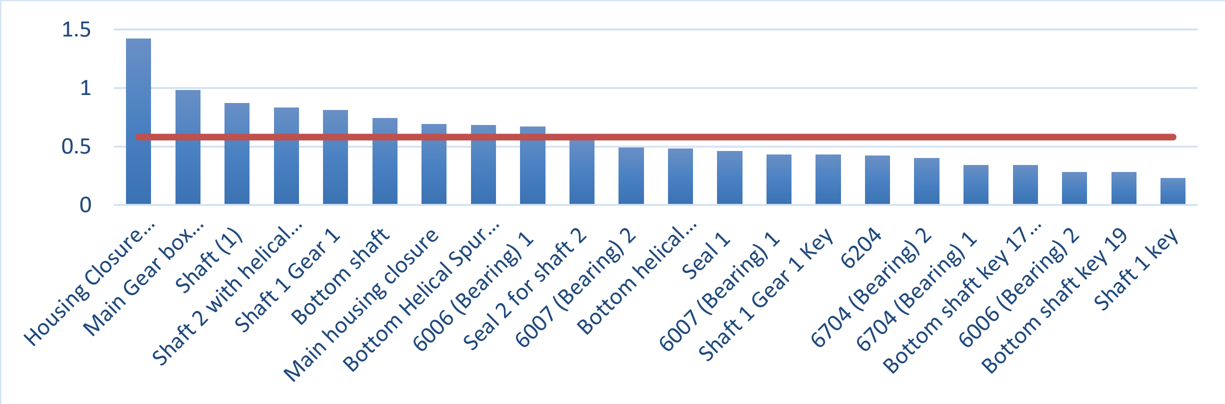

Figure 11_Disassembly index result for a redesigned gearbox assembly

Figure 12_Gas knob Assembly model

Table 2.Gas knob Assembly Icom Results

Disassembly Index	Value
Total	1.11
Min	0.21
Max	0.39
Mean	0.28

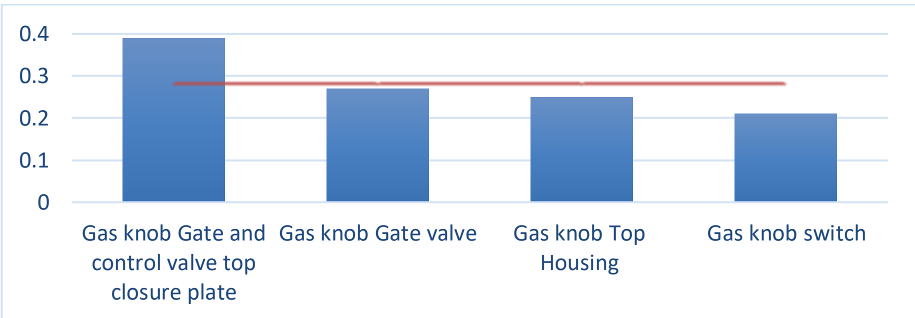

Figure 13_Gas Knob Disassembly Index Calculation and Results for Sub-assemblies

The original Gas Knob (Gate valve) assembly included four key parts joined by a hinge and nut mechanism. A slotted pin screw connected to the gate valve guide, with a brass pin linking it to the valve opener/closer. This setup enabled gate valve control via a cam mechanism.

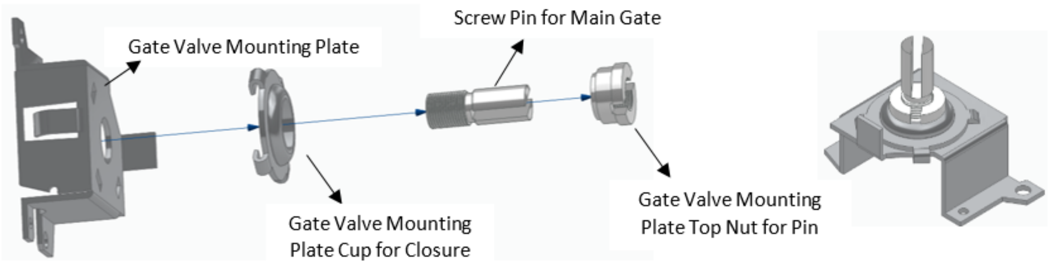

Figure 14_Gas Knob Gate and Control Valve Top Closure

The redesigned Gas Knob Gate simplifies the assembly by merging key components and reducing fasteners. A single brass pin now replaces two, serving both to regulate gas flow and secure the pin screw head, improving structural integrity and ease of assembly.

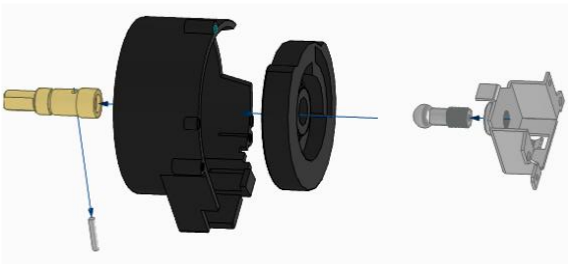

Figure 15.Redesigned Gate and Control Valve and its mounting Top Closure sub-assembly

The redesigned Gas Knob Gate and Control Valve Top Closure achieves a total disassembly index of 1.10 with a mean of 0.27, reflecting improved ease of disassembly. Key component Icom values are: Gate Valve (0.27), Switch (0.28), Top Closure Plate (0.29 – highest), and Top Housing (0.25). The redesign ensures balanced complexity, easier maintenance, and efficient 9assembly.

Table 3_Gas knob Assembly Icom Results

Disassembly Index	Value
Total	1.11
Min	0.21
Max	0.39
Mean	0.28

Conclusion

This study demonstrated the value of systematic digital disassembly analysis in improving the design of a speed reducer gearbox and gas knob assembly. Using DeSE software, key inefficiencies in disassembly—interference fits and an excessive number of fasteners—were identified and addressed through targeted redesign efforts, such as the introduction of spline connections and fastener minimization, resulting in a 32% decrease in the Disassembly Index of the gearbox. While the gas knob required fewer modifications, both products achieved a high degree of recyclability (Rcyc > 0.84) [5], [6].

The environmental impact analysis highlighted the energy-intensive use phase of the gearbox and material-related emissions from the gas knob, underscoring the importance of early-stage design decisions that support circular economy goals [10]. This research demonstrates an innovative and practical approach to integrating Design for Disassembly (DfD) and Design for Recycling (DfR) principles into real-world product development [8], improving maintainability, reducing environmental impact, and advancing sustainable engineering practices [4], [7].

Future work could explore automation-assisted disassembly simulations and broaden the scope to include economic feasibility and user-centered design factors for even more comprehensive product sustainability assessments.

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The Sustainable Big Bag: A Dry System for Reuse of Demolition Waste in Lightweight Vertical Enclosures

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Abstract

This study presents the "Sustainable Big Bag": a modular system made of recycled polypropylene and filled with demolition waste, designed for dry installation between the floor slabs of existing buildings. Its goal is to enhance the thermal performance of building envelopes through a sustainable and circular approach. Experimental tests in a climate chamber and thermal simulations revealed a significant increase in surface mass (from 85 to 245 kg/m²) and a reduction in periodic thermal transmittance (from 0.139 to 0.014 W/m²K). The results demonstrate that the system maintains high thermal performance while reducing time and costs related to material selection. It has proven to be a replicable, cost-effective, and efficient solution capable of increasing the thermal inertia of external walls, facilitating on-site management, and promoting circular construction strategies. It is particularly suitable for post-disaster or post-conflict scenarios, where rapid debris management and energy retrofitting are critical priorities.

Keywords: selective demolition, circular economy, material reuse, thermal inertia, big bag

Introduction

The construction sector is considered one of the main contributors to Europe's ecological footprint, generating over 30% of total waste [1], most of which comes from demolition and renovation activities. At the same time, climate change demands the rapid adaptation of the existing building stock to ensure indoor comfort and safety under increasingly extreme weather conditions, particularly during summer [2,4]. Highlighting the urgency and relevance of this issue, in August 2024, the European Union updated its protocol for the management of Construction & Demolition (C&D) waste, introducing new guidelines for "pre-demolition and pre-renovation audits" [3]. Numerous studies in the literature have explored various technical solutions to increase the thermal inertia of buildings, using either massive systems or phase change materials (PCMs). However, these solutions are often expensive, complex to implement, or environmentally unsustainable [5,6]. Within this complex framework, the present research goes beyond existing studies by proposing an innovative system that is fast to install, easily replicable, cost-effective, and sustainable. It enables the direct reuse of demolition waste, without the need for reprocessing, to enhance the thermal performance of existing buildings. The Sustainable Big Bag thus offers a concrete and sustainable response to the dual challenge of reducing environmental impact and improving the energy resilience of both existing buildings and the sites on which they stand.

Methods

The methodology adopted is structured into several integrated phases. First, a quantitative and qualitative analysis of Construction & Demolition (C&D) waste in Italy was conducted, identifying the most common inert fractions suitable for direct reuse [7]. Next, a selection of case studies representative of both the Italian and global building stock was carried out, focusing on buildings with reinforced concrete structures and load-bearing brick masonry. Given that the potential for reusing waste material fractions depends on the type of building, three design scenarios were analyzed, taking into account the increase in mass, airtightness, and light permeability: Case A, B, and C. Unlike Cases A and B, Case C (Figure 1) not only offers the greatest construction advantages (greater stability, ease of assembly and handling) but also involves placing the new envelope in the same position as the existing one [8].

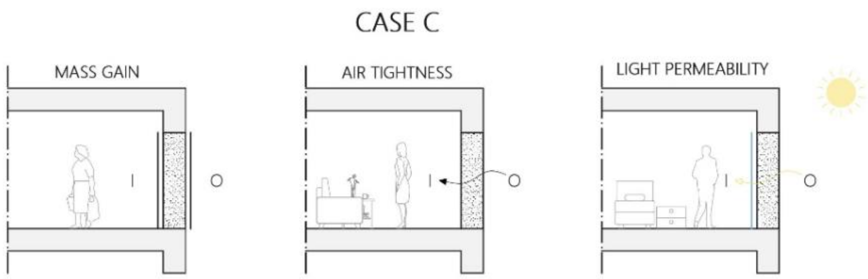


Figure 1_Increase in mass, air tightness, and light permeability of design scenario C.

Based on the results of these analyses, a modular, prefabricated component was designed using recycled polypropylene fabric, intended to be filled with inert materials from selective demolition. This component is inserted into the building envelope in a position similar to that of the original envelope, optimizing its mass [8]. Subsequently, the component underwent experimental testing using a controlled Hot Box (or climate chamber) setup, employing the Heat Flow Meter (HFM) method, at the "G. Parolini Lab" of the University of L'Aquila. The goal was to assess its thermal behavior as a function of the granulometry of the fill material and to verify that the integration of this component into the wall did not create thermal discontinuities that could negatively affect the envelope's overall thermal performance [8,9]. Finally, a dynamic analysis was carried out using the EdilClima 12.24.08 software [10] to experimentally determine the conductance (Λ) and transmittance (U) values of three wall samples made with "waste" materials. The objective was to evaluate the increase in surface mass and the periodic thermal transmittance of perimeter walls following the addition of the Sustainable Big Bag.

Findings

The Sustainable Big Bag is a polypropylene sack designed to be anchored to the existing reinforced concrete beam and filled with aggregates obtained from selective demolition carried out either on the same construction site or nearby locations (Figure 2). The bag has a height of 2.4 meters, corresponding to the standard floor-to-floor height in Italian buildings, and a square cross-section of 18 cm per side. These dimensions can be customized according to the specific requirements of the building. Each bag is equipped with 8 loop straps—4 at the top and 4 at the bottom—that allow for secure anchoring to the floors of existing structures. Once filled, the bag is installed vertically along the external vertical enclosures of the building. The stability of the system is ensured by the tensile strength of the polypropylene and the compacted fill material, which guarantees an even weight distribution and a secure anchorage to the existing structure. Polypropylene proves to be an advantageous solution both technically and environmentally: it is highly resistant to tearing and cutting, making it suitable for containing demolition materials, which often have irregular shapes and sharp edges. Additionally, it has a low density (0.9 g/cm³), is fully recyclable (plastic code 5), and its woven fibers allow for reuse across multiple operational cycles [11]. Although not biodegradable, responsible management can significantly reduce its environmental impact. Therefore, it offers a valid compromise between high functional performance and sustainability criteria. The service life of the bag can be influenced by various environmental factors, such as exposure to extreme temperatures, humidity, freeze-thaw cycles, and direct sunlight. While the bag can be manufactured in a controlled and protected environment, during on-site use, it can be placed at ground level or the base of the building, depending on the specific needs of the intervention. To further improve resistance to weathering and prevent premature aging, stabilizing additives can be incorporated during the polymer production process [8].

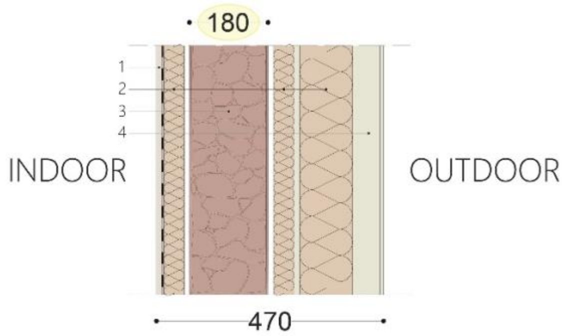
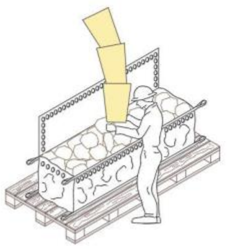
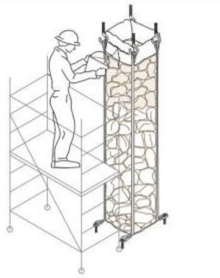


Figure 2_Internal finishing layer, 2 - Generic insulating layer, 3 - Big Bag, 4 - External finishing layer.

The design and execution phases are interconnected and mutually influence each other: principles of environmental, economic, and social sustainability are established from the earliest stages of the project's conception and guide all subsequent decisions on site, calibrated according to the characteristics of the existing building and the quantity and quality of rubble generated by selective demolition. Two operational modes can be distinguished: the ground-level site and the floor-level site. Both involve two strategies for filling and handling materials, to be adopted depending on the context and specific needs (Figure 3). In the first case, the Big Bags can be managed in two ways. In the first strategy, the bags are placed horizontally and filled using the rubble chute already available on site, which directs the material directly inside. In the second strategy, the bags are positioned vertically and held in place by steel frames; filling is carried out by an operator using a wheel loader to scoop and place the aggregates inside the bags. In both cases, once filled, the bags are moved by a forklift to the loading area and then lifted with a crane to the floor where they will be used. However, this type of site is less sustainable compared to the alternative, as it requires greater use of mechanical equipment both for filling operations and for vertical movement, leading to increased time and operational costs. In the second case, which also consists of two operational strategies, the process is more efficient. After selective demolition, the aggregates are temporarily stacked on the same floor where they will be reused and then introduced into the Big Bags through sorting. The first strategy involves positioning the bags vertically and anchoring them to a reinforced concrete beam using special hook fasteners; an operator fills the bags from above using a scaffold tower. The second strategy involves placing the Big Bags horizontally on the floor and supporting them with a hoist holding the straps, which facilitates filling and reduces the number of operators needed. Afterwards, the bag is rotated using the hoist and fixed to the concrete beam. In the first case, no additional handling is necessary because the bag's initial position coincides with its final position of use; in the second case, the only extra operation is the rotation. Overall, setting up the Big Bags on the floor shows better environmental and economic performance compared to the ground-level solution: it eliminates the need for lifting equipment for vertical transport, reduces loading/unloading cycles, working times, and costs. For these reasons, it is considered the preferred strategy for a low-impact, high-efficiency construction site.

GROUND-LEVEL CONSTRUCTION SITE	ON FLOOR CONSTRUCTION SITE
STRATEGY 1	STRATEGY 1
◦ STEP 1. Demolition and material selection. ◦ STEP 2. Rubble conveyor used to pour aggregates into the big bags. ◦ STEP 3. Vertical positioning of the bags supported by a steel frame. ◦ STEP 4. Transport of filled bags using a forklift to the lifting point. ◦ STEP 5. Lifting of the bags to the target floor using a crane. 	◦ STEP 1. Selective demolition of materials. ◦ STEP 2. Temporary storage of aggregates directly on the floor. ◦ STEP 3. Vertical positioning of the big bag, anchored to a reinforced concrete beam using special hooks. ◦ STEP 4. Gradual filling in layers with the help of an operator on a mobile scaffold. ◦ STEP 5. The big bag remains in its final position (no need for relocation). 

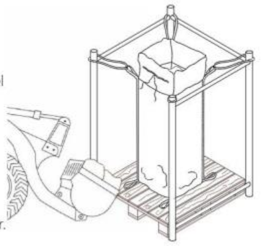
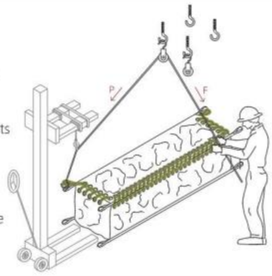
GROUND-LEVEL CONSTRUCTION SITE	ON FLOOR CONSTRUCTION SITE
STRATEGY 2	STRATEGY 2
◦ STEP 1. Demolition and material selection. ◦ STEP 2. The wheel loader pours material into the vertically positioned bags supported by a steel frame. ◦ STEP 3. Transport of the filled bags with a forklift. ◦ STEP 4. Lifting with a crane to the floor under intervention. ◦ STEP 5. Final positioning of the bag on the target floor. 	◦ STEP 1. Selective demolition of materials. ◦ STEP 2. Horizontal positioning of the big bag on the floor. ◦ STEP 3. Filling with the help of a winch (which supports the bag's straps). ◦ STEP 4. Bag is overturned using the winch. ◦ STEP 5. Anchoring the bag to the reinforced concrete beam (fewer operators needed, higher efficiency). 

Figure 3_The operational modes: the ground-level site and the floor-level site, and their respective strategies.

Three samples with different filling granulometries were created. Specifically, Sample 1 consisted of demolition rubble ranging in size from 2 cm to 30 cm mixed with sand, Sample 2 contained rubble sized from 2 cm to 30 cm, and Sample 3 included rubble sized from 10 cm to 30 cm. These samples were tested in a climatic chamber according to ISO 9869 [9]. The three samples were rigid cardboard containers measuring 25 cm in length, 25 cm in height, and 15 cm in thickness, placed inside the climatic chamber. A detailed description of the chamber is available in [12,13]. Although the theoretical approach and simulation aimed to use the flexible polypropylene bag system as the enclosure, it was decided not to place the bags inside the hot chamber, as this would have made the experiment incompatible with the chamber's size. This choice was deemed valid because the bag's material and thickness contribute negligibly to the thermal resistance of the analyzed sample [8]. Experiments were conducted maintaining the hot chamber temperature at 45 °C, while the external environment, the laboratory, was kept at 28 °C. According to ISO 9869 [14], to ensure reliable heat flow measurements, a temperature gradient between 15 °C and 20 °C must be established between the two sample surfaces. Data collection was performed using a datalogger with a 10-minute sampling frequency, over a total duration of 72 hours, as required by the standard. The results showed that variations in granulometry did not significantly affect the thermal performance of the system, confirming its effectiveness even under real construction site conditions where material selection is often limited, thus reducing time and costs.

The tests indicated a thermal transmittance between 1.58 and 1.96 W/m²K and a thermal conductance between 2.16 and 2.94 W/m²K. Software analysis compared a conventional lightweight vertical enclosure with one enhanced by the Big Bag to assess the thermal capacity benefits of the designed component (Figure 4). The conventional enclosure had an insufficient surface mass (85 kg/m²), whereas the enhanced one exceeded the minimum value required by Italian regulations (245 kg/m²) [10,15]. Additionally, the periodic thermal transmittance was reduced from 0.139 to 0.014 W/m²K, demonstrating a significant improvement in thermal capacity [16].

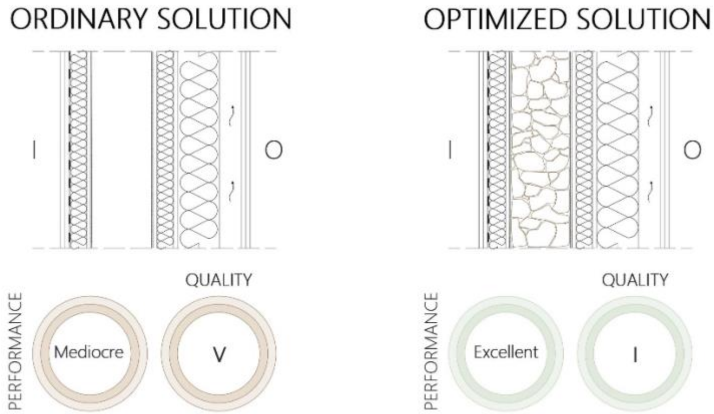


Figure 4_Thermal comparison between the vertical enclosure without the Big Bag and the vertical enclosure with the Big Bag.

Furthermore, according to the UNI EN ISO 13786 standard [16], the conventional lightweight vertical enclosure exhibits mediocre thermal performance, falling into class V, which corresponds to the least efficient performance category. In contrast, the vertical enclosure enhanced with the Big Bag—representing the improved solution—achieves excellent performance levels, placing it in class I, the highest-performing category according to the regulatory classification. The quantitative analysis of transmittance and conductance values made it possible to define the granulometry of the bag, which can contain various types of aggregates depending on the demolition materials, thus avoiding additional time for selecting the filling material. It also demonstrated that, despite being a dry system, increasing the mass of the wall assembly can produce an element that enhances its thermal capacity, benefiting the thermal inertia of the wall and energy savings for both summer and winter climate control [8].

Discussion/Conclusion

The effectiveness of the Sustainable Big Bag is attributable to its ability to increase the thermal inertia of perimeter walls without introducing additional production processes or new materials. This approach not only enables intelligent reuse of demolition materials but also simplifies construction site activities, reducing time, costs, and risks [8,17]. The system is particularly suitable for interventions in large areas affected by natural disasters such as earthquakes and floods, or even conflicts and destruction caused by war events, where rapid debris management and energy-efficient reconstruction are crucial [18]. Moreover, its use supports compliance with the DNSH (Do No Significant Harm) criteria to ensure that no significant environmental harm is caused, and with the Cradle to Cradle (C2C) principles, helping to promote sustainable circular construction models through regenerative design [3,19]. The Sustainable Big Bag represents a practical solution for the energy retrofit of existing buildings. By enabling onsite removal, classification, and direct reuse of demolition materials, it increases the thermal capacity of the building envelope through a dry, rapid, and low-impact approach. Experimental results and various simulations confirm the validity of the theoretical and design proposal, paving the way for future developments that may include structural verification of the elements and integration with BIM platforms for material traceability and life cycle management (LCA).

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VALUE CHAIN

The role of Circular Economy in the waste management sector: a focus on paper supply chain

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Abstract

The Circular Economy is a new model of production and consumption, in which today's goods become tomorrow's resources. In the Circular Economy, the concept of end-of-life is replaced with that of regeneration, aiming to create a production model that contrasts with the traditional linear economy. There is no single universally accepted definition of Circular Economy; according to the Ellen MacArthur Foundation, "the Circular Economy is a system where materials never become waste" [1]. So, Circular Economy is a type of economy designed to regenerate itself. Among the five fundamental pillars of the Circular Economy, material recovery involves promoting the replacement of virgin raw materials with secondary raw materials that can be reintroduced into the economic system. This Master Thesis suggests how the Circular Economy model can be applied, specifically to paper and cardboard waste sector, even within a small company, and the economic and environmental benefits that can be achieved.

Keywords: Circular Economy, material recovery, secondary raw materials, paper and cardboard waste

Introduction

Waste is the most evident proof that our economy is not circular, but linear. To transition from a linear economy model based on take-make-dispose to a Circular Economy model based on cradle-to-cradle principles, waste must shift its role, from being discarded to becoming a valuable resource. In fact, Circular Economy presupposes the absence of waste. A key element in this transition is the D.Lgs. 22/09/2020 n. 188 (Italian law) "End-of-Waste", which defines when a material ceases to be considered waste. Specifically, this refers to the process that enables waste to regain a beneficial role as a product. The criteria for "End-of-Waste" are regulated by Article 6 of Directive 2008/98/EC and transposed into Italian law by Article 184-ter of D.Lgs. 03/04/2006 n. 152, which states that "a waste ceases to be such when it has undergone a recovery operation." For a waste no longer to be classified as waste, it must fulfill specific criteria:

the substance or object is intended to be used for specific purposes; that is, it must be a product usable in known application areas to perform defined and recognized functions;

there is a market or demand for that substance or object, meaning the product will not be disposed of but it will be considered useful by others;

the substance or object owns technical requirements for the specific purposes and complies with the existing laws and standards applicable to products. Therefore, the output must have predetermined characteristics (technical requirements), it must be capable of ensuring the required performance in real conditions of use or consumption (specific purposes) and it must comply with both applicable mandatory legislation (regulations) and technical standards relevant to that type of good (standards);

the use of the substance or object will not have a negative overall impact on the environment or human health.

If all these conditions are met simultaneously, waste ceases to be such and it can be reused and reintroduced into the production cycle. From that moment on, it will refer to it as a raw material.

Figure 1_The structure and functioning of the Italian paper supply chain

Regarding paper and cardboard, D.Lgs. 188/2020 sets the rules for the cessation of waste status, stating that "upon completion of recovery operations carried out exclusively in compliance with the UNI EN 643 standard, paper and cardboard waste shall cease to be classified as waste and shall be considered as recovered paper and cardboard". [2] The paper supply chain has historically been a pillar of the Italian Circular Economy. Its structure is closed-loop, thanks to the fact that the material, once becoming waste, can be collected and recycled to be reused in the manufacture of finished products. The paper cycle is structured as follows:

-raw material: the amount of wood needed to start the production process, involving

-plantations and pulp manufacturing activities;

-paper mill: production of paper products;

-converter: creation of the requested products;

-user and/or customer: the phase of using the paper product;

-waste management company in the domestic and/or industrial channel: the phase of collecting used product, which can be carried out through either the public or industrial channel;

-recycling companies: mechanical recycling of paper and cardboard to produce waste paper to resale, with generation of non-recyclable residues that become waste;

-paper from recycling: at the end of the process, paper becomes raw material (End of Waste) under D.Lgs. 188/2020 and it can be used again.

In 2023, the waste paper sector strengthened its position within Italian Circular Economy, with a 5% increase in production and an overall recycling rate of 92.1%, a jump of over 16 percentage points from 75,7% in 2022. So far it exceeds the 85% target set by the European Union for 2030. A total of 6,9 million tons of waste paper were produced.

Methods

F.lli Baldini s.r.l. is a small company located in Assisi that operates in the collection, recovery, and disposal of waste. Within the paper supply chain, F.lli Baldini s.r.l. plays the role of a waste management company. All waste delivered to the company is accompanied by a Waste Transfer Note (WTN). This document outlines the transfer of waste from one location to another, ensuring a clear audit trail from production to disposal. Paper and cardboard waste are identified with the following European Waste Catalogue (EWC) codes:

15.01.01: cardboard packaging

15.01.05: composite food and drink cartons

15.01.06: mixed packaging

19.12.01: paper

20.01.01: paper

Paper and cardboard waste dumped at the F.lli Baldini s.r.l. company undergoes a sorting process, which can be either manual or mechanical. Manual sorting is carried out by workers who separate the various waste types by hand, dividing them into different

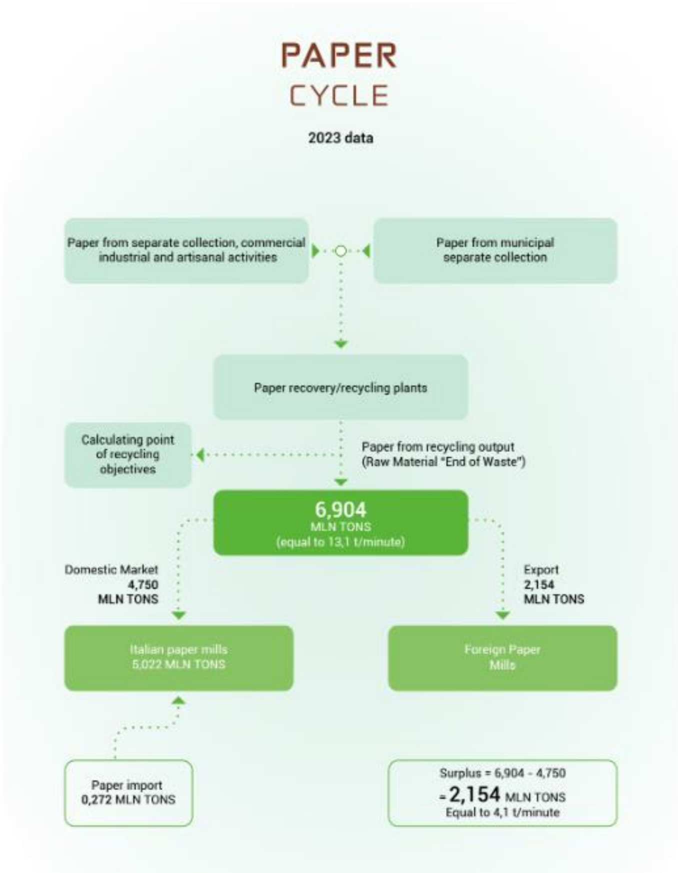

Figure 2_Summary data in the paper industries in 2023 [3]

categories to enable material recovery. Mechanical sorting, on the other hand, is done using equipment and machinery. The goal and purpose of the sorting process is recovery. From a Circular Economy perspective, waste sorting is a fundamental operation. The "End-of-Waste" raw materials obtained from the process are then sold to recycling companies.

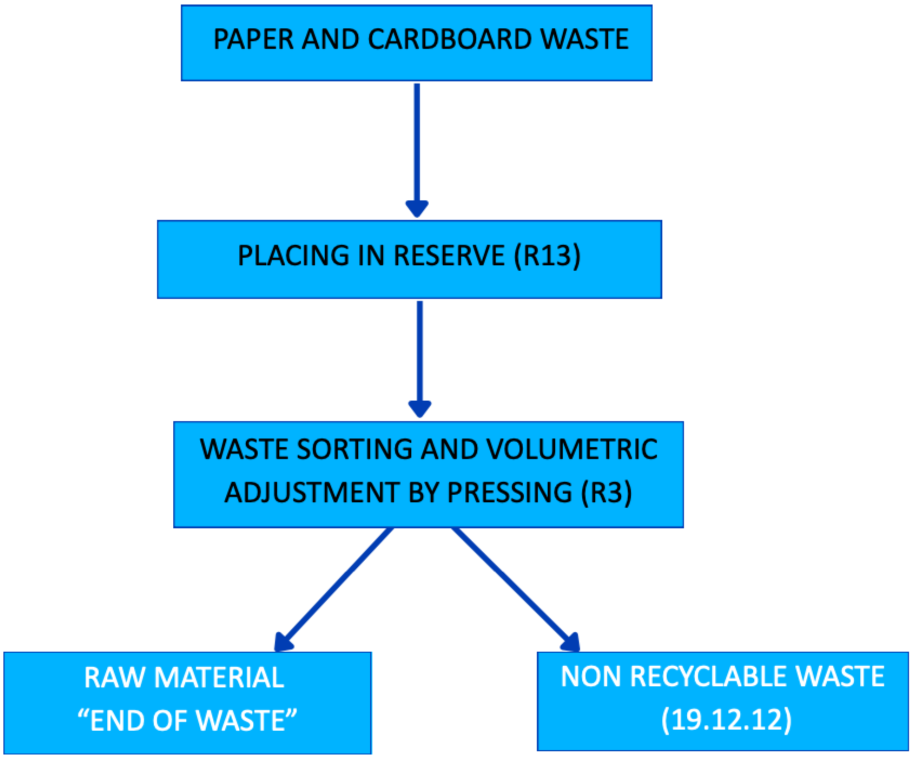

Figure 3_Activities on paper and cardboard waste

Findings

The production of "End-of-Waste" raw material in F.lli Baldini s.r.l. over the years is described by these numbers: 3,314,346 kg in 2020, 3,726,635 kg in 2021, 3,644,485 kg in 2022, 3,171,940 kg in 2023, 3,154,930 kg in 2024. The turnover from the sale of raw materials has been: €22,675.73 in 2020, €589,327.28 in 2021, €628,909.26 in 2022, €312,645.68 in 2023, €372,969.18 in 2024.

Figure 4_Average price delivered to customer (€/tons) for cardboard from August 2017 to September 2024 [4]

The market price level influences the turnover, which, despite an almost constant production of raw material, shows a fluctuating trend. Nevertheless, the economic benefits of converting paper and cardboard waste into “End-of-Waste” raw material are clearly evident. From the Circular Economy, a small company like F.lli Baldini s.r.l. can achieve significant economic growth while also making substantial contributions to environmental protection by saving tons of recovered paper and cardboard from disposal.

Discussion/conclusion

The Circular Economy represents an innovative and sustainable model that offers practical solutions to waste management including in the paper sector. This research aims to highlight how the implementation of Circular Economy practices in waste management can lead to significant environmental, economic, and social benefits, even within the paper supply chain.

The adoption of Circular Economy strategies enables the drastic reduction of waste sent to landfills. Recycling and reuse reduce environmental impact and, in the past, ensured a more efficient use of natural resources. A circular approach to waste management promotes greater awareness and responsibility among consumers. Educating and raising public awareness about the importance of recycling and responsibly consumption is essential to promote a culture of sustainability and encourage virtuous behaviors. The transition toward a Circular Economy is not only possible, but also necessary to tackle the environmental and social challenges of our time. Achieving this goal requires a joint effort from all stakeholders: businesses, institutions and citizens.

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Circular Economy in the Dairy Sector: Innovations in Whey Reuse – The IGOR Gorgonzola Case Study

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Abstract

The circular economy represents one of the key strategies for addressing the growing environmental and sustainability challenges facing the agri-food sector. The dairy industry, in particular, is responsible for significant greenhouse gas emissions and the generation of large volumes of by-products. Among these, whey stands out as an underutilized resource whose valorization can deliver environmental, economic, and social benefits. This paper explores the opportunities offered by the innovative reuse of whey, with a particular focus on the “Dolce Vita” project promoted by IGOR Gorgonzola. Through the application of advanced technologies and circular business models, the company demonstrates the feasibility of a sustainable transition. The results reveal a positive impact in terms of emissions reduction, economic value creation, and the strengthening of ties with the local community. The aim is to provide both practical and scientific contributions to the dissemination of virtuous practices that can be replicated nationally and internationally.

Keywords: Circular economy, whey, dairy sector, IGOR Gorgonzola, sustainability, bioenergy, by-products, environmental impact

Introduction

In recent decades, the growing global demand for food products has led to intensified industrial production, with severe environmental consequences. The prevailing economic model, based on a linear paradigm of extraction, use, and disposal, is no longer sustainable in the long term. According to the FAO, the agri-food sector accounts for approximately 20% of global anthropogenic greenhouse gas emissions, with the dairy supply chain alone responsible for 2.7%. Furthermore, nearly 1.3 billion tonnes of food are wasted each year, contributing roughly 8–10% of global greenhouse gas emissions.

The dairy sector also carries a significant environmental burden in terms of water and energy use. Producing just one liter of milk requires over 1,000 liters of water—a striking indicator of the resource intensity of this supply chain. This impact is further exacerbated by deforestation, biodiversity loss, and reliance on energy- and water-intensive feedstocks. The production, processing, and disposal of dairy-related waste make it clear that more sustainable models must be adopted.

Within this context, the circular economy emerges not only as an opportunity but as a necessity to ensure the resilience of food systems. It is a regenerative approach that reduces environmental impact, optimizes resource use, and creates value from materials traditionally treated as waste. Whey is one of the most significant underutilized resources in this regard. Following milk coagulation in cheese production, whey accounts for about 90% of the initial milk volume. Rich in nutrients, it holds potential applications in sectors ranging from nutrition and cosmetics to pharmaceuticals and bioenergy.

Recent studies emphasize the strategic importance of reducing food loss and improving the valorization of by-products. According to the Ellen MacArthur Foundation, each tonne of food waste avoided prevents the emission of approximately 4.5 tonnes of CO_2 equivalents. The transformation of whey into secondary raw material directly contributes to reducing the carbon footprint of the entire supply chain, improving overall efficiency and supporting the EU’s climate neutrality goals for 2050.

This paper aims to explore the strategic role of whey in the transition toward a circular economic model, with a detailed analysis of the “Dolce Vita” project launched by IGOR Gorgonzola, one of Italy’s leading producers of Gorgonzola PDO. Through an in-depth examination of the technologies used, the benefits achieved, and future prospects, the study offers a concrete contribution to the discussion on how to valorize by-products and reduce the environmental footprint of the dairy sector.

Methods

The analysis was conducted using a qualitative and multidisciplinary approach, integrating academic scientific literature, corporate technical data, European and national regulations, and sustainability reports. Specifically, a systematic review of scientific literature was carried out focusing on sustainability and circular economy topics as applied to the dairy sector, with particular attention to the studies by Smithers (2008), Rollini et al. (2020), Huffman et al. (2009), and Zamberlin et al. (2012), which explore the properties and transformation potential of whey.

In parallel, technical documentation related to the “Dolce Vita” project, provided by IGOR Gorgonzola, was analyzed. This material includes process data sheets, sustainability objectives, input/output data from processing operations, and internal environmental assessments. A SWOT analysis model was applied to identify strengths, weaknesses, opportunities, and threats, supporting the evaluation of the project’s replicability and scalability. Furthermore, the regulatory and policy framework was reviewed, with reference to key European instruments such as the Circular Economy Action Plan and the Green Deal, as well as national and regional incentives supporting ecological transition.

The methodological framework was further enhanced by benchmarking with comparable European case studies and consultation of sectoral reports (e.g., CLAL, FAO, Market Research Intellect). Finally, an environmental impact assessment model inspired by Life Cycle Assessment (LCA) principles was used to estimate the environmental benefits of whey transformation, with a specific focus on emission reduction, water savings, and the use of renewable energy sources.

Findings

The “Dolce Vita” project stands as a virtuous example of circular economy applied to the valorization of dairy by-products. Scheduled to launch in 2026, the initiative will be based in the city of Novara, at IGOR Gorgonzola’s historic Cameri site. It will involve the processing of approximately 20,000 tons of whey per year, which will be transformed into a high-quality raw material intended for the production of WPC-80, a high-value whey protein concentrate. The facility developed by IGOR Gorgonzola integrates various technologies, including pre-concentration, ultrafiltration, ion exchange, and spray drying. Additionally, the permeate and by-products resulting from the protein separation process are utilized in an anaerobic digestion plant to produce biogas, which contributes to covering part of the facility’s energy needs.

The plant’s production capacity allows for integrated material flow management, leading to a significant reduction in disposal costs and optimization of logistics. In particular, on-site pre-concentration reduces the specific weight of the whey being transported, resulting in an estimated 15% reduction in Scope 3 emissions. With a protein content exceeding 80%, the production of WPC-80 enables the company to meet the growing market demand for functional ingredients in the sports and clinical nutrition sectors, positioning itself in a high-value market segment.

From an environmental standpoint, internal Life Cycle Assessment (LCA) analyses have shown a reduction of approximately 3,500 tonnes of CO_2 equivalents per year. This reduction has been achieved through the replacement of fossil fuels with internally generated biogas, transport optimization, and reduced nutrient losses. The installation of a photovoltaic system further contributes to the plant’s energy self-sufficiency, enhancing the sustainability profile of the entire production site.

Economically, the project has led to a direct increase in revenue through the commercialization of WPC-80 and to savings in disposal costs estimated at over €250,000 per year. Indirectly, the improvement in the company’s brand image has resulted in greater customer loyalty and enhanced access to sustainability-related funding and certifications. Moreover, the initiative has stimulated local employment through the hiring of new technicians, plant operators, and researchers, reinforcing ties with the local community.

On the social level, the project has played a strategic role in building a territorial innovation ecosystem. IGOR has launched collaborations with research centers, universities, and start-ups to develop advanced solutions, including the use of blockchain for whey traceability and integration with digital systems for real-time monitoring of production flows. The dissemination of best practices through workshops and public events has contributed to spreading a culture of sustainability among supply chain stakeholders.

Discussion/Conclusion

The experience of IGOR Gorgonzola represents an effective model of transition toward a circular economy in a traditionally high-impact sector. The company's decision to invest in advanced technologies for the treatment and valorization of whey has demonstrated that an environmental cost can be transformed into both an economic and social opportunity. This case highlights how adopting a systemic approach—grounded in resource regeneration and continuous innovation—can yield multiple benefits in terms of sustainability, competitiveness, and resilience.

However, the large-scale implementation of similar models requires specific enabling conditions. First and foremost, access to adequate financial resources must be ensured through public–private support mechanisms and long-term investment tools. Second, regulatory support is essential, including administrative simplification, fiscal incentives, and rewards for virtuous enterprises. Lastly, the development of professional skills capable of managing complex technologies and interdisciplinary approaches is crucial.

From a strategic perspective, the future of the circular economy in the dairy sector will depend on the ability of companies to innovate not only in their processes but also in their business models. The creation of territorial alliances, the enhancement of local identity, the adoption of digital traceability systems, and the active engagement of consumers represent key levers for the success of circular initiatives. Moreover, integrating ESG (Environmental, Social, and Governance) objectives into corporate strategies can strengthen transparency and attract investors and partners.

Another critical element concerns the cultural dimension. Promoting a circular economy also requires a shift in consumption habits, educational practices, and perceptions of the value of by-products. The circular approach should not be viewed solely as a corporate strategy, but as a paradigm capable of profoundly influencing individual and collective behavior. Educational institutions and media can play a vital role in disseminating a new narrative that celebrates reuse, efficiency, and sustainability.

In conclusion, the IGOR Gorgonzola case provides tangible evidence of how the circular economy can become the engine of profound change in the agri-food supply chain. It is not merely about reducing negative impacts, but about rethinking the entire production system through the lens of regeneration, equity, and shared value. Global challenges call for coordinated local responses, and the approach adopted by IGOR stands as a best practice that is both replicable and adaptable in other production contexts. The future of the dairy sector can—and must—be circular.

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Sustainability in the Visual Arts Sector: A Critical Analysis of Museums, Market Institutions, and the Role of Charity Auctions

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Abstract
In response to growing global concern regarding climate change, social inequity, and corporate responsibility, the visual arts sector is increasingly called upon to engage with the principles of sustainability. This article, based on Marini's master thesis, examines the integration of sustainability within the operations and strategies of institutions of visual arts sector, in particular museums, galleries, fairs, and auction houses. Through an interdisciplinary framework that draws from cultural economics, sustainability studies, and humanities studies, the work explores how institutions within the art system may contribute to environmental and social goals, while highlighting the emergent role of charity auctions as a model of socially responsible practice.

Keywords: sustainability, visual arts, museums, auction houses, charity auctions, Gallery Climate Coalition, cultural institutions, environmental impact, social inclusion, SDGs

Introduction
The concept of sustainability, particularly in its contemporary tripartite formulation—environmental, social, and economic[1]—has progressively permeated all sectors of society, including the cultural and creative industries. While historically overlooked in discussions of sustainability due to their relatively low direct emissions, art institutions are increasingly recognized for their indirect environmental impact and their potential as catalysts for social and cultural change [2]. This work responds to this shift by offering a sector-specific analysis focused on the visual arts system, with particular attention to both museums and institutional organizations, as well as the dynamics of the art market.

Methods
The methodology of this work adopts a qualitative, interdisciplinary approach that combines theoretical research with applied case analysis. Drawing on frameworks from cultural economics, sustainability studies, and humanities, the research investigates how institutions within the visual arts sector—specifically museums, galleries, art fairs, and auction houses—are integrating sustainability into their practices. The study begins with a review of academic literature to define key dimensions of sustainability—environmental and social—and examines their relevance to both nonprofit and commercial cultural organizations. Empirical insights are gathered through the

examination of concrete case studies, including famous museums as MoCA of Los Angeles and leading art market's institutions such as Christie's and Art Basel, as well as emerging practices like charity auctions. The author's internship experience at Wannenes auction house further informs the analysis, offering grounded observations on the current challenges and opportunities in aligning the art market with sustainability goals.

Findings

Environmental Sustainability and the Visual Arts

The environmental footprint of the art sector has, until recently, remained largely unexamined. However, the high energy demands of museum buildings[3], the carbon-intensive logistics of international art transport, and the extensive use of printed and packaging materials all contribute to significant levels of emissions.

A particularly noteworthy initiative in this regard is the Gallery Climate Coalition (GCC), established in 2020. The GCC offers a carbon calculator for the art world and promotes the objective of a 50% reduction in CO_2 emissions by 2030, in accordance with the targets set by the Paris Agreement [4]. Its members—ranging from individual artists to major galleries and institutions—are required to publish annual emission reports and to implement concrete plans for decarbonization.

Among the most impactful strategies are:

Transitioning to sustainable transportation methods for artworks and personnel.

Retrofitting infrastructure to increase energy efficiency.

Employing recyclable and locally sourced materials for exhibition setups and art handling.

Engaging in carbon offsetting through verified environmental funds.

Case studies such as the Museum of Contemporary Art in Los Angeles (MOCA) [5] offer quantifiable evidence of emission sources and suggest prioritization strategies for energy consumption and water heating.

Social Sustainability and the Evolving Role of Museums

As a first step, attention must be directed to the evolution of the definition of museums, referencing the International Council of Museums (ICOM)'s 2022 formulatio[6], which explicitly incorporates the values of inclusivity, accessibility, community participation, and sustainability. This shift aligns with broader policy frameworks, such as the United Nations' Sustainable Development Goals (SDGs) [7], particularly SDG 4 (quality education), SDG 10 (reduced inequalities), and SDG 11 (sustainable cities and communities).

Contemporary museums are increasingly expected to:

- Ensure universal access to cultural heritage, both physically and intellectually.
- Develop programming that serves marginalized and underrepresented communities.
- Act as agents of urban regeneration and civic engagement.
- Address internal inequalities, particularly concerning precarious labor and gender disparity.

The European Parliament's 2023 resolution on the social conditions of cultural workers [8] underscores the urgency of these concerns and identifies the cultural sector as one of both high symbolic value and precarious employment.

The Commercial Sector: Gallerists, Fairs, and Auction Houses

The thesis identifies a structural tension within the commercial segment of the art world—galleries, fairs, and auction houses—where market-driven imperatives often conflict with sustainable aspirations. Nevertheless, several notable institutions are demonstrating a capacity for adaptation.

Two of the most important art fairs in the world Art Basel and Frieze have adopted environmental reporting frameworks and emissions reduction strategies. For example Art Basel has implemented a comprehensive sustainability strategy focused on reducing environmental impact across its operations [9]. Key initiatives include the use of renewable energy—covering 80% of the 2023 Basel fair's needs—and the exclusive use of renewable electricity at the Messe Basel venue. The organization emphasizes waste reduction through recyclable materials and reusable installations, optimized for long-term use.

Efforts also extend to sustainable shipping practices in collaboration with exhibitors, elimination of single-use plastics, and the promotion of locally sourced vegan and vegetarian food. Carbon emissions from staff travel are minimized. Additionally, Art Basel promotes climate awareness through conferences and editorial content, reinforcing its role in advancing sustainability within the art world.

Moreover, an increasing number of galleries, even those of smaller scale, are adapting their structures to enhance sustainability, in part due to the directives issued by the Gallery Climate Coalition (GCC)**.** Houser & Wirth serves as a representative example of this trend. This gallery exemplifies a holistic approach to corporate social responsibility, encompassing education, sustainability, and philanthropy.

One of the most active institutions in the art market sector is undoubtedly Christie's, which has developed its own corporate social responsibility program titled ART and

SOUL[10]. The historic auctions house has pledged to achieve net-zero carbon emissions by 2030, implementing sustainability metrics across all areas of his work. Since 2021, Christie's has issued an annual sustainability report, which provides evidence of the improvements achieved throughout the year in terms of both social and environmental sustainability. Through this initiative, Christie's positions itself as a benchmark for the auction house sector and the art market as a whole.

With regard to environmental sustainability, Christie's has undertaken an innovative project focused on the packaging of artworks. In an effort to protect the natural environment, Christie's has committed to minimizing the use of plastic in its shipping materials. A dedicated working group, composed of art logistics specialists, was established to redesign sustainable packaging solutions. One key initiative, the 'Luxury Packaging' project, focuses on developing eco-friendly shipping materials for high-end items such as watches and jewelry.

The company also promotes the reuse of packaging materials instead of discarding them.
In collaboration with its shipping partner Crozier, Christie's has supported the implementation of a maritime transport program that includes a technique to optimize container space usage. Currently, a reusable crate model is under development and testing, which holds potential for scalability at the industrial level. This innovation could significantly transform the transportation of artworks within the visual arts sector. As a result, Crozier has encouraged the adoption of this advancement among its other clients in the art market [11]Despite these promising developments, the studies emphasizes that smaller organizations frequently lack the structural and financial resources to implement such initiatives, highlighting a potential stratification in the sector's sustainability capacity.

Charity Auctions as a Model of Social Responsibility

A newly adopted instrument employed by arts organizations to pursue social sustainability is the charity auction, as a hybrid model that integrates economic mechanisms with philanthropic goals [12]. Charity auctions operate under various modalities—either entirely non-profit or with partial profit allocation—and mobilize both cultural capital and financial resources for social causes.

Through selected case studies, the research demonstrates that charity auctions:

- Enhance institutional reputations and foster public trust.
- Facilitate the participation of collectors and artists in social engagement.
- Encourage ethical marketing and brand alignment with social causes.
- Provide a framework for integrating environmental awareness (e.g., local logistics, digital platforms, low-emission events).

Thus, charity auctions emerge not only as fundraising mechanisms but also as strategic tools for corporate social responsibility within the art market.

Conclusions

This research contributes to scholarship aimed at bridging the fields of cultural management and sustainability studies. Findings reinforce the view that the visual arts sector possesses significant—though currently underutilized—potential to serve as a transformative force in response to climate and social crises. Future pathways for sustainable development within the art world may involve the establishment of standardized sustainability protocols tailored specifically to the cultural sector, as well as increased collaboration between public and private institutions[13]. Overall, the work emphasizes that sustainability in the arts must be embedded within the institutional structures, operational frameworks, and core values of art organizations. Positioned as both producers and interpreters of meaning, these institutions have a unique capacity to catalyze a broader cultural transition toward more ethical and sustainable futures.

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Characterisation and valorisation of defatted durum wheat germ flour for the development of new integrated biorefinery models

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Abstract

Durum wheat germ, a by-product constituting 2–3% of total grain weight, is typically removed during milling due to endogenous enzymes that promote rancidity. However, it is a rich source of bioactive compounds, including essential amino acids, polyunsaturated fatty acids, vitamins B-E, minerals, and polyphenols. This study, in collaboration with Casillo Next Gen Food S.r.l. aimed to characterize defatted wheat germ flour (DuoGerm®) obtained via hexane extraction. Analytical protocols were developed to quantify total polyphenols (2.35 mg/g), proteins (38.5 mg/g), antioxidant activity (IC_{50}: 127.8 µg/ml for extract) and antimicrobial effects (0.05 g/l against E. coli and S. cerevisiae). Enzymatic activity was also assessed: lipase (0.036 U/g), protease (0.022 U/mg protein), and α-amylase (0.006 U/mg protein). The results demonstrate DuoGerm®'s potential in biorefinery applications, functional food production, and bio-based industries. This valorization supports circular bioeconomy strategies by transforming a milling by-product into a high-value, multifunctional ingredient.

Graphical abstract

Keywords: Circular bioeconomy, Defatted wheat germ, Industrial biotechnology, Valorisation by-products

Introduction

The pressing challenges of limited resources, climate change, and ecosystem degradation, alongside a growing global population projected to reach 9 billion by 2045, necessitate innovative resource management. The demand for natural resources and food production is expected to increase by 35- 50% (FAO 2019), requiring a reorganisation of food supply chains around sustainability principles. With a projected 70% increase in food production and significant food waste—58 million tonnes in the EU (131 kg/inhabitant) [1]—it's vital to assess existing policies, such as the 2030 Agenda, and valorise discarded food processing by-products for new product development. In light of these factors and of the role of key production chains like the milling industry, it is evident that cereal processing and flour production play a pivotal role in the global agrifood scenario. Durum wheat, for instance, is one of the world's most important cereals, serving as the primary food source for 36% of the global population and as the primary raw material to produce pasta and bakery products. In Italy, the 2024 harvest yielded approximately 3.500.345,5 tons of durum wheat, with Apulia contributing 553.550 tons or 15.8% of the national total. [2] Despite the large volume of by-products derived from the wheat milling process, their use remains limited. In the context of cereal processing, the two principals by products derived from traditional milling are bran and germ, which are separated from the endosperm, the main component of refined flour, due to their negative impact on the technological properties of the final product. Wheat germ, bran and their fractions, which are currently used primarily as animal feed, contain about 80% of the grain's lipid content. From a management and production standpoint, removing wheat germ (WG) from refined flour is crucial, as its presence can negatively affect the technological and qualitative properties of the flour, as well as the stability of the dough during baking processes. WG is not merely a by-product, it is a rich source of macronutrients such as proteins and peptides (26-35%) carbohydrates (about 50 %, with 30 % as starch, followed by 17 % sugars plus dietary fibers between 1.5%-4.5%), and lipids (10-15%). Moreover, WG contains other bioactive compounds with health benefits that make it valuable in the production of functional foods. These compounds include polyunsaturated fatty acids, minerals (4%), tocopherols, phytosterols, carotenoids, thiamine, phenols, flavonoids, γ-aminobutyric acid (GABA) and quinones. [3-7] WG also contains a plethora of enzymes, including α-amylases, proteases and oxidases which play essential roles in its embryonic development in plant physiology. Additionally, it contains two other key enzyme classes: lipase and lipoxygenase. Lipase catalyses the hydrolysis of both water-soluble and insoluble esters, producing free fatty acids that contribute to hydrolytic rancidity. Lipoxygenase, on the other hand, deoxygenates polyunsaturated fatty acids such as linoleic acid, leading to the formation of hydroperoxide radicals. These radicals can further oxidize bioactive compounds, potentially compromising the nutritional and functional properties of WG. Despite its exceptional nutritional value, WG has notable drawbacks, notably its short shelf life. This is primarily due to its high contents of unsaturated fatty acids and lipid- metabolizing enzymes, which accelerate lipid degradation and rancidity. Consequently, these stability issues limit its application in food formulations. As a result, the approximately 25 million tonnes of WG produced annually by milling industries globally are currently undervalued. [7] In this scenario, a notable example of leveraging WG in a sustainable manner is Casillo Next Gen food S.r.l., a virtuous Apulian company. Adopting a circular economy perspective, this company aims to maximize the value of each molecule of WG, particularly through upcycling processes that align with the UN SDGs and promote circular bioeconomy approaches. The separation of the flour and WG is achieved through a series of processes, starting with debranning and followed by milling. The initial debranning process removes of the outer layers of the caryopsis, thereby facilitating the recovery of intact grains without damaging the endosperm. However, this process also generates by-products, including bran and germ. Specifically, within 30 minutes of milling the durum wheat kernel, oil extraction with n-hexane is performed to stabilise the de-oiled raw material and minimises alteration. This process results in the production of defatted pellet fraction that is free of colour due to the removal of lipids, particularly carotenoids, which are stripped away during deoiling. The residual solvent is carefully removed at a controlled temperature to ensure the quality of the by-product is not compromised. As part of the Casillo Next Gen Food S.r.l. project, the defatted material undergoes further valorisation. The removal of the lipid fraction renders the defatted flour more resistant to oxidative degradation, thereby minimizing associated risks. The defatted wheat germ is subsequently micronized using an impact mill and subjected to air classification to achieve further fractionation. This is followed by a crushing and sieving process, yielding an additional product, defatted wheat germ flour (DWGF), commercially branded as DuoGerm®. Through this integrated process, it is also possible to refine the extracted oil from durum wheat germ, marketed under the name DurOil®, a valuable source of essential fatty acids and bioactive compounds. These outcomes highlight the effectiveness of Casillo Next Gen Food S.r.l.'s strategy in valorizing by-products of durum wheat milling. By repurposing residues from the primary flour production process, the company contributes meaningfully to the shift from a linear to a circular economy within the durum wheat value chain. The objective of this study was to characterise DWGF, a residual biomass resulting from an initial treatment of wheat germ enhancement, itself a waste product of the milling process of more refined flours. The characterisation of the defatted wheat germ flour (DWGF) is related to the content of polyphenols, total proteins, bioactivities (antimicrobial and antioxidant) and finally, the enzymatic activities present. This approach aims to explore potential reuse pathways of this biomass and to validate circular bioeconomy practices that could inspire new market opportunities and biorefinery models integrated with the Apulian territory. Accordingly, the objective of this study was to develop protocols for the extraction of the aforementioned bioactive molecules and for testing antioxidant, antimicrobial and enzymatic activity, through a systematic literature analysis.

Methods

A systematic approach was employed in the literature search for protocols for the extraction of polyphenols and total proteins and for enzymes detection and related enzyme activity assays in defatted durum wheat germ flour samples. Specifically, a variety of keyword and Boolean operator combinations were employed to search major databases, including Google Scholar, Scopus, MDPI, and PubMed. In order to quantify the total polyphenol content, it is first necessary to proceed with their extraction, as evidenced by the results of the literature search [8-10]. The latter was performed by testing six different conditions: pure methanol/ethanol (100%); pure methanol/ethanol 70-30% (v/v solvent/water) at room temperature and placed under agitation; methanol/ethanol 70-30% (v/v solvent/water), acidified with 1M HCl (final pH 2), heated to 65°C and placed under agitation.

The resulting supernatant was collected and subjected to quantification via the Folin & Ciocâlteu assay [11]. In order to quantify the total protein content, it is first necessary to extract the proteins using an alkaline solution and isoelectric precipitation. This is because the majority of wheat germ proteins are solubilised at a pH of 9. Adjusting the pH to the isoelectric point of 4 favours the precipitation of the extracted proteins [12]. The protein extract obtained, was quantified using the Bradford protein assay [13]. The bioactivity analysis was conducted in accordance with the antioxidant activity, employing the DPPH assay [14] and the antimicrobial activity, against yeast Saccharomyces cerevisiae and bacteria Escherichia coli, by microplate growth tests. The enzyme activities in the defatted durum wheat germ flour following the preparation of a total enzyme extract, based on methods identified through literature review. The extraction buffer employed was a 0.1 M acetate buffer (pH 5.3) [15]. The enzymatic activity of lipase present in the total enzyme extracts obtained from the DWGF samples was assessed using a 96-well microplate as described in [16]; protease enzyme activity was assessed using a colorimetric assay based on [17] and α-amylase enzyme activity was assessed using a colorimetric assay based on [18].

Findings

Defatted durum wheat germ, the main by-product of the wheat germ oil extraction process, contains valuable nutritional components, including protein, carbohydrates, B vitamins, pigments and minerals.

Among these polyphenols, as bioactive compounds with known health benefits, are of particular interest. Their concentrations in cereals vary based on the types, variety and part of the grain. Polyphenols has been the subject of considerable interest across various sectors, including food processing, preservation and pharmaceuticals, especially for their role in combating oxidative stress. The extraction of polyphenols is a crucial preliminary step in the analysis of the total polyphenol content (TPC), which has potential applications in pharmaceuticals and functional foods. The most effective condition involved 70% ethanol (in water), acidified with HCl 1M (pH 2), heated to 65°C and stirred for 90 minutes determining 2.35 mg TPC/g DuoGerm®. A possible explanation for this evidence is that polyphenolic compounds in cereals exist mainly as glycosides, bound to sugars or other complexes via ether-ester bonds, to organic acids, amines, lipids and carbohydrates. Increasing the extraction temperature may help weaken these bonds, facilitating polyphenols migration into the solvent. Moreover, acidifying the solvent can further enhance the process by hydrolysing the bonds between polyphenols and macromolecules. [19]

Figure 1_Results of characterisation of defatted durum wheat flour DuoGerm®

Compared to the existing literature reporting a protein content of 29% per 100 g of defatted wheat germ flour [3-9], the experiments yielded approximately 10% less protein. As illustrated in Figure 1, the mean yield for the various conditions examined was 38.5 mg/g of sample. This result may be related to the different solubilities of the various protein fractions in wheat germ. Wheat proteins has traditionally classified into prolamins (gliadins and glutenins) and non-prolamins (globulins). Indeed, as outlined by D. Osborne in his classification, wheat proteins include fractions with varying solubilities: albumins (water-soluble), globulins (soluble in dilute NaCl), gliadins (soluble in 70% ethanol), and glutenins (soluble in dilute NaOH or acid). The smallest wheat proteins are albuminins and globulins.

[20] Consequently, in order to enhance the extraction yield of the total protein content, fractional extraction methods may be necessary. Supplementary techniques, such as microwave, ultrasound and supercritical CO2 could further increase the extraction yield [21]. As previously highlighted, defatted durum wheat germ is a rich source of polyphenolic compounds, a promising class of phytochemicals with antioxidant activities. The antioxidant activity of the defatted wheat germ extract was evaluated in accordance with the DPPH radical scavenging assay by the IC50 value (µg/ml), indicating

the concentration of the extract required to extinguish 50% of the initial DPPH under the specified experimental conditions. The IC50 value is indicative of the extract's scavenging activity, with lower values suggesting a stronger antioxidant activity: TPC extract demonstrated an IC50 of 127.8 µg/ml, while the flour exhibited an IC50 of 132 µg/ml. These promising highlight the potential of DWGF as a functional food additive and in the pharmaceutical industry, given its high antioxidant capacity. Polyphenols are a class of compounds known for their inhibitory effects against microorganisms and pathogens in various settings, including medical and food applications. In light of the aforementioned evidence and the beneficial characteristics of wheat germ and polyphenols as biomolecules with antimicrobial properties, the potential antimicrobial potency of the TPC extract obtained from DuoGerm® on E. coli and S. cerevisiae cultures was evaluated. The results demonstrated probable antimicrobial activity at a concentration of 0.05 g/l TPC extract, which can be validated in future colony- forming unit count experiments. With regard to the endogenous enzyme activities present in DuoGerm® flour, the results obtained indicate a lipase activity of 0.036 U/g sample, which is lower than that observed in wheat germ (2.49-4.50 U/g). This discrepancy could be attributed to the oil extraction process, which may result in the denaturation of the endogenous enzymes. Additionally, the protease activity was found to be 0.022 U/mg protein, in comparison to the activity observed in wheat-milling streams (0.115-0-165 U/mg protein). The α-amylase activity was found to be 0.006 U/mg protein, which is compatible with the enzyme activity found in wheat-milling streams (0.004 U/mg protein). [22-23]

Conclusions

This work provides a comprehensive analysis of wheat germ and its potential valorization, emphasizing its role as a by-product of the milling industry that offers rich nutritional and functional components. Despite its health benefits WG is often underutilized due to its tendency to cause rancidity and its short shelf life. This is due to the presence of endogenous enzymes, such as lipase and lipoxygenase, which lead to rancidity and a reduction in shelf life. This limits the optimal use of wheat germ, which is often used as animal feed. Casillo Next Gen Food S.r.l.'s development of a de-oiled wheat germ product, DuoGerm®, offers a promising approach to overcoming these limitations by extracting valuable components. The characterisation of DuoGerm® revealed significant antioxidant and antimicrobial properties, notably due to its polyphenol content. However, protein extraction yields remain suboptimal, indicating the need for improved methods. With regard to the bioactivities tested, DuoGerm® demonstrated notable bioactivities. In particular, it exhibited significant antioxidant capacity, as confirmed by its ability to scavenge DPPH radicals. The total polyphenol extract showed an IC_{50} of 127.8 µg/ml, while the flour itself yielded an IC_{50} of 132 µg/ml. Based on these findings and the recognised antimicrobial properties of wheat germ polyphenols, the extract was tested against E. coli and S. cerevisiae. At a concentration of 0.05 g/l, the polyphenol extract exhibited probable antimicrobial effects, which warrant further validation through colony-forming unit assays. Additionally, the detection of proteases and amylases supports its use in bakery applications enhancing the rheological and nutritional quality of baked product, while lipases, though undesirable in flour matrices, could be extracted and employed in industrial contexts such as biodiesel production, oil waste treatment, and bioremediation reflecting a biorefinery-oriented approach. The characterization of DuoGerm® flour has demonstrated the potential for this biomass to be integrated into a biorefinery system. The extracted polyphenols and proteins can be used in the production of functional bakery products with enhanced antioxidant and nutritional properties and they also have applications in the nutraceutical and cosmetic sectors. Additionally, the presence of endogenous enzymes (i.e. proteases and α-amylase, could improve the quality of bakery products, while the extracted lipases could be employed in fields such as food production, biodiesel manufacturing, oil waste treatment and bioremediation.

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Innovative Circular Technologies and Environmental Impact Assessment in Textile Finishing Processes: A Case Study of Jeanologia's Sustainable Solutions

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Abstract

This paper presents a detailed case study of the Spanish company Jeanologia and its pioneering circular technologies aimed at enhancing sustainability in textile finishing processes, with a particular focus on the jeans supply chain. The study explores how the company's circular solutions – including laser systems, ozone-based technologies, the closed-loop water treatment system "H2Zero", and the Environmental Impact Measurement (EIM) software – enable a more sustainable, digitized, and automated production model grounded in the principles of the circular economy. These disruptive digital innovations significantly reduce environmental impact, lower operational costs, and improve worker health and safety. By fostering collaboration among value chain actors, this interconnected approach transforms how value is created, encouraging the co-development of innovative, sustainable, and resource-efficient solutions. The Findings underscore significant environmental benefits and highlight the role of integrated technologies and measurement tools in driving sustainable transformation in both the jeans supply chain and the broader textile industry.

Keywords: Circular Economy; Textile processes; Jeans supply chain; Digital technologies; Sustainable manufacturing; Measurement tools

Introduction

Circular Economy (CE), a cyclical and regenerative economic paradigm, represents the only viable path toward building a sustainable future for coming generations. In a world where natural resources are limited, CE emerges as a necessary response to today's environmental challenges – such as climate change, pollution, and biodiversity loss – while also offering opportunities to boost employment, drive innovation in production processes, and support sustainable economic growth. In this context, the textile industry stands out as a key sector for implementing circular economy principles, due to its high environmental impact and traditionally linear production and consumption model [1]. As one of the oldest, most dynamic, and globally significant industries, it faces both the urgency and the opportunity to drive meaningful change. The textile sector mainly uses synthetic fibers, which account for two-thirds of the textiles used in production [2]. These fibers heavily rely on non-renewable raw materials and require a significant amount of energy for their production [1]. Furthermore, during use, such fabrics release plastic microfibers during washing, which can disperse into the environment and the ocean [1]. This issue is particularly evident in the jeans supply chain, which is characterized by a production process that still requires large amount of water, energy, and chemicals, while its design is not conceived for reuse and recycling at the end of its useful life. According to the United Nations (2018), it takes 3,781 liters of water to produce a single pair of jeans, which corresponds to 33.4 kg of CO_2-equivalent emissions [3]. For decades, the textile industry has relied on manual garment washing and finishing processes to achieve desired effects on jeans, such as softness, vibrant colors, and the typical vintage look. However, these traditional methods often involve high environmental costs. In response, the Valencia-based company Jeanologia, founded in 1994, has established the world's first jeans finishing factory [4] designed according to circular economy principles, operating with zero environmental impact. The facility features closed-loop systems that ensure no contamination, while also reducing lead times and streamlining production processes. Compared to conventional finishing methods, it achieves up to 85% water savings, ensures zero discharge, and eliminates pollution [4]. Currently, approximately 35% of the 5 billion jeans produced annually worldwide are made using Jeanologia's circular technologies [5].

Methods

The study is based on an analysis of Jeanologia's circular solutions as described in technical reports and scientific literature, that emphasize quantitative resource savings and environmental impact scores. The company's operating model connects design, production, and consumption, offering five key benefits to the textile sector [4]: it is eco-efficient, cost-neutral, scalable, agile, and digital.

Jeanologia is a leader in the field of laser technologies, which have been part of its innovation journey for 25 years. Through these technologies, the company can replicate vintage and stone-washed effects while reducing environmental impact, health hazards for workers, and operating costs. Among these innovations is "Handman", through which automation achieves unprecedented results. Handman consists of two "Twin Super" lasers and one robot per cabin, which positions garments to reduce errors [6]. An operator loads a maximum of two jeans units, which are then automatically unloaded into separate bins [6], with a daily production capacity of up to 5,000 garments [6]. The mannequin's configuration parameters are stored through software, and a system of sensors enables fully automated diagnostics, while maintenance is performed remotely [6]. The "Twin Super" lasers [7] are equipped with digital power control, which allows simultaneous processing of both legs of a pair of jeans. The twin lasers operate at high speed thanks to the most advanced laser marking software, called "eMark X".

Jeanologia's revolution continues with its ozone-based technologies known as "G2 Ozone". Based on the principle of being "washed by atmosphere", the G2 technology uses atmospheric air to generate ozone, which reacts with dyes in fabric fibers to give garments the typical worn-out look of outdoor use [8]. Additionally, a finishing technique called "Atmos", inspired by the motto "leave stone age behind", replaces traditional pumice stones and potassium permanganate in fabric abrasion to achieve the classic faded vintage effect [8]. The machine introduces air into an oxygen generator, where it is decomposed into oxygen atoms [9]. These atoms are then converted into ozone – up to 500 g/hour – which is released into the tumbler or drum dryer to treat the garments, by reacting with the dyes in the fibers. Finally, the ozone is safely destroyed and released as air. The drying process is based on the patented "Indra" technology, which adapts atmospheric temperature inside the drum, enabling full control of temperature and humidity levels [8].

One of Jeanologia's most ambitious circular inventions is undoubtedly "H2Zero", the first closed-loop water treatment system designed to recycle water in washing processes without the need for chemicals or additional costs [10]. Mechanical filtration removes solid waste from the water, while a cyclone system eliminates suspended solid particles through a centrifugal force. The water is then purified using an ozone-based process, creating a tank of pure water, perfectly suited for reuse in washing and finishing processes [11].

The last solution Jeanologia offers to its partners is the "Environmental Impact Measurement" (EIM) software. Launched in 2011, it is the only software that measures the environmental footprint of textile finishing processes [12]. It provides voluntary certification for producers, brands, and retailers to monitor the amount of water, energy, and chemicals used in production, as well as the social impact on workers' health [13]. EIM is an open-source platform accessible to the entire textile industry, allowing participants to integrate their individual projects and initiatives [13]. It has become a global standard, currently used by over 50 brands and 250 industrial laundries [13], to optimize production processes and improve transparency for end consumers, who can now be informed about the sustainability goals and achievements related to the products they purchase. EIM measures environmental impact in four distinct categories [12]:

1. Water consumption, measured in liters per garment produced. The total consumption depends on the volume of water used in each phase of the process.
2. Energy consumption, which includes both mechanical energy (to operate machinery) and thermal energy (to heat water for washing and air for drying). Both are measured in a single unit, kWh, and total energy is calculated as the sum of energy used across all stages.
3. Chemical impact, aligned with the ZDHC MRSL (Zero Discharge of Hazardous Chemicals Manufacturing Restricted Substances List). Every chemical substance is rated using an EIM CIS (Chemical Impact Store), assessed by third parties based

on ZDHC compliance. The score ranges from 0 to 100 and is color-coded: red for substances to eliminate, orange for acceptable ones, green for preferred ones, and grey for substances with insufficient data to evaluate.

4. Worker impact, which assesses the effect of jeans production processes on workers' health. Each operation is evaluated based on its physical injury or psychological stress risk, and the total risk determines the overall impact on workers.

The assessment involves three phases [12]:

- Quantification of each category
- Benchmarking against critical environmental thresholds for each category
- Classification of the process and final score, calculated as the average of the four categories, each with equal weight.

The final score follows a traffic light system (Figure 1) [12]:

- Low impact: green, score between 0-33
- Medium impact: orange, score between 34-66
- High impact: red, score above 66.

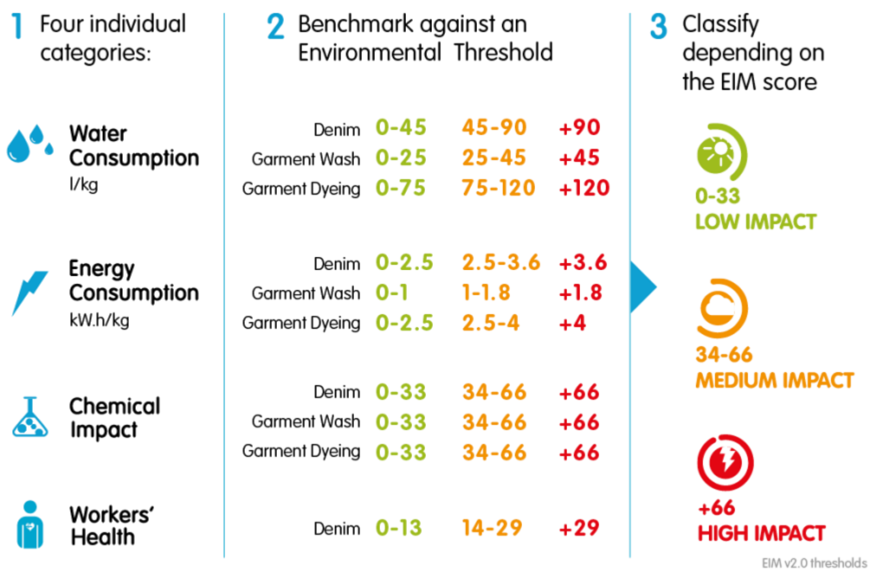

Figure 16_ Environmental Impact Measurement (EIM) traffic light system.

Findings

Jeanologia's sustainable technologies demonstrate substantial reductions in water consumption, chemical use, and energy demand, while increasing overall process efficiency. In particular, laser technology reduces marking time by 15% and eliminates manual abrasion, thereby improving both productivity and worker safety. G2 Ozone represents a major shift toward chemical-free and dry denim finishing. Traditional decoloration processes consume up to 10 liters of water and 250 ml of bleach per kilogram of fabric [14], whereas ozone technology allows for a 96% reduction in water usage, 62.2% reduction in chemicals, and 24% energy savings [8]. It also eliminates the traditional desizing stage, ensuring zero water and chemical consumption, 20% time savings, and a 20% increase in washing capacity [8]. Additionally, the new extraction system reduces ozone destruction time, further boosting productivity [8]. Overall, G2 Ozone improves results by 70% compared to traditional methods, as measured by Jeanologia's Environmental Impact Measurement software [8]. For example, conventional stonewashing has an EIM score of 76 (high impact), whereas "G2 Ozone" achieves a significantly lower score of 23 (low impact) [8]. Likewise, the H2Zero system enables water circulation and reuse for up to 30 days, leading to a 95% reduction in water consumption [10]. Additionally, it operates with minimal energy requirements (2-3 kWh/m^3) [11], fully aligning with the three R's principle: Reduce, Reuse, and Recover.

Discussion/Conclusion

Jeanologia's holistic approach, integrating advanced technologies and measurement tools, represents a benchmark for sustainable innovation in the jeans supply chain. Each technology contributes to a distinct dimension of sustainability:

- Laser technology reduces energy consumption and eliminates the need for manual abrasion, thereby improving both worker health and energy efficiency.
- G2 Ozone addresses water and chemical use, eliminating traditional wet processes and minimizing environmental contamination.
- H2Zero enables water reuse, drastically cutting freshwater consumption.
- EIM provides transparency and accountability, allowing companies to define, track, and monitor clear short- and long-term environmental goals [12].

The transition from high-impact to low-impact processes, as reflected in EIM scores, confirms the transformative potential of circular, clean, and automated textile finishing solutions. The study clearly underscores the importance of objective environmental measurement as a catalyst for continuous improvement and transparency in textile manufacturing. Jeanologia thus offers a scalable and replicable model, encouraging other economic players to adopt similar practices, creating value not only for companies but for society as a whole.

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END OF LIFE MANAGEMENT

PENELOPE – separate, recycle, regenerate. Technology and craftsmanship in the reuse of textile materials

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Abstract

The Penelope project was developed in response to the growing need for a sustainable approach to textile waste management, driven by the environmental and social impacts of fast fashion. In an era of overproduction and rapid consumption, Penelope proposes a circular vision of reuse supported by the design of a fiber separation machine. Based on the triboelectric effect, the device separates different fiber types without using chemicals, enabling a dry and low-impact process suitable for mixed textiles. The recovered materials can be reused in artisanal contexts, fostering local production and craft practices. The project integrates technological innovation with a broader system that includes collection, transformation, and reuse, promoting conscious consumption and valuing manual work. More than a machine, Penelope is a tool for cultural and systemic change. It responds to environmental challenges, aligns with current regulations, and supports alternative, small-scale textile regeneration models rooted in sustainability and local engagement.

Keywords: Conscious consumer; Sustainable fashion; Local craftsmanship; Textile recycling; New technology

Introduction

The fast fashion industry generates enormous quantities of textile waste, with significant environmental and social consequences. Overproduction and the rapid turnover of clothing lead to massive consumption of natural resources, emission of pollutants, and accumulation of waste in landfills or incinerators. Despite these challenges, only a minimal percentage of textile waste is effectively recycled. One of the main obstacles is the technical difficulty in separating blended fibers, commonly used to improve performance and reduce production costs.

Mixed fibers, particularly those combining natural and synthetic components, are difficult to process using conventional recycling methods. This results in the accumulation of unusable textile waste. At the same time, the production of virgin fibers requires high energy consumption, extensive land use, and significant water input—especially for cotton—and depends on fossil sources in the case of synthetics. Large-scale industrial solutions are often not economically viable or attractive for major players, which prefer cheaper, linear production models. In this context, European Union regulations are beginning to impose new strategies for sustainable textile management, but technological gaps remain. Penelope was developed as a response to this critical scenario, introducing a system that is both environmentally conscious and socially embedded.

Methods

The design and development of the Penelope system followed the Double Diamond method, a strategic design framework that alternates between divergent and convergent thinking. This approach allowed the project to unfold through iterative phases of exploration and definition: identifying problems, generating insights, defining opportunities, and delivering solutions. The process was repeated multiple times, adapting to both technical findings and system-level considerations.

The research began with an in-depth analysis of the textile industry and its environmental and structural issues, particularly regarding waste management, recycling inefficiencies, and the challenges posed by blended fibers. The reuse of textiles is hindered by the technical complexity of separating fibers that have been chemically or mechanically bonded. During an internship at the Sport Technology Lab, at the Department DICAM of the University of Bologna, the potential of triboelectric separation emerged as a promising technology. This method exploits the electrostatic properties of materials to achieve fiber separation without chemical treatments, making it particularly suitable for pre-carded mixed textiles. From there, a comprehensive review of the state of the art in textile recycling was conducted, focusing on leading institutions and companies working in this field. The analysis revealed the limitations of industrial-scale approaches, which are often constrained by the need for short-term economic return and therefore lack adaptability and local integration.

This led to a shift in focus toward the world of craftsmanship, collectives, and handmade production. Here, the role of artisans became central—not only as users of recovered materials but as agents of social and cultural change in response to fast fashion's negative impacts. The project thus explores the broader social implications of a restructured textile economy rooted in sustainability and local value. Within this context, the development of the machine was framed as part of a collective design environment.

Findings

The result of the research was the design of a machine capable of separating textile fibers using the principle of triboelectricity - the natural tendency of certain materials to become electrically charged when they come into contact and are then separated. The machine was not conceived as a complex industrial tool, but as an accessible device, designed for use in artisanal, collective, or small-scale laboratory settings. From the early stages, the design was oriented toward ease of use, modularity, and safety, to ensure adoption even by non-specialist users.

The device is modular, intuitive, and low-impact, suitable for integration into shared production spaces and decentralized environments. The design process led to the definition of key characteristics such as material selection, manual mechanical adjustments, a simplified user interface, and the inclusion of a Faraday cage — all aimed at ensuring operational safety and functional efficiency. The system manages different fiber pairs through five preset programs, each with specific voltage levels and panel spacing configurations.

The machine becomes the starting point of a broader regenerative system capable of connecting technology, craftsmanship, and sustainability. The complete process includes the collection, sorting, preparation, separation, and reuse of recovered fibers, which can be used as padding or spun into yarn. These materials are then transformed by artisans into new products, helping to close the production cycle and redefine the relationship between technology, material, and manual making. The entire system was conceived to be replicable, accessible, and locally scalable, offering a tangible model for distributed and sustainable textile regeneration.

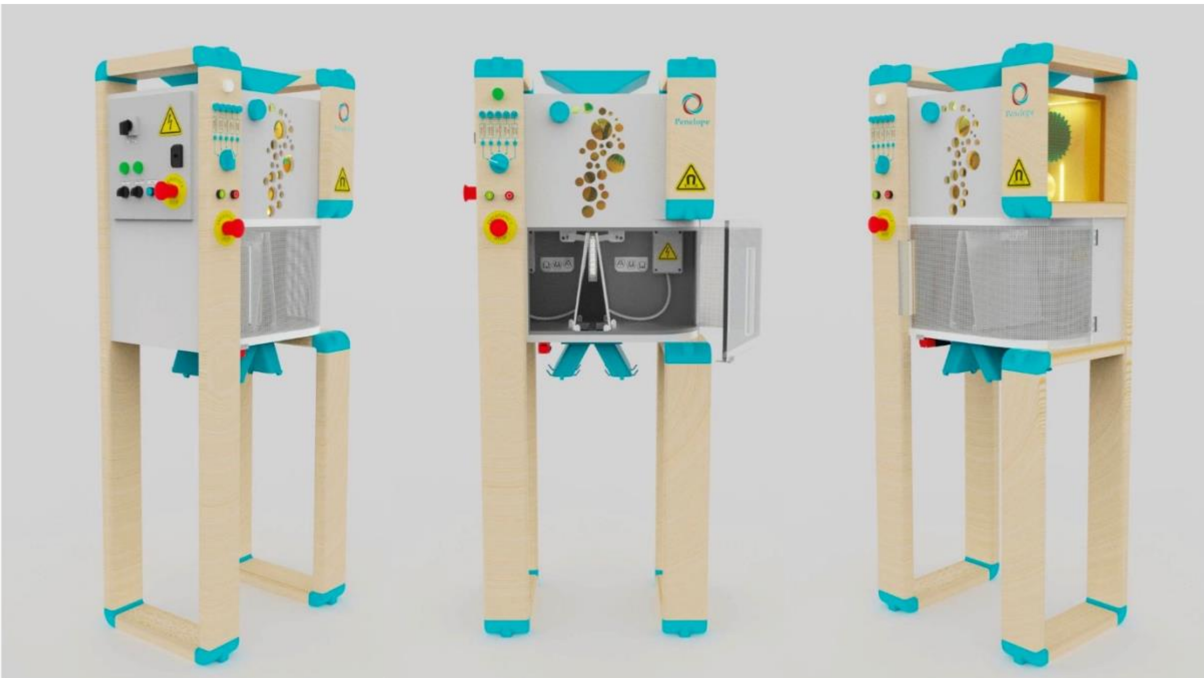

Figure 1_Prototype of the Triboelectric separator

Discussion/Conclusion

The Penelope project demonstrates how a relatively simple technological device can generate significant impact when embedded in a coherent system focused on sustainability. The machine itself is not presented as an isolated solution, but rather as a catalyst that activates an alternative, circular supply chain capable of giving new value to resources typically regarded as waste.

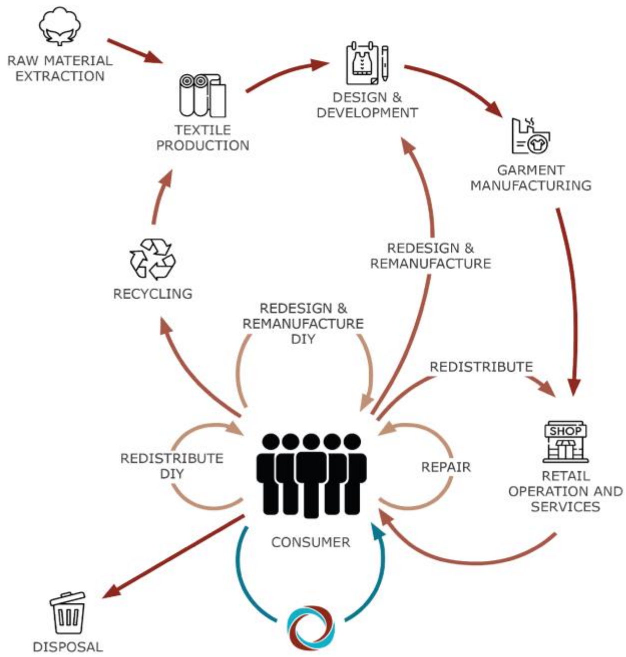

Figure 2_Penelope system diagram

The use of the triboelectric principle (never before systematically applied to textile recyclin) offers a practical and replicable pathway to address one of the industry's key technical challenges: the separation of blended fibers.

However, the true value of the project lies not only in the functionality of the device, but in the broader system in which it operates. The Penelope system connects collection, transformation, and reuse of materials, creating a circular chain that integrates craftsmanship, a culture of reuse, and a locally grounded model of production. Within this framework, the consumer becomes the key to real change: through conscious choices and active participation, individuals can help redefine the meaning of textile products and give new value to what would otherwise be discarded.

In the face of challenges posed by European regulations, market dynamics, and the limitations of traditional industrial systems, Penelope offers a decentralized, replicable, and accessible model for textile regeneration. Penelope, therefore, is not just a machine, but a systemic project that encourages a broader reflection on the role of design in building more equitable, sustainable, and shared futures.

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Effectiveness and safety evaluation of the laser powder bed fusion process for mechanical components' production in AISI 316L steel doped with Nd_2O_3 recovered from permanent magnets

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Abstract

This thesis explores the application of Laser Powder Bed Fusion (LPBF) for the additive manufacturing of AISI 316L stainless steel doped with neodymium oxide (Nd_2O_3), with a focus on sustainability and safety. Nd_2O_3 was recovered from permanent magnets through a patented hydrometallurgical process called New-RE. This research evaluates the feasibility and safety of reusing rare earth elements in advanced manufacturing, comparing also the performance of recycled versus laboratorygrade Nd_2O_3. It also assesses the impact of doping on mechanical and microstructural properties of the steel, using tensile tests and microscopic analysis. Furthermore, the study includes a comprehensive safety assessment for each stage, from powder preparation to 3D printing, highlighting the importance of intrinsic safety and risk minimization in Industry 4.0 environments.

Keywords: Additive Manufacturing, Hydrometallurgical process, Rare Earth materials, Safety, Risk Assessment, LPBF

Introduction

Additive manufacturing (AM), particularly Laser Powder Bed Fusion (LPBF), has emerged as a disruptive technology capable of producing complex, high-performance components [1] . This thesis investigates the use of LPBF to fabricate AISI 316L stainless steel parts doped with neodymium oxide (Nd_2O_3), promoting both material enhancement and environmental sustainability [2] . The doping element is sourced from end-to-life NdFeB permanent magnets via a hydrometallurgical recycling process known as New-RE [3] , developed and patented by the University of L'Aquila [4]. Given the criticality of rare earth element supply chains, this study explores the potential for closing material loops in advanced manufacturing. Moreover, it assesses whether recycled Nd_2O_3 exhibits performance comparable to laboratory-grade material. This dual objective is complemented by a comprehensive safety evaluation across the entire process chain, aligning with Industry 4.0 standards emphasizing safety, efficiency and sustainability. Furthermore, this thesis covers the safety aspects of the entire process.

By using different methods as the Risk Matrix [5] [6] [7] [8] and the Inherent Safety Index [9] , both hydrometallurgical extraction and 3D printing were studied, evaluating their safety and confronted with other processes, to classify them through those indexes for a better understanding of the hazards involved for the operators and the environment.

Methods

The research methodology encompasses both material processing and safety analysis. Recycled Nd_2O_3 was obtained through the patented New-RE process [4] , involving selective leaching with citric acid, solvent extraction and oxalate precipitation. The oxalates were calcined in a furnace, obtaining the desired oxide. Through the study duration, this process has been optimized, removing the organic solvent extraction and substituting that with a precipitation, using sodium carbonate. Those carbonates were treated in a furnace, giving the desired oxide despite a slightly worse purity. The leaching phase has been studied with a deeper focus, since it is the most delicate part of the entire patent. Thanks to the studies brought on by Romano et al. [10] , the desired parameters were found.

The recovered rare earth oxide was milled through the RetschMill and homogeneously mixed with AISI 316L powder in 1%wt proportion [1] . Samples were fabricated using a MySint100 LPBF system, employing optimized process parameters. Post-processing involved polishing, chemical etching, and tensile testing. Microstructural analysis was conducted using optical microscopy, while mechanical properties were evaluated through standard tensile tests. Safety assessments were conducted using the Intrinsic Safety Index (ISI) framework, which includes subindices for chemical reactivity, toxicity, flammability, explosiveness, and corrosiveness. Risk assessments covered powder handling, milling, printing, and postprocessing operations. ISI has been used for the hydrometallurgical process. The analysis has been made on the laboratory scale, confronting that with the pilot scale of the process and with a different hydrometallurgical one, hoping to emphasise the “green “ aspect of the patent. On the other hand, the risk matrix has been used for both additive manufacturing and hydrometallurgical processes, for a better understanding of the possible hazards (chemical, environmental, ergonomic, electric…) involved into this supply chain process. This analysis helped to demonstrate both the safety and the feasibility of the entire process, granting a secure and almost risk-free operation. An example of the risk matrix used is reported in the following figure (Figure 1).

S=Severity / P=Probability	Mild S=1	Medium S=2	Serious S=3	Very serious
Very probable P=4	4	8	12	16
Probable P=3	3	6	9	12
Occasional P=2	2	4	6	8
Unlikely P=1	1	2	3	4

Figure 1_Risk Evaluation Matrix [8]

Findings

The AM results indicate that doping AISI 316L with Nd_2O_3, whether laboratory-grade or recovered, affects microstructure and mechanical performance. The components' density is reported to be slightly inferior to the one from the non-doped components, due to the rare earth doping [11]. As shown after polishing, etching and chemical attack in aqua regia, microstructure shows signs of better refining, as reported in other publications [2]. Properties such as Young module present a higher value than the non-doped component. On the other hand, the doped samples report a decreased elongation and toughness, revealing a more fragile (less ductile) behaviour.

From the hydrometallurgical point of view, the process shows >95% recovery yield for the first phase at the optimized conditions. That value tends to decrease with the proceeding of the phases, although granting high purity in the final product. The optimized process (simplified) allowed us to recover higher quantities (wt) of the desired powder. The contamination due to other elements (iron, boron, dysprosium) showed no particular problem through the LPBF process.

The safety evaluation brings excellent results for both the processes: the additive manufacturing process is completely safe for an operator. Every risk can be prevented with the correct usage of PPE and a complete knowledge of the machines involved and the substances treated (such as AISI 316L powder). The higher risks were found in gas leakage, powder leakage and incorrect or no use of PPE, easily manageable [12].

The hydrometallurgical process has been analysed with both indicators, confronting the results with a second process that involves traditional chemical agents for the leaching phase [13] . As foreseen, the New-RE patent [4] is set to be the less dangerous process usable, thanks to the citric acid, far less hazardous than phosphoric acid or sulfuric acid, used in traditional ones. However, the index presents the maximum value for the temperature parameter: due to the furnace calcination, this value pushes the index higher. Optimizations in order to lower the temperature are ongoing. Compared to the pilot scale, the laboratory one presents a higher value due to the organic compound used in the non-simplified process and to the material used for beckers and other instruments. Overall, the process chain adhered to safety principles suitable for pilot-scale implementation.

The comparison between recycled and pure Nd_2O_3 showed marginal differences in performance, supporting the feasibility of reuse. This is the greater goal obtained with this work, setting camp for a vast rare earth recycle industry, necessary for those territories that lack this kind of raw materials.

Table 1.Inherent Safety Index calculated

INHERENT SAFETY INDEX	CHEMICAL	PROCESS	TOTAL
New-RE Laboratory	11	10	21
New-RE Pilot	10	10	20
Traditional Process	12	10	22

Discussion/Conclusion

This thesis demonstrates the viability of doping AISI 316L with recycled Nd_2O_3 using LPBF, offering performance enhancements with sustainable material sourcing. While mechanical improvements were moderate, the circular use of rare earths represents a significant advancement in sustainable engineering. Recovered Nd_2O_3 showed comparable results to laboratory-grade material, validating the New-RE process as a highly efficient recycling route. The study also highlights the importance of risk management in Additive Manufacturing and Hydrometallurgical recovery, identifying potential hazards and proposing mitigation measures and strategies. These findings align with the broader goals of Industry 4.0, integrating innovation, environmental responsibility and worker safety. Future research may expand on optimizing doping levels, scaling up recycling processes and extending this methodology to other critical materials, adapting the processes while keeping the same critic eye on the risk assessment. The integration of material science with process safety modelling presents a replicable framework for responsible innovation.

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Characterization techniques of polymethyl methacrylate for the recovery and valorization of processing waste

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Abstract

This work aims to optimize the recovery and depolymerization process of PMMA by critically analyzing the experimental results obtained. The introduction provides an overview of polymethyl methacrylate (PMMA) and its main chemical and physical properties. A company supplied five different PMMA-based samples, and the research focused on identifying additional components present in the materials. To this end, analytical techniques such as Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FTIR) were employed, which proved essential in understanding the composition of the samples and improving the recovery process.
A sheet of pure PMMA was also used as a reference to compare its properties with those of the analyzed samples and to identify any significant differences.

Keywords: recovery, depolimerization, FTIR, DSC

Introduction

Polymethyl methacrylate (PMMA), also known as acrylic or by the trade name Plexiglass, is a thermoplastic material belonging to the family of synthetic polymers. It is derived from methyl methacrylate (MMA), a monomer primarily obtained through industrial chemical processes. PMMA is characterized by its high transparency, with a light transmittance similar to that of glass (approximately 92%) [1], and is valued for its low weight and ease of processing. It is resistant to atmospheric agents, although it may yellow after prolonged exposure to UV radiation without adequate protection. It exhibits good stiffness and hardness but has low resistance to impact and scratching (around 20 HB) [2], which is significantly lower compared to stainless steel 316 (140–190 HB) [3] and glass (approximately 1550 HB) [4], whose hardness on the Mohs scale ranges between 6 and 7 [5]. The density of PMMA ranges from 1.15 to 1.19 g/cm^3 [2], considerably lower than that of glass (2.40–2.80 g/cm^3) [6], making it lighter and easier to handle. Additionally, it is a good electrical insulator and shows fair chemical resistance, although it is sensitive to substances such as acetone and chloroform.

Methods

As previously mentioned, two analytical techniques were employed. Differential Scanning Calorimetry (DSC) is an analytical method that measures the difference in heat flow between a sample and a reference while both are subjected to a controlled heating or cooling program. The main goal of DSC is to identify the thermal transitions of a material, such as melting, crystallization, glass transition (Tg), as well as exothermic or endothermic chemical reactions [1]. Fourier Transform Infrared Spectroscopy (FTIR), on the other hand, is an absorption-based spectroscopic technique widely used for material characterization and chemical bond analysis [2]. The measurement is carried out using an interferometer, which enables the simultaneous scanning of all frequencies present in the IR radiation emitted by the source. This is achieved through a moving mirror that, by shifting, introduces an optical path difference. This difference generates constructive or destructive interference with the beam reflected by a fixed mirror, resulting in an interferogram from which the spectrum is obtained by Fourier transform.
A schematic representation of the scanning mechanism using a moving mirror is shown in Figure 1 [3].

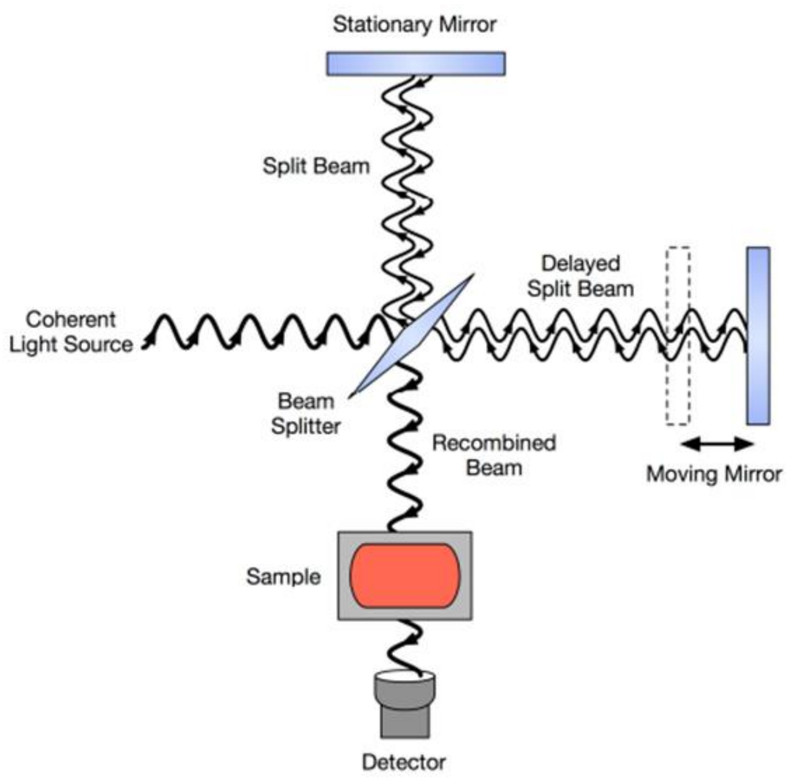


Figure 1_Scanning with a moving mirror

Findings

In the thesis work, DSC was employed to determine the glass transition temperature of the five samples. As an example, Figure 2 shows the graph for one of the samples.

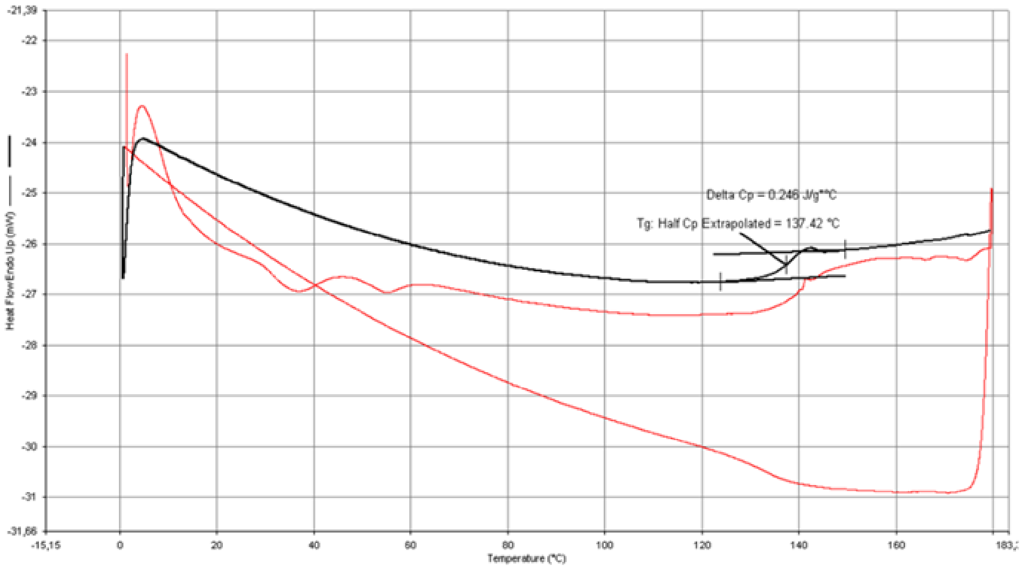


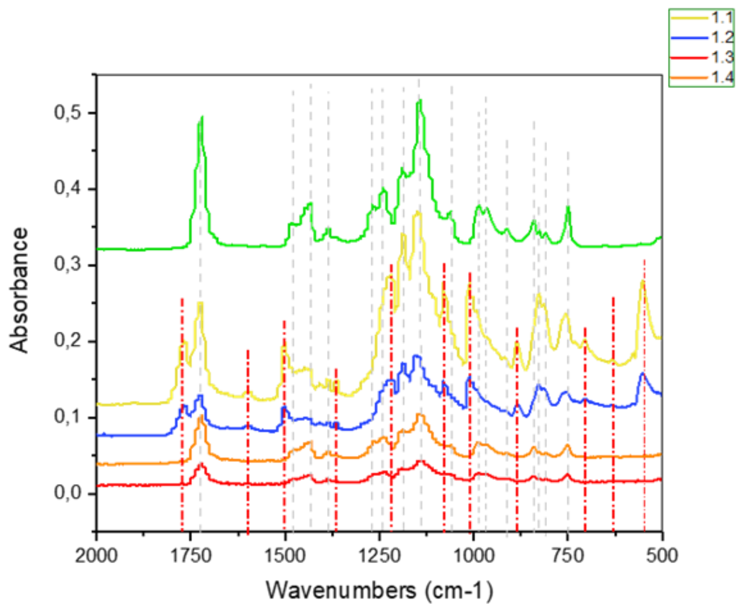
Figure 2_DSC

The obtained Tg is 137.42 °C, which is significantly different from that of PMMA, typically reported between 110–113 °C in the literature [7]. This is a clear indication that the sample is not composed solely of PMMA. Regarding FTIR, as an example, Table 1 shows the characteristic peaks of PMMA [10].

Table 4. Characteristic peaks of PMMA

Wavenumber (cm^{-1})	Band Assignment
1720	C=O stretching of ester group
1480	CH_2 bending
1430	CH_3 asymmetric bending
1390	CH_3 symmetric bending
1270	C–O stretching (ester)
1240	C–O–C stretching (ester)
1190	C–O–C asymmetric stretching (ester)
1140	C–C–O stretching
1060	C–O stretching
985	CH_2 out-of-plane bending
964	CH_3 rocking
910	C–H out-of-plane bending
840	CH_2 wagging
827	CH_2 rocking
810	C–H bending
750	C–O–C out-of-plane deformation

Figure 3 shows the characteristic spectra of the sample, divided into different samples due to its heterogeneity, compared with those of pure PMMA, represented by the spectrum in green.



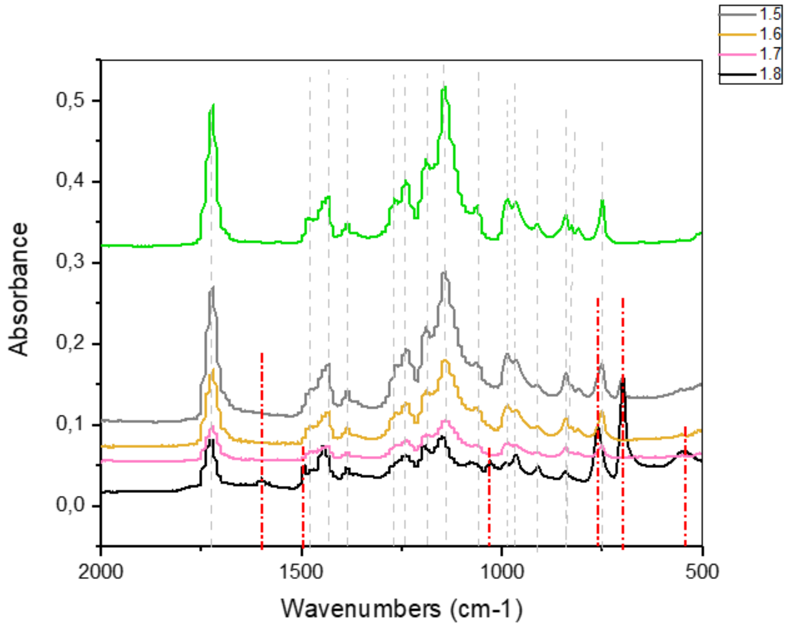


Figure 3_FTIR Spectra

The dashed lines indicate the peaks that differ from those of PMMA, and analysis using the OMNIC SPECTA software confirmed the presence of polycarbonate in the sample alongside PMMA [8] and polystyrene [9].

Conclusions

FTIR proved effective in detecting compositional differences in heterogeneous samples not composed solely of PMMA. Analyses revealed that the samples contain other substances alongside PMMA, which alter their properties. FTIR identified signals suggestive of additives, impurities, or other polymers, confirmed by DSC measurements showing a glass transition temperature different from that of pure PMMA. These differences are critical for optimizing recovery and depolymerization processes, as the presence of additional components can affect efficiency and yield. Identifying and separating these substances is essential to improve the quality of recycled PMMA. Further developments may focus on optimizing process conditions and conducting a deeper sustainability assessment to promote more efficient and environmentally friendly recovery strategies aligned with the circular economy.

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Recycling of Lithium-Ion Batteries: Technologies, Safety, and Sustainability

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Abstract

This work looks at how to manage lithium-ion batteries (LIBs) in a more sustainable way, highlighting the importance of recycling to cut down on raw material dependency and reduce environmental impact. It reviews the main recycling technologies, focusing on hydrometallurgical and pyrometallurgical processes, and describes experimental work on recovering metals from NMC cathodes using citric and hydrogen peroxide. The findings show nearly complete recovery of valuable elements like lithium, cobalt, nickel, and manganese, and it also gives a safety view of the main kind of recovery technologies through the use of intrinsic safety index with the inherent safety. This study underscores why circular economy strategies for critical raw materials are so important within the European Union due its very low supply.

Introduction

Lithium-ion batteries have become a backbone of today's energy transition, especially as we move toward more electrification and sustainability. They're widely used in electric vehicles, portable devices, and energy storage systems because of their high energy density, long lifespan, and quick charging. But making these batteries requires large amounts of critical raw materials [5]—like lithium, cobalt, nickel, manganese, and graphite—most of which come from outside the EU. This dependency brings risks to supply security and raises serious environmental and ethical issues, particularly linked to mining in unstable regions like the Democratic Republic of Congo and in the south America. To face these challenges, we need to apply circular economy principles throughout the LIB value chain. Recycling spent batteries lets a massive recovery of valuable materials, degrowth the environmental footprint and reduce the demand for virgin resources. This paper explores different LIB recycling technologies and presents experimental work on a hydrometallurgical process aimed at maximizing metal recovery and gives some advice for keeping safety and environmental risks low.

Methods

The experiments focused on hydrometallurgical treatment of NMC cathodes taken from end-of-life LIBs [1],[3]. The material, supplied by COBAT, went through mechanical pretreatment including disassembly, crushing, and homogenization. The particle size was reduced to improve leaching efficiency. Leaching tests were performed using sulfuric and citric acids under varying conditions. A two-level factorial design helped to evaluate how temperature, solid-to-liquid ratio, acid concentration, and oxidant addition (citric acid) impacted the process. Parameters were optimized through statistical analysis, with ICP-OES used to examine leachate compositions. After leaching, a multi-step liquid-liquid extraction process was carried out using organic solvents and complexing agents like DMG to selectively separate metals. Precipitation was then used to recover lithium as Li_2CO_3 and transition metals as hydroxides. Material balances and green metrics such as E-factor has been calculated.

Equation 1 Environmental Factor

$$EF = \frac{m_{waste}}{m_{main\ product}}$$

It was used for the evaluation of waste's amount in a process related to the quantity of main products obtained from itself. The Intrinsic Safety Index (ISI)[4] method evaluated process risks through two sub-index that represent: toxicity, flammability, explosivity corrosiveness and other for the Chemical Inherent safety sub-index and level of: pressure, temperature, volume of storage and the kind of equipment for the Process (or Physical) Inherent safety index, the sum of them gives the total index.

Equation 2 Safety Index formula

$$I_{SI} = I_{CI} + I_{PI}$$

Findings

The results showed the process was highly effective: leaching reached 100% for lithium and nickel, 99% for cobalt, and 98% for manganese under optimized conditions.

Table 1. Leaching condition (table 53 on thesis)

H2SO4	2,5	M
A.C.	0,02	g/ml
S/L	0,15	g/ml
t	30	Min
T	80	°C

Citric acid with sulfuric acid proved better than sulfuric acid with hydrogen peroxyde in terms of selectivity and mineral acid's concentration, especially by limiting unwanted copper dissolution. The process allowed for efficient separation and recovery through solvent extraction and sequential precipitation. Lithium was recovered as carbonate, while cobalt, nickel, and manganese were separated by adjusting pH and using complexing agents.

Mass balances and process flow diagrams revealed high recovery rates with minimal reagent use whether in the process itself is implemented the recirculation of solvents. This side was highlighted by the green metrics that were nominated before. The safety analysis showed the hydrometallurgical process had same amount of risk than pyrometallurgical, for the first one the risk came almost totally from the Chemical factors for the other one the concentration of risk came from physical side of the process (using high temperature and pressure mainly).

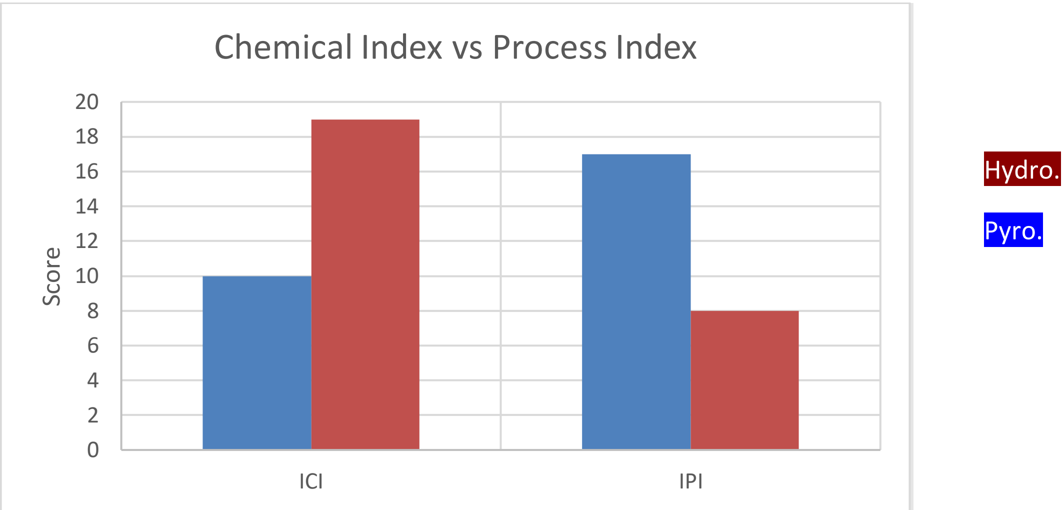

Figure 1_Confrontation between Chemical and Process sub-index for inherent safety factor (figure 98 on thesis)

The main difference between these two typologies of risk is that chemical risk is more manageable than the physical that might originate for T and P very high, so for this reason, or at least for Laboratory scale, the hydrometallurgical process was considered better.

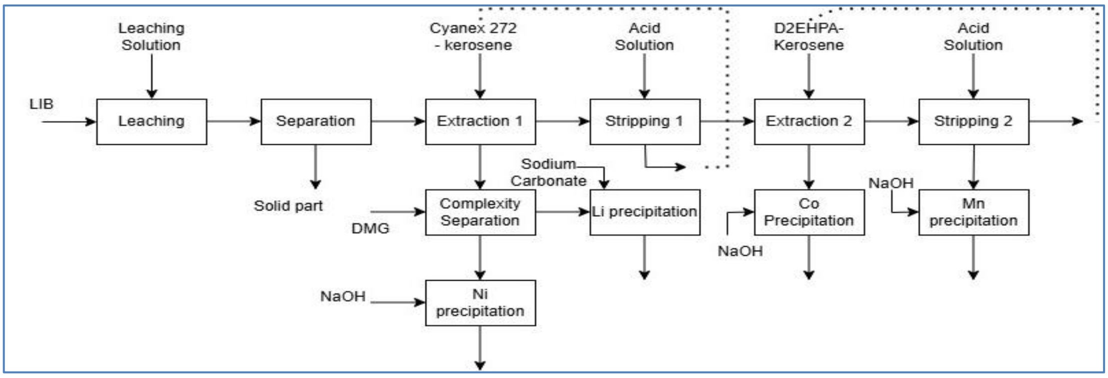

Figure 2_Flow diagram of the whole recovery process (figure 78 on thesis)

Discussion/Conclusion

Overall, this study demonstrates the potential of hydrometallurgical recycling for LIBs, achieving excellent recovery rates with improved safety. Using citric acid and reduce quantity of sulfuric acid. Unlike energy-intensive pyrometallurgical methods, this approach reduces CO_2 emissions and hazardous by-products. These findings have major implications for building a circular battery economy in the EU, cutting strategic dependencies and strength supply chain resilience. Still, challenges remain in scaling up, keeping costs down, and dealing with the variety of battery chemistries and designs in real-world waste streams.

Future research should look at combining second-life applications with recycling, developing continuous flow systems for industry, and considering safety into process design from the start. Policy support, standardization, and investment in recycling infrastructure will be key to creating a sustainable LIB ecosystem.

Acknowledgments

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Circular economy and waste toward sustainability.Basell Poliolefine Italy, a case-study.

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Abstract
The role of circular economy as a solution to the waste management emergency is analyzed. The objective is twofold: both to reconstruct the environmental regulatory framework and explore the potential of a new circular economic model, where waste is protagonist; and to examine how regulations translate into business operations as in the case-study. The first chapter examines the sources of environmental law, with particular reference to European and Italian regulations. The second chapter delves into the principles of the circular economy, tracing the impact of waste on the economic system and the benefits in terms of its reduction and sustainable end-of-life management. The third chapter is dedicated to Ferrara plant (LyondellBasell), which is making significant progress by tying corporate strategy to sustainability goals to close the “circle” and align with environmental regulations. The case is an example of how companies can adopt circular practices, improving their economic and environmental sustainability.

Keywords: Circular economy; Waste; Law; Sustainability; Recycle

Introduction
In the past, man has found himself faced with the need to introduce innovations to counter situations that threatened humanity. Among the many current emergencies, the problem of waste management is looming over the prospects of life’s quality of the women and men who inhabit the Planet today and of future generations that will follow. There is an urgent need to deal with a situation, in some ways silent and under the radar, in which determining factors get many roles and where it is very hard to identify the most appropriate and effective "points of attack" – also because they are the subject of political speculation, disputes and interpretations – to impact on the critical issues of global socio-economic development that has exceeded its limits [1]. One of the levers available to society to address the topic of waste is identified in some applications of Circular Economy [2] that are based on an organizational chain based on "*sharing, lending, reconditioning, reusing, repairing and recycling*" as opposed to a conflicting vision, nowadays running and partly still in use, in which a linear flow is realized according to the unsustainable scheme "*collect, produce, consume and throw away*". The motivations that inspired this work contribute to identifying a double objective: on the one hand, to analyze the European and Italian regulatory framework [3,4] in the field

of Environmental Law and its emergence throughout history, to study the relationship between waste management and the circular economy from a sustainability perspective, to explore the legal principles and policies that characterize these issues. On the other hand, to examine – using an integrated approach that allows to highlight not only the challenges but also the opportunities that companies can seize by adopting environmentally sustainable models – how regulations related to waste management and circular economy translate into operational practices within a specific business context [5].

Methods

The adopted working methodology combines the analysis of sources of jurisprudential literature and current regulations with empirical research carried out during a curricular internship at the Emilia-Romagna site of one of the most important realities of the global petrochemical industry: Basell Poliolefine Italia (BPI) – LyondellBasell group [6]. A work articulated, fundamentally, in interviews with managers and technicians, direct observation of production processes, acknowledgement of operating procedures, examination of company practices relating to waste management, study of the implementation of recycling technologies in a circularity perspective and analysis of the sustainable approach adopted by the Company which clearly highlights the potential that these can have towards a sustainable and balanced future. More specifically, the survey intends to give structure to the collection of information regarding a very advanced industrial experience of circular economy and to contextualize it in a legal "framework" both national and European and international, not limiting itself to describing the current state of affairs but aiming to present possible future options for environmental policies and industrial practices, identified among those present in the field, with the objective of promoting sustainable and responsible development.

Findings

In recent decades, the topic of environmental sustainability has become central to political, legal and economic debates, driven by the growing awareness of damages caused to the ecosystem by traditional development models. In this scenario, waste management and circular economy have emerged as global priorities, requiring a profound cultural, regulatory and productive transformation. Environmental law, in its historical evolution, has assumed a fundamental role in defining the rules and principles that govern the relationship between human activities and the environment. This regulatory complex, born as a reaction to environmental crises and disasters, it has progressively been structured through international, European and national sources, until it was also recognized in the Italian Constitution, as demonstrated by the 2022 Amendments to Articles 9 and 41 [7]. However, this process has not been linear: case law has often anticipated the Legislator, filling regulatory gaps and paving the way for new forms of environmental protection, as in the famous case of the “Italian Court of

Cassazione" in 1979 which recognized the right to a healthy environment as a fundamental right. This evolutionary Jurisprudence has brought out an approach to environment matter as a transversal legal asset, unfit to consolidated categories, but in strong need of dynamic and intersectoral regulation. In our Country, the regulatory framework has been enriched with increasingly sophisticated tools to address environmental issue, but there has been, and still is, no shortage of critical ones: the fragmentation of competences between Central and Regional Administrations, excessive bureaucracy and the slowness in implementing European Directives have often hindered effective and timely action. In this context, the National Recovery and Resilience Plan (PNRR) [8] offers an extraordinary opportunity to overcome the historical weaknesses of the Italian system. The PNRR, in fact, allocates very significant resources to the ecological transition and the circular economy, setting ambitious goals for decarbonisation, waste management, green infrastructure and technological innovation, but a result with positive effects will depend on the ability of the Institutions to translate strategic directions into concrete interventions, capable of producing long-lasting effects on the productive and social context.

At the same time, circular economy has established itself, on a conceptual level, as an alternative paradigm to the linear model of production and consumption: not only a different waste management strategy, but as a comprehensive vision of the economy that promotes the reduction of waste, the reuse of resources and the recycling of materials but its adoption requires the active involvement of all the actors in the field: Institutions, businesses, citizens.

In this context, the need for a profound cultural and systemic review emerges forcefully, including environmental education, regulatory incentives and a synergic and un-conflicting multilevel governance. Civil society, actings a key role, must be "listened" and local public services must become part of integrated waste management systems.

And, last but not least, the transition to a completely circular economy cannot ignore Companies that are called upon to rethink their production models, plan in the medium-long term and invest in innovative technologies.

An emblematic case of this change is represented by Basell Poliolefine Italia, a production settlement of LyondellBasell group. This Company, active in the Ferrara's chemical hub, has distinguished itself for its ability to integrate sustainability into its corporate strategy: the approach adopted is based on three main guidelines: process optimization, reduction of environmental impact and technological innovation.

Among the most significant interventions is to be noted the development of the MoReTec-1 project, a chemical recycling technology that allows mixed plastic waste to be transformed into secondary raw materials, overcoming the limits of traditional mechanical recycling. The goal is to close the plastic cycle, allowing a potentially infinite regeneration of the resource and reducing dependence from virgin raw materials.

But the commitment of the LYB is not limited to technological process, in fact a structured environmental governance has been adopted, based on certified management systems, continuous monitoring of performance and transparency towards stakeholders.

Emissions have been progressively reduced, solvents recovered and waste increasingly valorised with the aim of becoming “net zero” by 2050, with a 42% reduction in direct emissions by 2030.

The Ferrara settlement also stands out for its attention to the territory, with collaborative projects with local Authorities, Universities and research Centres. This experience demonstrates how plastic, often the subject of a demonising narrative, can actually play a fundamental role in sustainability, if managed responsibly. Its characteristics – lightness, resistance, versatility – make it indispensable in many strategic applications, from medicine to construction, from food packaging to automotive. Eliminating plastic indiscriminately often means replacing it with more impactful materials; the solution is not its removal and abandonment, but its conversion into a resource through integrated and intelligent life cycle management. This study case represents a virtuous example of how it is possible to combine economic growth, industrial innovation and environmental responsibility. In a still uncertain regulatory context, the Company wanted to interpret sustainability not as a constraint, but as a competitive opportunity and this proactive approach could become a reference to face the challenge of ecological transition. Finally, the results of this research show that sustainability is a complex and multilevel construction, which requires the integration of law, politics, technology and culture. The future of environmental management cannot ignore a regulatory reform aimed at simplification, clarity and support for innovation. At the same time, a true commitment from the private sector is needed, capable of promoting systemic change. Plastic, chemistry and industry are not enemies of the environment: well-guided they can be fundamental allies. We need to abandon dichotomous logics and build a more mature narrative, which recognizes the complexity of environmental challenges and gives value to the concrete solutions already available today.

Discussion/Conclusion

"How waste is being something else": one of the most significant steps in the transition [9] from a linear economy to a circular model concerns the ability to rethink the very concept of waste: the legal system – both European and national – has introduced two fundamental tools: the qualification of by-product and the concept of End of Waste [9]. They represent a cultural and regulatory turning point in the management of resources, opening the possibility that what was once discarded can instead find new life, value and function. In the European regulatory framework, Directive 2008/98/EC (later

updated by Directive 2018/851) has established clear criteria to distinguish what is waste from what, despite being a production residue, can be reintroduced into the economic cycle without causing harm to the environment or human health; national legislation, implemented with Legislative Act n° 152/2006, has made these tools operational, albeit with many interpretative ambiguities that still generate uncertainty among operators. In the direct experience of Basell Poliolefine Italia, this distinction materializes daily in the management of production flows; materials that, in a traditional industrial model, would have been destined for disposal are now classified as by-products according to well defined technical and legal criteria: traceable origin from a production process, certainty of use, no further treatments needed. For example, plastic waste that can be reused in other internal production cycles or sold to other industrial plants as secondary raw material. The legal recognition of a residue as non-waste has significant practical implications: reduction of management costs and emissions associated with disposal, increase in the rate of circularity. But it also has a symbolic value: it demonstrates that, with a correct regulatory, managerial and technological vision it is possible to give new dignity to materials that until now were considered waste.

This research path clearly highlights how plastic materials, if properly managed, not only do not represent an obstacle to sustainability, but rather constitute an enabling element of high value for a more resilient and circular society. Its demonization turns out to be not only unfounded, but also counterproductive, as it distracts attention from the real critical issues of the system: the lack of infrastructure for recycling, the lack of environmental education and the poor diffusion of eco-design.

The main problem is the mismanagement of polymers, just two numbers are enough to understand the global dimensions of this problem: out of total amount of plastic produced a rate of 29% is destined for disposal through landfills while, but even more alarming, is the percentage of 31% of total plastic that escapes management and is dispersed in the environment. These are huge numbers that make it clear, once again, what is the real problem linking plastic and the environment and in which the human's management plays a decisive role why, unfortunately, it has “sullied” the reputation of the role and usefulness that plastics have had in recent human history.

The experience of LYB, with particular reference to the Ferrara site, provides a solid and replicable case history. The integrated approach – which includes technological innovation, climate commitment, responsible management of resources and stakeholder involvement – shows how the plastic industry can be part of the solution, not the problem.

Sustainability cannot ignore a systemic vision. Only by adopting a life cycle perspective, which considers production, use and end of life of materials, is it possible to make informed and truly effective choices. In this sense, the LCA (Life Cycle Assessment) approach, still poorly spread in the public debate, should become the basis of every regulatory and design decision.

For the future, it will be essential to promote cooperation between businesses, institutions, the academic world and citizens to build a plastic economy that is circular, responsible and sustainable. Therefore, plastic must not be seen as an enemy, but as a material to be "reconciled" with the environment. It is time to overcome simplifications and build a more balanced narrative, which recognizes the complexity of the issue and enhances the concrete solutions already available today: a path that will not be able to make progress if the Legislator does not consolidate the regulatory basis and the industrial world does not give itself medium-long term programs.

Finally, the transition to a circular economy model can no longer be postponed and must start from a joint action, not only driven in a top-down approach by institutions and businesses but also fuelled by the active and conscious involvement of citizens. The empowerment of society, flanked by adequate public policies and a thorough regulatory review, will be decisive in addressing the complex environmental challenges of our time.

However, this transition [10] cannot be based on slogans or ideological approaches: it requires a genuine rebalancing of the relationship between man and the environment, based on pragmatic solutions and supported by solid scientific evidence. Only a rational approach, capable of integrating technological innovation, effective regulatory tools [11] and targeted environmental policies, will be able to generate systemic change and tackle the current ecological crisis with realism - but with ambition too. Sustainability, in this perspective, becomes a collective and intergenerational responsibility [12], to be built day by day with conscious choices, competence and vision.

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Recycled aggregates in urban redevelopment processes: The "Magone" of Colle Aperto

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Abstract

This thesis deals with the theme of sustainable urban regeneration through the recovery of abandoned buildings, with particular attention to the reuse of demolition materials. The case study is the "Magone" in Colle Aperto, Mantua: an unfinished commercial building that has been abandoned for over thirty years. The project proposes a strategy of selective demolition and on-site reuse of recycled concrete (from demolition) in combination with wood, a renewable material, in order to improve its structural and environmental performance. Experimental laboratory tests have validated the compressive strength of mixtures containing up to 60 per cent recycled aggregates. The intervention envisages the construction of new buildings with different uses, valorising existing resources and reducing the use of virgin materials. The results confirm the possibility of using recycled concrete for structural reinforcement, cladding and fire protection, promoting a replicable model for the sustainable management of disused building stock and the reduction of the environmental impact of construction.

Keywords Disused Buildings; Waste Of Resources; Building demolition; Concrete with recycled aggregate; Renewable Material

Introduction

This research stems from the analysis of a critical issue that is widespread within the entire Italian territory: the presence of a large number of abandoned and unused buildings that shape both the urban and rural landscape. According to data collected in 2020 by the National Institute of Statistics (ISTAT) and the CESCAT Study Center, the number of disused and abandoned buildings in Italy is estimated at approximately 7 million units [1]. These buildings represent a representative case of inadequate land and material resource management. In particular, the latter are not properly valued either during the building's life cycle—often due to abandonment even before construction is completed—or at the end of the building's service life. Frequently, following demolition, the material is not reused on-site but is instead typically sent to treatment facilities. Although this process complies with current regulations for the management of construction and demolition waste, it appears to be environmentally unsustainable. The research developed is aimed at defining a system for the recovery and enhancement of existing resources, utilizing local opportunities to minimize material waste and the use of new resources. Among the most significant environmental impacts within the life cycle of a building are land consumption, energy and material resource use, and the resulting greenhouse gas emissions, as well as the production of construction waste that occurs during the industrial manufacturing of building components, on-site construction, and building decommissioning[2]. The study is motivated by the necessity to avoid the exploitation of new material resources in construction and to promote the reuse of existing ones, through the development of a strategy that can be applied to the numerous abandoned commercial and industrial buildings within the Italian territory. Due to their disuse, these structures can contribute to social issues and safety concerns. The analyzed strategy was applied in the development of a project based on a case study located in the peripheral area of Mantua. The intervention concerns a commercial building whose construction began in 1992. However, already in 1993, work was halted after the completion of the reinforced concrete structural framework, leaving the building abandoned for over thirty years. Following the reversion of the surface rights on October 26, 2023, the municipality started demolition operations, which were completed within approximately three months [3].

Methods

For the definition of the project, special attention was paid to the nature of the site of interest, the observations of the residents and the various information provided during the meetings with the local administration of Mantua. The project intervention is primarily aimed at the regeneration and enhancement of an underused urban area with evident signs of degradation and abandonment. It provides for the preservation of a portion of the pre-existing structure corresponding to the bottom floor and the foundation slab, which will be subjected to reinforcement works to allow the development of the building complex. In addition, the selective demolition of the above-ground floors and the following complete material recovery was considered in order to use the recycled concrete for the construction of three new buildings (Figure 1).

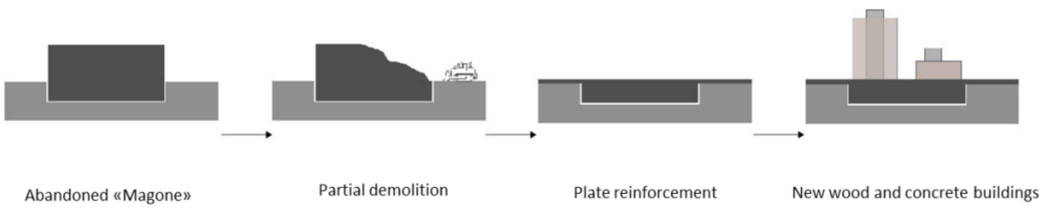

Figure 1_Development phases of the project

The strategy is oriented towards the recovery of existing material already produced, in the form of aggregate, avoiding the use and exploitation of new energy- and carbon-intensive material resources. On the contrary, the use of renewable materials is promoted to ensure a more responsible use of natural resources through continuous regenerative processes. The research objective, therefore, aims at improving the management of existing building materials through the reuse of materials that, despite having lost part of their initial value, can improve the characteristics and performance of other materials with a lower environmental impact, such as wood. Through the construction of test specimens and subsequent compression fracture tests, it was possible to validate the strength of concrete containing different percentages of recycled aggregate, from the demolition of the case study building, as a replacement for virgin concrete to be used in different applications. In particular, two mixtures were defined with 30% and 60% recycled aggregate, respectively, and although these percentages exceeded the limits set by the regulations in force [4], the strength was found to be slightly lower than that which would have been obtained with natural aggregates. The selective demolition of the Magone di Colle Aperto resulted in a total of 2045 m³ of concrete, to be recycled, derived exclusively from the ground and first floor, as the basement kept its original use as a car parking area (Table 1). During the development phase of the project, it was possible to estimate the total quantity required of 1928 m³ of concrete for the construction of the new building structures, designated to provide different functions according to its use.

Table 1. Quantities of materials and dimensions of the elements of existing building (re-elaboration from executive design by SOPRINT engineering).

EXISTING CONCRETE TO BE POTENTIALLY RECYCLED		
	Thickness (m)	m³
Parapets - precast R.C. panels	0,1	55
BOTTOM FLOOR of which rectangular beams, "L" shaped perimeter beams, "T" shaped dock beams, pillars, R.C floor slab, predalles slab	0,2 (R.C. slab)	1146
GROUND FLOOR of which rectangular beams, "L" shaped perimeter beams, "T" shaped dock beams, pillars, R.C floor slab, R.C. slab and façade panels	0,1 (R.C. slab); 0,2 (panels)	922
FIRST FLOOR of which rectangular beams, "L" shaped perimeter beams, "T" shaped dock beams, pillars, R.C floor slab, R.C. slab and façade panels	0,1 (R.C. slab); 0,2 (panels)	999
Total concrete of the "Magone" (including iron)		3191
Concrete to be recycled (non considering bottom floor that is not demolished)		2045

The development of the project led to the definition of two units. The first volume, to the north-west, is a multifunctional building developed on seven levels: the ground floor houses commercial activities, while the upper floors contain a gymnasium, polyclinic, library and a public terrace overlooking the Andr gardens and the new park [Figure 2]. The structure is made of X-Lam wood, with recycled concrete slabs. The glazed facades, with fixed and pivoting elements, are protected by mechanised movable larch sunshades. A central concrete volume integrates the system substations and the independent stairwell, also made of concrete, equipped with a smoke-proof filter with REI double doors. This core ensures separate access to the floors and improves the structural rigidity of the entire construction. The second volume, to the east, is on two levels: on the ground floor there is a pharmacy, on the first floor the complex's facilities. The structure is also made of wood, clad with larch slats that also extend over the sloping roofs, generating visual continuity. The third volume, to the south, is accessed by a timber and glass foyer connecting the new 180-seat theatre (to the east) and a restaurant space (to the west). The theatre is served by a staircase leading to a projecting volume with a 14 m high stage tower clad in recycled concrete, visually related to the stairwell of the main building. The refreshment area has a separate entrance and a second access allows the use of youth association spaces on the upper floor [Figure 3].

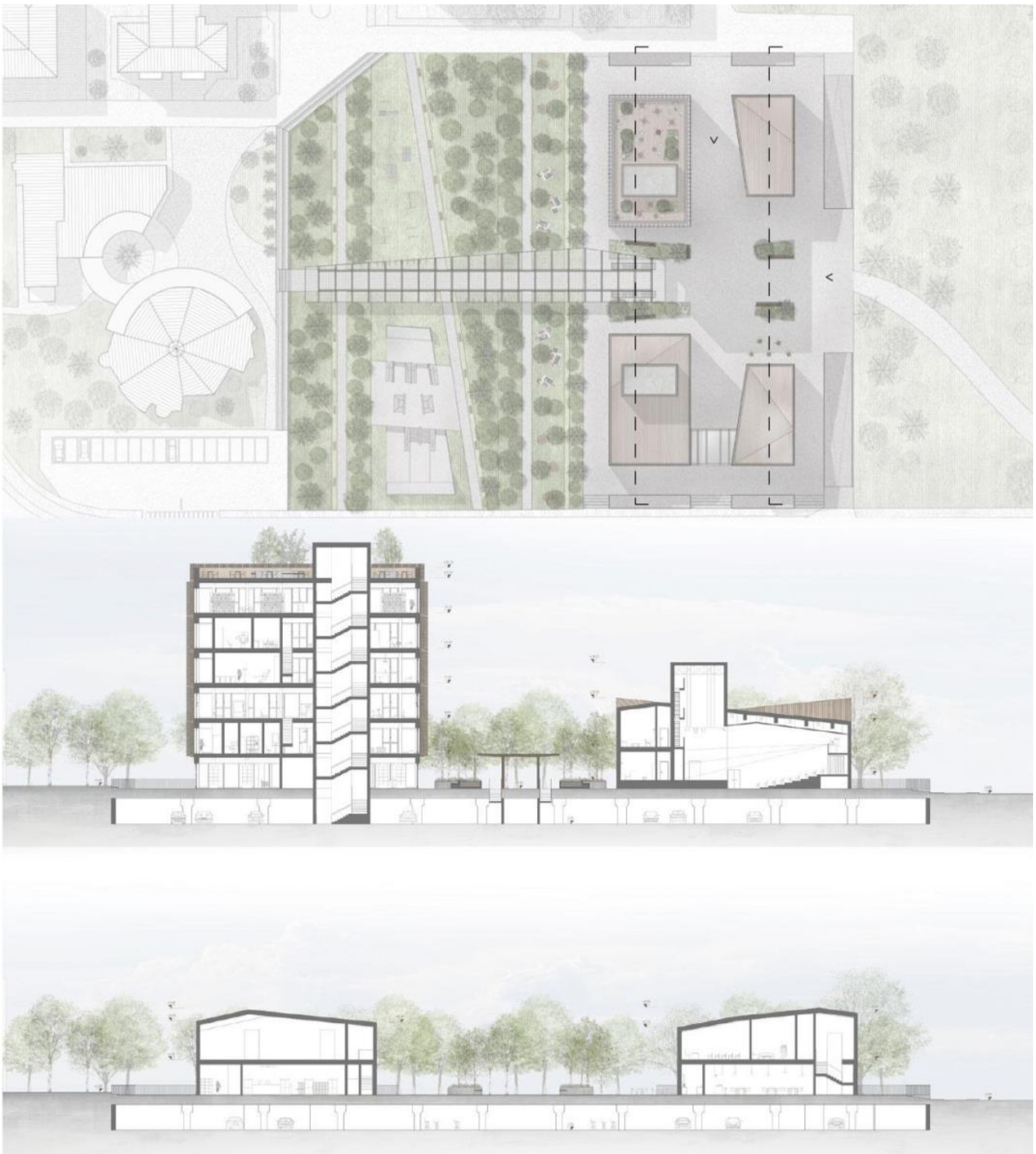

Figure 2_Project plan and sections.

Figure 3_Project views, north access (left) and east access (right).

Findings

The proposed construction system involves the combination of wood and recycled concrete, allowing the use of the latter, which has been little used in construction to date, in structural applications as well, limiting the consumption of new material resources. This combination contributes to different benefits such as improved structural performance, reaction and fire resistance characteristics, and protection of the timber elements, allowing the reduction of their load-bearing section also with a view to careful management of resources, although renewable. This system makes it possible to exploit and optimise the best properties of the two materials for the installation of 'frameworks' capable of bearing large loads, obtaining a structure with high stability and resistance, as well as allowing the construction of larger spans. Recycled concrete, therefore, is used in both structural and non-structural functions. The former is evidenced by the insertion of collaborating slabs for the reinforcement of the new timber structures and the foundation slab so that an independent construction system can be adopted that is unrelated to the pre-existing one. Its reinforcing function also allows the development of a larger number of levels for the construction of new buildings. For this application, for which the use of concrete with a medium percentage of recycled aggregate was planned, a total of 911 m³ of concrete was required. The second, non-structural function is that of cladding internal partitions and vertical and horizontal closures of buildings for protection against both fire (internally) and weather (externally). For the latter type of application, assuming the use of concrete with a high percentage of recycled aggregate, this results in the use of a total of 111 m³ of concrete for reaction and fire resistance purposes, while a total of 150 m³ is required for the protection of timber elements. In addition to this, it is also used as flooring inside the building and outside. A total of 642 m³ of recycled concrete is also used for the street furniture and paving of the square. On the other hand, for the construction of the pedestrian paths in the park, some of the material recovered from the demolition is used directly following its crushing, for a total of 113 m³ (Table 2).

Table 2. Material quantities of the project for the three different uses of recycled concrete.

RECYCLED CONCRETE USED IN THE PROJECT	
STRUCTURAL PERFORMANCE	
Total reinforcing slab	911 m³
FIRE REACTION AND RESISTANCE	
Total coating for fire reaction and resistance	111 m³
PROTECTIVE COATING	
Total coating for element protection	150 m³

In reference to the quantities of recycled aggregate foreseen above, a percentage of 30% recycled aggregate was considered for concrete with a structural function, and 60% for the other cladding functions. As a result, the total amount of aggregate required is 1092 m^3 equivalent to 53% of the volume of material from the demolition of the building. Following the breakage tests carried out in the Betonrossi Laboratory, it became possible to increase the use of recycled aggregate up to 60% for structural uses and up to 80% for cladding elements. According to this second hypothesis, the total aggregate requirement is 1636 m^3, corresponding to 80% of the total volume of concrete obtained from demolition.

Discussion/Conclusion

The mixes made and tested in the laboratory showed that, despite the use of recycled aggregates, the mechanical strength obtained is comparable to that of traditional concrete with natural aggregates. The results confirm the possibility of using concrete with a structural function even with a recycled aggregate percentage of 60 per cent, significantly exceeding the 30 per cent limit stipulated by the Technical Standards for Construction. However, it is not technically possible to achieve 100 per cent recycling of material from demolition, since a part, such as fine sand, cannot be recovered. Consequently, it is always necessary to integrate a minimum proportion of natural aggregates to ensure a complete granulometry suitable for concrete production. Recycling is not the only strategy to reduce construction waste and limit the environmental impact of landfilling and extraction of natural resources; reuse, according to the European Waste Hierarchy, is a priority option. Indeed, reusing materials conserves embodied energy, reduces resource consumption and CO_2 emissions, while potentially having a greater impact than recycling, which often requires energy-consuming processes [2]. Since about 70 per cent of a building's environmental impacts are related to the materials used, reuse is preferred wherever possible. However, in the presence of highly degraded structures, as in the case analysed - an unfinished concrete building - reuse was not possible, necessitating demolition with subsequent recovery and reuse of the material on site. The thesis project addresses the issue of building abandonment by proposing a recovery strategy that valorises demolition materials, such as recycled concrete, in synergy with renewable materials with a low environmental impact. This integration reduces the use of virgin resources and promotes sustainable management of construction materials. The approach is applicable to numerous cases of disused buildings, encouraging urban regeneration processes and reducing environmental and social impacts.

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Waste prevention and recycling in schools: the role of nudges in shaping sustainable practices

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Abstract

Waste management and environmental sustainability have become pivotal concern in the face of global environmental challenges. This study investigates the role of behavioural interventions, specifically nudges, in shaping students' attitudes and behaviours toward waste prevention and recycling in a high school setting. The research explores three hypotheses: the immediate effects of nudges on behaviour, the differential impact of specific nudges, and the persistence of their influence over time. The experimental design involved treatment and control groups, with questionnaires and monitoring sheets administered in three phases. Data were analysed using statistical tests, including Fisher's Exact Test. Findings show that nudges significantly improved environmental awareness and pro-recycling attitudes, though some practical behaviours, such as sorting accuracy, revealed limitations. Nevertheless, results highlight the potential of nudges as scalable, low-cost tools to foster pro-environmental actions in educational settings. The study concludes by emphasizing the importance of integrating behavioural strategies into sustainability education and provides recommendations for refining program design and for future research.

Keywords: Waste Management, Recycling Behaviour, Waste Prevention, Nudge, Behavioural Economics, Social Influence, Environmental Policy, Peer Behaviour, Attitudinal Change

Introduction

In today's context of escalating environmental challenges, sustainable practices are increasingly urgent. Waste management emerges as a critical issue with strong environmental, social, and economic implications. This thesis explores the intersection of behavioral economics, environmental psychology, and waste management, focusing on how subtle interventions, or *nudges*, can promote sustainable practices within schools. As microcosms of society, educational institutions provide an opportunity to instill behaviors that extend beyond the classroom. The study is based on an overview of waste management, including definitions, classifications, and practices such as prevention and recycling, emphasizing EU directives and the waste hierarchy. It then examines behavioral theories such as the Theory of Planned Behavior and Nudge Theory, along with the EAST framework (Easy, Attractive, Social, Timely), to establish the theoretical foundation.

The empirical study, conducted in an Italian high school, tested nudges designed to correct misperceptions about peers' recycling and waste prevention behaviors. Findings highlight their immediate and lasting effects, as well as implications for sustainability education.

Finally, the study discusses limitations, scalability challenges, and future research directions, stressing the role of schools in cultivating environmental awareness. It contributes to the growing field of sustainable waste management by showing how low-cost behavioral insights can support education, policy, and practice.

Methods

This study investigates the role of behavioral interventions, specifically "belief update" nudges, in shaping waste prevention and recycling behaviors among high school students. While economic instruments have been shown to influence waste management, research emphasizes that intrinsic motivations and pro-environmental attitudes often exert a stronger impact than financial incentives. Building on this evidence, the study tests whether correcting students' misperceptions about peer behaviors and attitudes can promote sustainable actions. The study was built around three main hypotheses. The first assumed that students exposed to information correcting misperceptions about their peers' recycling behavior would improve both their waste sorting and their ability to reduce waste. The second focused on attitudes, suggesting that students informed about classmates' positive environmental views would be more inclined to prevent waste than those who only received the behavior-based nudge. Finally, the third hypothesis addressed durability, expecting that the effects of the interventions would continue even after their removal, though with a gradual decline in intensity. The experiment took place at *Istituto di Istruzione Superiore G. Romani* (Casalmaggiore, Italy) over a 20-day period (17 October–8 November 2024). A total of 116 students, aged 14–20, were divided into treatment and control groups across six classes. To avoid contamination, treatment classes were placed on one floor and control classes on another. Random assignment by the school principal reduced bias linked to pre-existing environmental attitudes.

The following table explain the organization of the whole context.

	Control Group	Treatment Group
Number of participants	59	57
Description of Treatments	Students completing all three rounds of the questionnaire without receiving nudge	Students completing the questionnaire and: - 37 students exposed to the beliefs update nudge about peer's behavior - 20 students exposed to both the beliefs update nudge about peer's behavior and attitudes
Educational Program	- 2nd year, Linguistic High School - 4th year, Technical Institute for IT and Telecommunications - 2nd year, Health and Social Care Services Institute	- 4th year, Scientific High School with Applied Sciences - 1st year, Electrical Operator Institute - 5th year, Health and Social Care Services Institute (20 students exposed to both nudges)

Table 5. Group organization and treatment

As procedure, students completed a questionnaire at three stages: before the intervention, 10 days after the introduction of nudges, and 10 days after their removal. The survey assessed personal behaviors, recycling knowledge, attitudes, and perceptions regarding waste management. A final section included reflections on the project.

The mentioned nudges that were presented to the treatment group in form of poster arepresented in this text as “*Figure 1*”. The posters have a clear and visually appealing structure, divided into various sections aimed at promoting environmentally sustainable behaviors, particularly recycling and waste reduction. Different versions of the communication materials were displayed based on the student groups involved, as outlined in the figure. In the first page, the panel introduced recycling with an emphasis on both personal and collective responsibility. A visual breakdown of the school’s waste categories (plastic, paper, glass/cans, general waste) was shown, accompanied by the call to *“do your part”* for a sustainable future. The key message highlighted that recycling is simple and that every small action counts. To leverage peer-to-peer influence, the poster displayed data from the first questionnaire: *“XX% of students at your school are already practicing proper waste recycling.”* In the second page, the same approach was applied with a focus on waste prevention. The poster encouraged collaboration through the message: *“XX% of your classmates bring a reusable water bottle every day.”* These data aimed to create positive social pressure, encouraging students who had not yet adopted such practices to feel part of a virtuous community. Finally, the third page was presented in two versions: the first reiterated the importance of individual action and waste prevention, while the second introduced the belief update nudge about peers’ attitudes: *“XX% of students at your school believe that reducing waste has a positive impact on the environment.”.* This message was designed to reshape students’ perceptions of the impact of their actions, showing that many peers already believe in the value of waste reduction and encouraging broader participation.

Figure 17_Posters with Nudges presented to the treatment group. From the left: first poster, with explicit message to leverage the concept of peer-to-peer influence focusing on waste recyclig. The second poster applied the same strategy but with a focus on waste prevention. n the first version, the Peer Behavior Nudge reiterated the importance of individual action and waste prevention, while in the second, the Peer Attitude Nudge aimed to modify students' perceptions of the environmental impact of their behaviors

Overall, half of the treatment group received only behavior-related nudges, while the other half also received attitude-related nudges.

At the end of the experimental phase, the results were analyzed through the different administrations of the questionnaire to identify any changes in students' beliefs and behaviors. Moreover, to ensure consistency between students' self-reported behaviors on the questionnaire and their actual actions, a common challenge was addressed: participants may overstate sustainable behaviors to appear more favorable, potentially creating an artificial gap between reported beliefs and actual behaviors. To manage this, a monitoring sheet was given to the cleaning staff, who completed it weekly, helping verify alignment between stated intentions and observed actions. The purpose of this document is to record any variations in the quantity and correctness of waste recycling and separation. The monitoring sheet is divided in three main areas: bin availability, correctness of waste sorting, and proportion of avoidable waste using a five-level scale. This mixed-method approach allowed for triangulation between reported attitudes and observed behaviors, strengthening the reliability of findings.

Findings

Before introducing the nudges, baseline data were collected to design the posters. Results showed that about 63% of students already recycled correctly, while only 33% of the treatment group (vs. 51% in the control) regularly used a reusable bottle. Regarding attitudes, 51% of the treatment group (vs. 89% in the control) believed that reducing waste has a positive environmental impact. These gaps suggested that the treatment group had more room for improvement and would likely benefit more from the interventions.

For the statistical analysis, the Fisher Exact Test was applied. This method was chosen because of the relatively small sample size and the categorical nature of the data. By converting survey responses into success/failure categories, the test allowed for robust comparisons between treatment and control groups across different phases. This approach ensured that even subtle changes in behavior and attitudes could be detected with reliability. The experiment revealed several interesting patterns about how students respond to peer-based nudges on recycling and waste prevention. The first intervention focused on correcting misperceptions about classmates' recycling behavior. Here the results were encouraging: students in the treatment group became more aware of the shared importance of recycling and waste reduction, and many strengthened their belief that individual actions can truly make a difference. They also reported being more willing to improve their own habits, and fewer admitted to throwing waste in general bins without seeking proper information. In other words, the nudge succeeded in reducing some careless practices and in boosting both awareness and personal responsibility. At the same time, not everything changed. Despite the posters promoting specific behaviors such as using reusable bottles, there was little evidence of concrete progress in these areas. Students' perceptions of how many peers were already engaged in waste reduction also remained only partially aligned with reality. This suggests that while attitudes shifted, everyday habits proved harder to influence. The second intervention, which emphasized the positive environmental attitudes of classmates, produced similar results with some additional nuances. Students exposed to this version of the nudge showed even stronger recognition of the value of waste reduction and greater confidence in the role of individual responsibility. They also declared more effort to cut down on waste in their daily routines. However, as in the first case, their view of how engaged their peers really were did not change significantly. This gap highlights a recurring challenge: nudges can raise awareness and strengthen motivation, but they do not necessarily succeed in reshaping perceptions of collective behavior. Perhaps the most surprising result came from the third hypothesis, which tested the durability of these interventions. The expectation was that the effects would gradually diminish once the posters were removed. Instead, the opposite occurred: the positive changes remained stable throughout the final phase of the study. Students continued to value recycling and waste reduction, to believe in the importance of their individual contribution, and to show greater willingness to act responsibly. The absence of decline suggests that even a short intervention, when well designed, can have a lasting influence on environmental attitudes. These trends were also reflected, at least in part, in the observational data collected by school staff, as it's showed in *"Figure 2".* During the intervention period, the treatment group displayed a noticeable reduction in avoidable waste, particularly in the first week after the nudges were introduced. Importantly, this lower level of waste was then maintained consistently, while in the control group waste levels fluctuated and eventually rose again. This stabilization indicates that the nudges were effective in embedding more sustainable habits, even if modest. On the other hand, improvements in recycling accuracy were far less evident. Mistakes such as throwing bottles, tissues, food leftovers, or packaging into the wrong bins remained frequent across the experiment. Awareness alone, it seems, was not enough to translate into technical precision when it came to waste sorting.

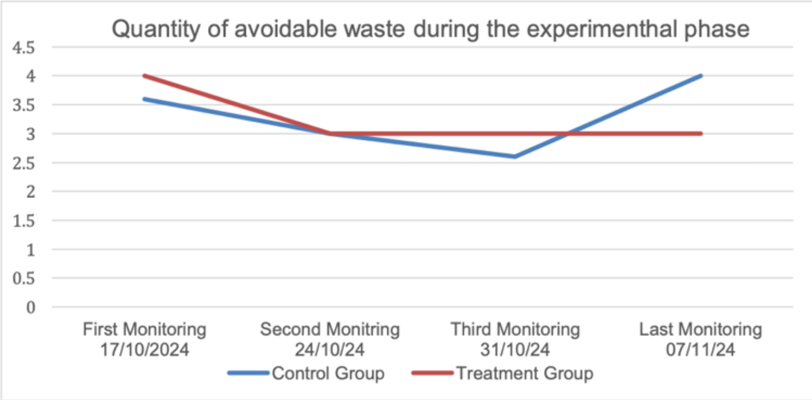

Figure 18_Graph reporting the percentage of avoidable waste registered

Taken together, the findings suggest that nudges can be powerful tools to foster environmental awareness and a sense of responsibility among students. They helped reduce some negative behaviors, encouraged positive attitudes, and, perhaps most importantly, proved capable of leaving a lasting mark even after the intervention ended. At the same time, the limits are clear: turning awareness into consistent daily habits, such as always bringing a reusable bottle or sorting waste correctly, requires more than information and peer influence. It calls for strategies that combine nudges with more practical, hands-on experiences capable of reshaping not just perceptions, but everyday routines.

Discussion/Conclusion

This study shows how simple nudges can help students pay more attention to recycling and waste prevention, but it also points out some limits that should be considered.

The experiment involved only 116 students from a single high school, so the results cannot be easily generalized to other contexts. The short timeframe (just 20 days) also makes it difficult to understand whether the observed changes would last over months or years. Another issue is that the intervention was based only on posters: while useful for raising awareness, they lacked interactive elements that might have made the project more engaging. Feedback from students suggested adding workshops, games, or activities to make the experience more dynamic. Finally, the monitoring relied on staff observations, which may not always have been precise. Despite these limits, the project revealed interesting outcomes. Students exposed to the nudges showed greater awareness of their role in protecting the environment and more willingness to recycle. The “peer behavior” nudge was particularly effective in encouraging a sense of personal responsibility, while the “peer attitude” nudge boosted awareness but did not strongly change perceptions of what classmates were actually doing. Importantly, the positive effects did not disappear once the posters were removed, suggesting that well-designed nudges can create lasting impact. Looking ahead, the study suggests that nudges work best when combined with more interactive activities and when extended to different schools and age groups. Long-term studies would also help to better understand how durable these changes really are. In the end, this research confirms that schools can play a key role in building a culture of sustainability. With the right mix of information, social influence, and practical activities, young people can develop everyday habits that contribute to a cleaner and more responsible future.

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REGULATION AND POLICY

The new frontiers of the circular economy in the era of ecological transition. Perspectives of comparative law.

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Abstract

Starting from the origins of the concept of circular economy up to its current and most widely accepted definition given by the Ellen MacArthur Foundation, the genesis and maturation of the key principles in environmental matters is reconstructed, first of all the principle of sustainable development. A path that led to the birth of a real unitary environmental law up to the European Green Deal and today's global policies to combat climate change.

Keywords: Circular economy; Sustainable development; European Green Deal; Climate change

Introduction

According to the Ellen MacArthur Foundation's definition, now considered among the most accurate and comprehensive, the circular economy is a term for an economy designed to regenerate itself: *A systems solution framework that tackles global challenges like climate change, biodiversity loss, waste and pollution. It is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature* [1]. More broadly, according to the Ellen MacArthur Foundation, the circular economy, as opposed to the so-called linear economy model, is a system in which products and materials are kept in circulation through processes such as maintenance, reuse, repair, recycling and composting. The aim is to minimise the use of natural resources by preserving them as much as possible in order to protect the ecosystem, tackle climate change and its effects, such as the loss of biodiversity, increased waste production and pollution, and decouple economic activity from the consumption of natural resources.

The concept of the circular economy is closely connected to that of "sustainable development", topics that have their roots in reflections long before they were theorised, which as far as sustainable development in particular is concerned, occurred and gradually matured through various stages leading to the development of an international environmental law.

The beginning of reflection and a full debate on sustainable development and limits to growth due to the exhaustibility of natural resources can be traced back to the late 1960s. Sustainable development, in its most widely accepted meaning, is understood as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The literature commonly traces the birth of the term "sustainable development" back to the so-called "Earth Summit", the first world conference of Heads of State and Government on the environment, held in Rio de Janeiro in 1992 and whose contents were based on the "Brundtland Report" (also known as Our Common Future), the document issued in 1987 by the World Commission on Environment and Development (WCED), established in 1983, from which modern thinking on sustainable development began. According to this Report, *sustainable development is the ability of humanity to meet the needs of present generations without compromising the ability of future generations to meet their own needs*. Sustainable development can be considered the most important principle in environmental protection, which has inspired national and international legislation.

In 2005, the principle of sustainable development was brought to the attention of the Brussels European Council, which adopted the *Declaration on Guiding Principles for Sustainable Development*, stating that *sustainable development is a key objective, enshrined in the Treaty, for all European Community policies* [2].

As far as the circular economy is concerned, however, it is more difficult to identify or fix a precise starting point where the concept was first theorised. The genealogy of the concept, at least from a semantic point of view, could be attributed to Barry Commoner, a master of environmentalism, who clarified the concept of "circularity" on a scientific level in his work *The Circle to Close* [3]. It is, however, with Walter R. Stahel that it acquires economic significance. Stahel, in 1976, together with the researcher Geneviève Reday-Mulvey, outlined the profile of the circular economy in the modern sense in a report for the European Commission (*Potential for Substitution Manpower for Energy*), i.e. emphasising the potential from the point of view of employment and economic competitiveness as well as reduced environmental impact and waste reduction.

It is precisely this relationship that can make Stahel be considered the putative father of a theory of economic development that is prodromal to "today's" circular economy: for the first time, the issue of resource waste was analysed and related to the disposal of goods and products instead of their reuse.

In December 2015, the European Commission adopted its first Circular Economy Action Plan, providing measures to help stimulate Europe's transition to a circular economy, boost global competitiveness, promote sustainable economic growth and generate new jobs.

In March 2020, the European Commission adopted a new Circular Economy Action Plan, replacing the 2015 package. Conceived as one of the key pillars that make up the European Green Deal, the Circular Economy Action Plan is a massive package of European reforms aimed at transforming the way we produce and consume from a linear to a circular approach.

All this to decarbonise the European economy and meet the climate targets of the Green Deal and the so-called "Fit for 55" package, a package of measures by which the EU commits to reduce net greenhouse gas emissions by at least 55 per cent by 2030 compared to 1990 levels.

Regarding the concept of ecological transition, it officially appears in the "Nextgeneration EU", a temporary tool for economic recovery and relaunch (also known as the "Recovery Fund") decided by the European Union in July 2020, aimed at repairing the losses caused by the COVID-19 pandemic. This involves over 800 billion euros that have been included in the European budget for 2021-2027 intended for all member states. One of the cornerstones and priorities of NextGeneration EU is precisely the "ecological transition" aimed at implementing measures to combat climate change. By April 30, 2021, Member States were called to present their respective National Recovery and Resilience Plans (NRRPs) for the use of resources. The Italian NRP (titled "Italy tomorrow") outlines investments and reforms in six missions. The mission dedicated to the ecological transition (Mission 2) is the one for which the majority of resources have been allocated: €59.47 billion of the total €191.5 billion assigned. This Mission is aimed at addressing the structural gaps that hinder the achievement of a new and better balance between nature, food systems, biodiversity, and resource circularity, in line with the objectives of the Circular Economy Action Plan launched by the European Union.

Findings

In the founding Treaty of the EEC, there were no references to environmental matters, both because there was not yet a widespread sensitivity to environmental issues and because the EEC was created with the aim of establishing a single European market, through the gradual alignment of state policies. Nevertheless, the Community was able to indirectly operate in the sector based on Article 2 of the Treaty, which mandated the promotion of a harmonious development of economic activity and continuous and balanced expansion. The extensive interpretation of this provision, together with the clause of the so-called "implicit powers" and measures to ensure the alignment of the regulations of Member States, allowed for the adoption of measures aimed at protecting the environment [4]. It was from the 1960s that the Community began to have an impact on the entire environmental matter, generating a true body of Community environmental law that had decisive development in the following decade. The creation of a community environmental law has been contributed to, in addition to the Environmental Action Programs, by directives, treaties, and rulings of the Court of Justice. Among these, the ruling of February 7, 1985, is particularly noteworthy, in which the Court qualified environmental protection as a fundamental objective of the EEC, on par with the internal market, and that the two objectives must find a fair balance. In this regard, it has been asserted that the aforementioned ruling anticipated the contents of the Single European Act (SEA) of 1987, which introduced among the community objectives the safeguarding and improvement of environmental quality, the protection of human health, and the careful and rational use of natural resources. We are in a historically decisive phase for community environmental law, which, with the SEA, has gained a place in the Treaty, and the objectives outlined in the first Action Program have taken on the status of original community law, thus relevant for the legal systems of all member states. Another important step in the path of recognition and assimilation of environmental principles within the global policies of the Union, which matured with the Lisbon Treaty, occurred in 2000, when the aforementioned principles found a place in the Charter of Fundamental Rights of the European Union, which, in Article 37, referred to the concept of sustainable development. Subsequently, the Sixth Environmental Action Program, concerning the period 2002-2012, established the need to apply the legislation in all Member States to integrate and implement policies for environmental protection. The Lisbon Treaty (TFEU, signed in 2007 and entered into force in 2009) marked the beginning of a new phase in the process of European integration: environmental principles became legally binding for all Member States and Europe acquired specific competencies. The environment has been placed in the sphere of shared competences under Article 4, paragraph 2, TFEU and regulated by Title XX TFEU. In this context, Articles 191, 192, and 193 are particularly important as they define the European principles in this area and regulate the legislative procedure for the adoption of environmental legal acts. Community environmental law has ultimately developed progressively through the adoption of decisions, directives, and treaties that have led to significant changes in the regulatory framework established by the Treaty establishing the EEC. Starting from the aforementioned Environmental Action Programs and the Paris Agreement of 2015, the European Union's commitment to ecological transition and the circular economy, as well as its efforts to combat climate change, has become increasingly significant. In this context, the so-called "European Green Deal" (European Green Deal, EGD) was launched in 2019 by the European Commission, aiming to transform the EU into the first climate-neutral continent by 2050 through a legislative roadmap. Originally conceived as a decarbonization strategy, the Green Deal, according to the European Commission's intentions, aims to promote a new industrial paradigm and a revitalization of the European integration project. In the context of a growing global awareness around the climate emergency, evidenced by the aforementioned Paris Agreement and the 2030 Agenda for Sustainable Development Goals, the European Green Deal is positioned as a strategy, comprising a package of measures, aimed at aligning the various EU policies with the climate neutrality target set for 2050. With the Green Deal, the EU aims for an industrial transformation that ensures technological leadership in decarbonized supply chains and in those increasingly considered strategic – clean energy – in line with the ambition to build European energy autonomy. The key measure of the Green Deal is the European climate law adopted in

2021, which introduced, for the first time, a binding long-term emissions reduction target. The climate law also aligned the 2030 emissions reduction target with the long-term one, increasing it from 40 to 55%. To achieve this goal, the Commission presented in July 2021 the legislative package 'Fit for 55', the plan to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels.

The notion of the circular economy has recently been receiving increasing attention from scholars in various disciplines, far beyond the confines of economic and environmental studies.

This growing attention is certainly determined by the transversal nature that “sustainability” has gradually taken on in the economic and social policies of the so-called industrialised countries.

Law, in particular, is among the disciplines that is carving out a not inconsiderable space for itself, as demonstrated by the significant number of doctrinal contributions that have appeared in recent years, not only in Italy [5] but also internationally [6]. By examining the laws and policies adopted by different countries, it is possible to understand how different jurisdictions address the challenges related to the environmental crisis and climate change. This comparison allows not only for the identification of the most effective regulations, but also for the adaptation of innovative solutions to specific local contexts, fostering a more flexible and resilient approach. The integration of comparative legal analysis, therefore, is essential to develop regulations that are both ambitious and realistic, capable of responding to contemporary environmental challenges.

At the same time, comparative analysis facilitates the harmonisation of laws internationally, reducing trade barriers and fostering cooperation between states. This is particularly important in order to standardise the legislation of different countries and to promote the harmonisation of national measures also to protect the market and competition. It is therefore clear that comparative law has a significant impact on the development of environmental law, especially in a context in which the harmonization and integration of legislation has become of primary importance to address the epochal challenges of climate. At the same time, it must be considered that legislation comes in considerably different forms depending on whether it is guided by binding legal norms or whether it is entrusted to simple "good will" influenced, to a greater or lesser extent, by economic actors and the so-called stakeholders. From this perspective, the distinction between Hard Law and Soft Law sources emerges in international law. This distinction assumes even greater relevance if it is a question of promoting incisive changes in production methods and types of consumption. It follows that the role of rules can only be to impose and/or promote certain changes, perhaps by sanctioning and/or discouraging the maintenance of practices that prove incompatible with the circularity of the economy. Here the alternative between Hard Law and Soft Law comes into play [7]: if it is a question of influencing consolidated behaviors, the possibilities offered by Hard Law norms are decidedly higher precisely because of the binding nature that characterizes them and which may prove to be the only useful tool that can be used to obtain what simple advice, suggestion or advocacy can ensure. Hard Law and Soft Law play complementary roles in promoting and regulating environmental legislation with particular regard to circular economy policies and strategies, providing both concrete legal obligations and guidance and incentives to foster the adoption of sustainability policies and regulatory frameworks.

Method

Starting from the origins of the first reflections on the relationship between environmental protection and economic development, the analysis traces the development of environmental principles that, accepted in international Treaties, have represented the premise for the birth of a real European environmental law. The reasoning leads to a reflection on the importance of comparing different environmental legislations on the assumption that they find their regulation at a harmonized level through European legislative acts.

Discussion/Conclusion

The theme of environmental protection and related issues have taken on increasing relevance and centrality both in our legal system and at supranational and global level and are, today more than ever, the subject of great interest in legal studies.

The concept of environmental sustainability itself has rapidly evolved. We no longer speak of sustainable development only with reference to the environmental aspect, but this pivotal principle that, as we have seen in the discussion, has inspired the development of policies, strategies and regulations that govern and regulate the circular economy and the ecological transition, is now permeated with meanings and implications that make sustainability one of the main levers, if not the main one, for addressing the global challenges of climate change.

The goals of the UN 2030 Agenda have introduced issues related to poverty and the dignity of the person, where the issue of peace is also considered a priority, and it could not be otherwise, for the good(s) of future generations.

In this respect, it is no coincidence that a large part of the economic resources made available by the European Union in the post-pandemic NextGenerationEu Plan has been earmarked for ecological transition policies. The challenge of climate neutrality to 2050 is a global one, which makes it necessary for circular economy regulations in the era of ecological transition to be increasingly harmonised. However, globality is made up of multifaceted socio-economic and legal contexts with peculiarities that cannot be ignored. In an increasingly harmonised regulatory context such as the European one, accurate impact analyses based on reliable data are indispensable. In this, it is possible to grasp the full scope and importance for legislators to move from an effective comparison of different contexts so as not to approach sustainability in an ideological manner by lowering regulations and models 'the same for all' from above, but leaving room for technologies and organisational models that guarantee, in each context, the best achievable environmental result. This is why at EU level the directive instrument is always preferable to the regulation one when it comes to setting medium- and long-term objectives, since the former, in dictating principles and objectives, leaves the best implementation methods to the individual Member States according to the peculiarities that characterise the respective national and legal context.

There is no doubt that what started out in the last century as a purely environmental challenge has now become a geopolitical challenge that, as such, calls for accurate impact analyses and comparisons of existing legislation in different contexts. We have seen how indispensable it is to have a harmonised regulatory framework to implement common policies and strategies. However, it is necessary to act on the lever of so-called "technological neutrality" in order to favour a flexible approach to the best available technologies that are better adapted to the reference contexts and the different socio-economic-industrial realities. The supranational legislator, therefore, can only proceed from a comparative law perspective.

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The organized environmental crime. The national interest between enforcement gaps and corruption

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Abstract

The aim of this discussion is to analyze the phenomenon of organized environmental crime, as a specific sector of the mafia operating illegal activities with a harmful environmental impact, highlighting the multiplicity of aspects and the terms of repercussions on society. The paper begins by illustrating the origin of the phenomenon and its impacts on the country, then providing the related data and the repercussions both on the economic system and on the health and safety of citizens. The thesis explores how organized crime obtains easy revenues from both the waste sector and illegal construction, causing serious damage to natural ecosystems. Moreover, it is shown how the circular economy and green procurement are a powerful weapon against this criminal organization and how the waste supply chain needs to be shortened, both nationally and internationally. The paper shows how indispensable the fight against corruption and collaboration between states is in the battle against these criminal groups.

Keywords: Organized environmental crime; Circular economy; Green public procurement; International cooperation

Introduction

After reconstructing the general picture of the critical issues on the subject and providing the main cognitive tools useful for the analysis, the action of criminal networks was examined, both in relation to the international phenomenon of environmental dumping and to the problems of the illegal cement cycle and the waste sector. In relation to the latter, the analysis focused on the management chain in its entirety, paying particular attention to the close connection, both at national level and in the Euro-Mediterranean area, between the activities of the organized environmental crime and the activity of money laundering and other crimes, therefore, not only of an environmental but also of an economic nature. The thesis then analysed the European strategies against eco-crime, paying particular attention to central issues such as the fight against illegal waste trafficking and the falsification of "end of waste" processes.

Additionally, the investigation focused on green procurement and the circular economy, fundamental resources against the action of these criminal organizations. The analysis highlighted, in fact, how this circular economy model represents an epochal challenge that aims at the eco-design of durable and repairable products, both to prevent the production of waste and to maximize its reuse and recycling, in compliance with the ambitious international commitments of which Italy is a protagonist. This dissertation also aimed to provide a general view of the need to guarantee the country an adequate number of waste treatment plants; This issue proves to be central to making it possible to virtuously close the waste cycle and thus ensure the recovery of raw materials, even the so-called "critical" ones, which are more strategic than ever for the ecological and digital transition of society. The reasons for the revision of the European regulation on waste shipments were then explored, then ample space was dedicated to the study of the vast problems of the public procurement system. In fact, the importance of monitoring PNRR contracts was discussed with knowledge, in order to prevent them from being a great opportunity for green development to becoming easy tools for profit for the mafias.

Methods

The study made use of the in-depth analysis of both investigations carried out by the police, judgments by the judiciary, institutional reports, parliamentary committees, intelligence services and independent authorities but also the study activities carried out by the doctrine and associations of the Third sector. Through these, the thesis also aims to deepen the proposals for changes to the discipline and the possible lines of intervention available to the legal system. In a historical period that sees the environmental issue becoming increasingly central to the public debate, it seems vitally important to deal with the topic of organized environmental crime as much as possible even in the academic field.

The paper, in fact, highlights, also through the comparison of different police operations in third countries, how these activities constitute not only an important source of income for transnational organized crime but also a serious threat to human health, the stability of ecosystems and entire economies. Through this multiplicity of sources, the thesis has deepened the proposals for changes to the discipline and the possible lines of intervention available to the national and European legal system. The analysis referred not only to the specific subject of environmental law, but also to the broader administrative law, opening the field of investigation also to contaminations of European law as well as to inevitable hints of criminal matters. The thesis turned its gaze to the triple national, European and international dimension, which were strongly interconnected due to the very nature of mafia action in the environmental field.

The argumentation of the theme was guided by the desire to operate a synthesis that would systematize the different angles of research on the phenomenon in question. In particular, the examination first investigated the origins of these criminal organizations, contextualizing their different modes of action, and then presented their tools of contrast and their prospects for reform.

Findings

This dissertation provided a general view on the need to review the national system of environmental protection but also to investigate the need for the tightening of penalties on the subject, not neglecting the reasons to guarantee free access to justice for Third Sector associations working for the defense of ecosystems.

A scarcity of in-depth studies on the subject of crime in the environmental field has been found, in fact it is believed that the doctrine should pay more attention to this topic, in order to be able to guarantee institutions a research framework on the subject that is interdisciplinary and constantly updated. In fact, as we have seen from the investigation activities reported in the text, eco-criminal organizations possess a great ability to renew themselves and adapt according to the context in which they operate. The interdisciplinary nature of the study on contrast tools appears to be more strategic and fundamental than ever, due to the technicality and specificity of the environmental matter.

It has been ascertained, in fact, that both in the field of pollution and waste trafficking, crime infiltrates also through the help of professionals into the folds of a very technical and complex system. In the light of these elements, it is therefore a priority both to increase controls on specialized operators in the supply chains most subject to mafia infiltration, and to carry out a moral suasion that raises a cultural barrier in these areas against organized crime

In the supranational dimension, research has identified great potential in the fight against the organized environmental crime. European and international bodies, judicial and police cooperation are, in fact, a fundamental forum for the fight against organized crime in the environmental sector. The analysis shows that through these bodies not only operational coordination between countries, but also a fruitful exchange of information useful for defining the modus operandi used by the various criminal groups is implemented. This exchange of information gives the investigative bodies greater awareness of the phenomenon and an additional tool in the activity of contrast.

Discussion/ Conclusion

In the discussion addressed, the most neuralgic aspects of the Organized environmental crime topic were touched, investigating with criterion the repercussions of this both in the different areas of society and with respect to national interests. In fact, the study underlined how much the work of the clans in environmental matters undermines these national interests and the achievement of strategic objectives for the country, such as those of circular economy and ecological transition, as well as compliance with the commitments made at EU and international level.

In the complex mission of fighting the organized environmental crime, the legislator is therefore not alone, in fact he is supported not only by countless environmental and third sector associations, but also by all public institutions, and by the whole of civil society. Because every body, every association and every citizen is called upon to do their part in order to defeat this unjust and unacceptable phenomenon.

The words of Giovanni Falcone, who maintained that "the mafia is a human phenomenon and like all human phenomena it has a beginning, its own evolution and will therefore also have an end", appear inspiring and very suitable to conclude this discussion.

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Prospects for the Integration of CO_2 Emissions Trading Markets

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Abstract

The thesis explores the potential for integrating different Emissions Trading Systems (ETS), which are market-based tools designed to reduce greenhouse gas emissions. Following a general overview, three ETSs are compared—those of the European Union (EU ETS), California, and China—highlighting regulatory, pricing, and sectoral coverage differences, as well as the risk of carbon leakage. The second part analyzes a theoretical model simulating the integration between the EU and China, showing how linking markets with different marginal abatement costs can lead to more efficient use of environmental resources. The analysis is further extended to scenarios involving a third or fourth ETS, examining both the benefits and political implications. The concluding proposal recommends a 30% cap on emission allowances sourced from external markets, aiming to balance efficiency with economic sovereignty. ETS integration emerges as a promising path forward, provided that shared rules and strategic vision are ensured.

Keywords: ETS, sustainability, circular economy, CO_2, EU ETS, California C&T, China ETS, carbon leakage

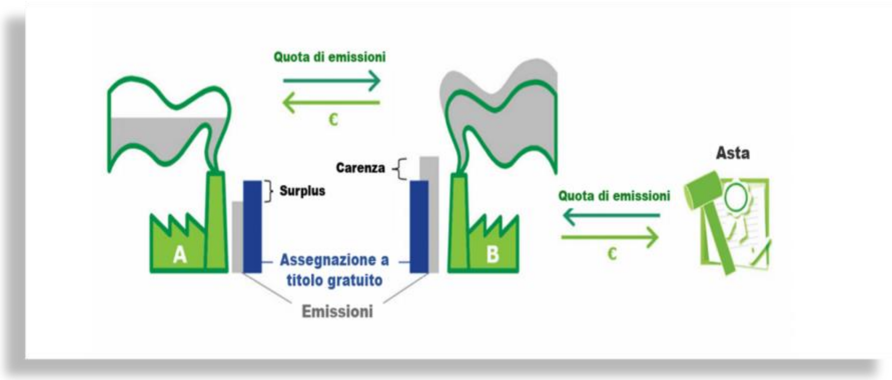
Introduction

ETSs were introduced under Article 17 of the Kyoto Protocol as a system for trading emission allowances. Essentially, they constitute a market in which companies from certain sectors can trade permits that grant them the 'right to pollute.'

Each market is regulated by a competent authority that sets the maximum emissions cap and the rules for allocating allowances, referred to as quotas or permits.

All companies operating in sectors covered by the ETS are required to surrender each year a number of allowances equivalent to the tons of CO_2 they emitted in the previous year.

Figure 1_Efficiency gains in terms of welfare following the linkage of three regions



Source: EU ETS Handbook (2015)

In the example, we observe two companies that have received free allowances: Company A emitted less than the amount of allowances received and therefore has a surplus of permits that it can sell to others, such as Company B, which emitted more than its allocated allowances and must thus purchase the missing permits either from other companies or from authorized auctions.

Allowances are allocated by the Competent Authority of each market, which can assign them:

- Free of charge based on past emissions from the previous year or biennium (Grandfathering);
- Free of charge provided that specific efficiency targets are met (Benchmarking);
- For a fee through auctioning (Auctioning).

Three ETS markets were selected for comparison:

- The EU ETS: the European market active since 2005, currently the largest in terms of trading volume;
- The California Cap and Trade: in operation since 2012, one of the leading ETS markets in the United States and the first example of a cross-jurisdictional linked market;
- The Chinese ETS: operational since 2021, still relatively new but potentially significant due to its large scale.

The aspects considered include:

- Sectoral coverage: which sectors are annually required to surrender emission allowances;
- Greenhouse gas coverage: which emissions must be reported annually to the authority;

- Allocation methods, as mentioned above;
- The emissions cap: the maximum level of CO_2 emissions a country cannot exceed;
- The average auction price or secondary market price: the price at which a permit is sold on the primary market or among users

Figure 2_Comparison between: EU ETS, California Cap & Trade, China ETS

Caratteristiche	Unione Europea	California	Cina
Giurisdizione	UE 27 + Norvegia e Liechtenstein	California	Cina
Atto legislativo	Direttiva 2003/87/CE	Legge AB 32 (2006)	Piano nazionale 2017
Copertura settoriale	Energia, Industria, Aviazione nazionale Marittimo	Energia, industria, trasporti ed edilizia	Energia
Copertura gas serra	CO_2, N_2O HFC e altri	CO_2, CH_4, N_2O e altri	CO_2
Metodo di allocazione	Asta 57%, benchmarking 41%, riserva 2%	Asta 70%, benchmarking 30%	Grandparenting 100%
Carbon Offsetting	Non più consentito	Consentito (nazionale)	Consentito (nazionale)
Tetto massimo in $MTCO_{2e}$	1.386 (ETS1) e 28,9 (ETS2)	280,7	5.000
Prezzo medio d'asta o second market (17/06/2024)	83,24 € (90,25 $)	28,84 € (32,93 $)	8,78 € (68,35 ¥)

Source: https://icapcarbonaction.com/en/compare

It is evident that all three markets include companies from the energy sector, and CO_2 emission allowances must be reported.

The price differences arise from the stricter standards of the EU ETS compared to other markets—particularly due to its stringent emissions cap and the linear reduction factor, a coefficient that gradually lowers the cap each year, resulting in a scarcity of allowances.

These differing standards between the markets lead to the risk of emission relocation, known as carbon leakage. In practice, facilities with high emissions—such as those in the energy or industrial sectors—might relocate to ETS regions with less stringent regulations, like the Chinese market, in order to reduce abatement costs.

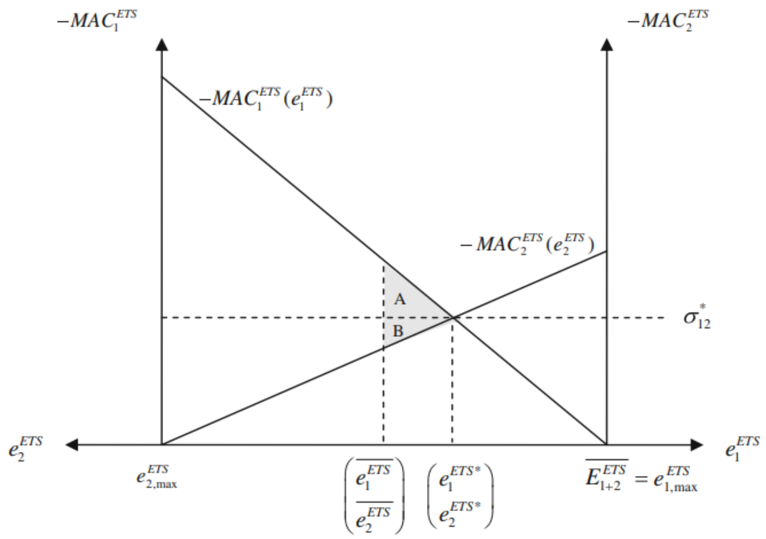
To mitigate this risk, competent authorities grant free allowances to energy-intensive industries, which, paradoxically, are the biggest polluters.

Methods

According to several scholars, linking ETS markets presents a potential solution to carbon leakage. However, it is essential to strike the right balance between the market price of permits and the marginal abatement costs of the participating countries.

Two such scholars, Alekseeva and Anger, have developed a model that analyzes the distribution of welfare between two countries participating in a potentially linked carbon market.

Figure 3_Sectoral efficiency gains in terms of welfare due to the linkage



Source: Alekseeva et Anger, 2016

The model is based on a dual Cartesian axis system

- on the X-axis, we find the emission levels, and for each level, the corresponding marginal abatement cost;
- on the first Y-axis, the marginal abatement costs of ETS 1 are shown;
- on the second Y-axis, those of ETS 2 are represented.

The initial assumptions of the model are as follows::

- the integrated trading system initially includes only two countries—Country 1 being the European Union and Country 2 being China;
- the ETS linkage involves exclusively companies from the energy sector in both countries;
- both regions are assumed to have marginal abatement costs represented by the curves $MAC^{ETS}_1(e^{ETS}_1)$ (Marginal Abatement Cost) for Europe and $MAC^{ETS}_2(e^{ETS}_2)$ for China;
- it is assumed that the $MAC^{ETS}_1(e^{ETS}_1)$ curve has a steeper slope than the $MAC^{ETS}_2(e^{ETS}_2)$ curve, as Region 1 (EU) faces higher marginal abatement costs than Region 2 (China);

Finally, it is assumed that both regions adopt the same overall emissions Cap, $E^{ETS}{}_{1+2} = e^{ETS}_{r,max}$, and that 50% of this cap is allocated in the form of free allowances.

In the figure above, the initial allocation of permits in each ETS results in an economically inefficient level of emissions.
Why is it inefficient? Because at the emission levels (e_1 ETS, e_2 ETS), the marginal abatement costs of the two ETSs differ, leading to a risk of emissions relocation.

Once the linkage between the two markets is established, Country 1 (EU), which faces higher abatement costs, imports emission permits from Country 2 (China) and consequently increases its emissions. Conversely, Country 2, with lower marginal costs, exports permits to Region 1 and reduces its own emissions by the same amount.

At the intersection point of the two curves (eETS1, eETS2), the economically efficient level of emissions is achieved, as the marginal abatement costs of the two regions are equal.

Therefore, if the permit price could be maintained at σ *12, a Pareto improvement would theoretically occur, generating gains for both Region 1—in terms of reduced marginal abatement costs (area A)—and Region 2, which would earn revenues from the export of permits (area B).

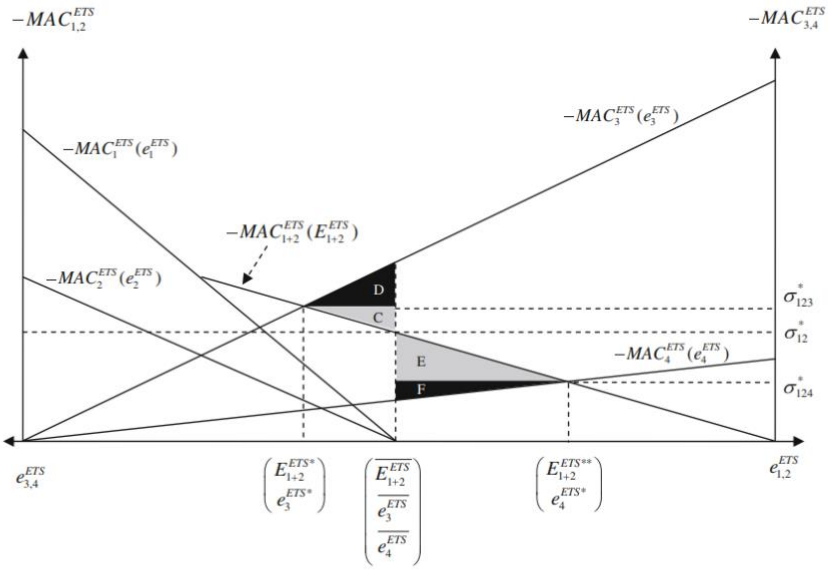
Findings

It should be noted that these revenues would be partly offset by the increase in marginal abatement costs for firms in the Chinese ETS market.

The discussion can be extended to the linkage with a third ETS, under the following assumptions:

- The overall emission cap within the integrated market is E^{ETS}_{1+2} and is characterized by the marginal abatement cost function -MAC $^{ETS}{}_{1+2}(E^{ETS}{}_{1+2})$;
- it is assumed that the potential new entrants are two regions: l'ETS 3 with higher marginal abatement costs compared to the aggregated abatement costs of the integrated system, represented by the curve -MAC $^{ETS}{}_{3}(e^{ETS}{}_{3})$; and l'ETS 4 with lower marginal abatement costs compared to the integrated market, indicated by the curve -MAC $^{ETS}{}_{4}(e^{ETS}{}_{4})$;

Figure 4_Efficiency gains in terms of welfare following the linkage of three regions



Source:Alekseeva et Anger, 2016

Hypothesis 1 → If Region 3 joins the integrated market, it is logical to assume that it will import emission permits from the integrated system, as its marginal abatement costs are higher than those of the integrated market. This continues until the equilibrium point (E^{ETS*}_{1+2}, e^{ETS*}_3), where both marginal costs are equalized.

This would lead to an increase in the international permit price to σ^*_{123} (rispetto a σ^*_{12}) and optimal emission levels.

Compared to the pre-linkage scenario, the integration of Region 3 would lead to efficiency gains for both the integrated system—in terms of permit sales revenues (area C)—and for Region 3 through a reduction in marginal abatement costs.

Hypothesis 2 → If, instead, Region 4 were to join the integrated market, it is reasonable to assume that it would export its emission permits to the integrated system, since the latter has higher marginal abatement costs. This would continue until the equilibrium point (E^{ETS**}_{1+2}, e^{ETS*}_4), where the marginal costs become equal.

The availability of lower-priced emission permits would result in a reduction in the permit price within the integrated system to σ^*_{124}.

Region 4 would reduce its emissions compared to the pre-linkage scenario, while the emissions of the other regions in the integrated system would increase by the same amount.

Conclusions

According to several scholars, this scenario could generate political friction from the Chinese government. To make the linkage between the two markets more politically acceptable, it is recommended to introduce a 30% cap on the share of the national emissions cap that can be traded with international ETS markets.

In other words, only 30% of each country's emission allowances could be sourced from external markets, while the remaining 70% would have to come from the domestic market. According to the same authors, a 30% cap would allow countries to benefit from the advantages of a linked market without compromising internal economic balance.

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Circular economy standards: the new series ISO 59000, UNI technical standards and CEN perspectives

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Abstract

Given the pressing need to transition from a linear economy to a circular one - and considering that neither scholars nor practitioners have yet reached a shared understanding of what the circular economy (CE) and its corollaries truly entail (e.g., strategies, business models, actions, and metrics) - voluntary technical standards can serve as valuable tools. They help establish a common language and direction, enabling a cohesive and consistent transformation of production and consumption models on a global scale. This study aims to analyze the most prominent voluntary technical standards related to the CE (including BS, XP, the new ISO 59000 series, UNI/TS 11820, UNI/TR 11821, and forthcoming CEN standards), and to assess their relevance in the Italian context. Primary data were collected by examining both the perspective of standard developers - interviewing the Chairwoman of UNI's Technical Committee on CE - and that of adopters – through a dedicated survey.

Keywords: Circular economy standards; circularity measurement; ISO 59000 series; UNI/TS 11820

Introduction

Over the years, numerous literature reviews have highlighted the existence of hundreds of definitions, frameworks, business models and indicators related to CE, often struggling to reconcile divergent perspectives [1, 2, 3, 4, 5, 6, 7, 8].

In this context, standardization plays a crucial role in establishing a level playing field and enabling reliable benchmarking [9]. Yet, CE standards remain voluntary, placing the responsibility on adopters to recognize their value.

Since 2017, standardization bodies have worked to develop technical documents to harmonize and clarify the complex, multi-dimensional nature of the circular economy (CE).

2017. The British Standards Institution (BSI) launched BS 8001, a general guide for implementing CE principles in organizations. However, its lack of specific indicators led to critiques about its practicality [10].

2018. In response, France developed XP X30-901, a more detailed standard outlining circular actions and offering certification upon compliance [11]. Its success spurred the creation of ISO Technical Committee (TC) 323 "Circular Economy" in 2018, led by France.

2019. Italy subsequently established TC/057 "Circular Economy", in alignment with the structure of ISO TC/323.

2022-2023. Italy released two key documents, UNI/TS 11820[1] and UNI/TR 11821 [12, 13]. The former presents 68 circularity indicators across six areas (resources, energy, waste, logistics, products/services, and governance), using radar charts to visualize performance and identify improvement areas.

At the European level, CEN/TC 473 "Circular Economy" was established in 2023 to standardize vocabulary, business models, measurement, Extended Producer Responsibility (EPR), and information sharing about circularity [7].

2024-2025. ISO introduced the ISO 59000 series, including ISO 59004 (terminology and guidance), ISO 59010 (business model transition), ISO 59020 (circularity measurement), and others [14, 15, 16, 17, 18, 19, 20]. ISO 59020 differs from UNI/TS 11820 by offering only six mandatory indicators and allowing flexibility in developing additional key performance indicators (KPIs). Unlike UNI, ISO does not provide a certifiable circularity score, but promotes self-assessment. Overall, the ISO 59000 series supports organizations in understanding and integrating CE principles while considering SDGs and social impacts.

Methods

Interview. To explore the topic of CE technical standards in greater depth, a semi-structured interview was conducted with Dr. Laura Cutaia, Chairwoman of Technical Committee (CT) 057 "Circular Economy" of UNI, representing the perspective of standard preparers. The interview was conducted under the following conditions:

- Number and type of questions: 18 qualitative, open-ended questions.
- Platform: Zoom.
- Duration: 40 minutes.

Survey. To provide a more comprehensive perspective, the paper also includes insights from adopters through a survey carried out from 20 January 2024 to 5 February 2024, with the following characteristics:

- Objective: To assess the maturity level of circular economy practices in the Italian business sector and the level of awareness about CE standards.
- Sample: Approximately 300 companies operating in Italy (not necessarily of Italian origin), reached via the Technical Committees "Environment" (UNI/CT 004) and "Circular Economy" (UNI/CT 057), with a total of 200 responses obtained through contacts provided by Dr. Claudio Perissinotti Bisoni, Technical Project Manager at UNI, as well as through the ICESP platform and LinkedIn; responses were collected anonymously.

[1] The revised version of the document was published in November 2024.

- Question types: Binary single-response (yes/no), multiple choice, and Likert scale evaluations (from 1 = completely disagree to 7 = completely agree).
- Estimated completion time: 10–15 minutes.
- Data analysis tools: Descriptive statistics methods using Qualtrics.
- Survey structure: Four sections—company profile, circular economy practices, drivers and barriers to circularity, and awareness of CE standards.

Findings

Interview. Many insights emerged during the interview, with particular focus on UNI/TS 11820. First, it was emphasized that this type of standard is primarily intended to support companies in voluntary self-assessment. Specifically, UNI/TS 11820 is a valuable tool for initiating proper data management - from collection to indicator calculation - and for tracking performance with the potential to certify an organization's circularity level. Another advantage is the possibility of identifying benchmarks and a characteristic set of KPIs for each sector, based on user feedback. The CE KPIs included in such standards can also serve as reference points for national and European environmental policies that aim to promote circular economy practices, since policy-making generally requires measurable and reliable targets.

When asked which sectors should be prioritized to accelerate the circular transition through the use of this standard, no definitive answer was provided due to a lack of conclusive evidence. However, the interviewee stated that many companies are beginning to apply UNI/TS 11820, albeit not for external communication purposes such as certification.

Artificial intelligence (AI) and blockchain technology were not considered in national CE standards due to UNI’s traditionally conservative approach. Nonetheless, future collaboration with technical committees of public institutions seems plausible, as these bodies are increasingly exploring such technologies.

The main challenges in implementing CE measurement standards - particularly for SMEs - were also highlighted, with boundary definition and information tracking being the most critical issues.

As for the absence of a prescribed minimum level of circularity in UNI/TS 11820, the rationale is that the standard is intentionally designed to avoid imposing such requirement. Instead, any performance constraint in terms of a minimum circularity level would stem from the specific application of the standard - for instance, in a green public procurement context.

Regarding UNI/TR 11821, the interviewee clarified that no practice is inherently superior. A CE best practice is one that enhances an organization's circularity while also promoting sustainability - since circularity does not automatically imply sustainability.

The relationship between CE standards and business management systems like ISO 14001 or ISO 9001 was also addressed. These systems are currently not directly linked. However, once ISO develops a dedicated management system standard for circularity, it would be desirable for organizations already certified under EMAS or ISO 14001 to integrate it seamlessly.

The strong emphasis on industrial symbiosis in UNI/TS 11820 - reflected in a significant number of indicators - stems from the fact that Italy lacks data on the extent of industrial symbiosis taking place. The standard's attempt to monitor such activities is therefore a positive development, as no other statistical tool currently tracks this information. Mapping these synergies would mark a turning point in assessing progress toward the circular transition. At present, certification systems and public procurement only consider individual organizations, not their systemic interconnections.

Survey. A total of 38 complete survey responses were collected[2], primarily from SMEs based in Northern Italy (Piedmont and Lombardy), as showed in the first part of the survey.

Regarding the second section, 70% of respondents reported adopting circular economy practices, while just under 30% expressed an intention to do so. Among those already engaged, the most common actions involve the use of secondary or recycled materials, low-impact materials, and renewable energy. This leads to a key insight: more advanced companies in terms of circularity tend to focus on upstream phases of the value chain (such as design and sourcing), which are critical for achieving sustainability goals. Conversely, companies beginning their circular journey prioritize areas with more immediate returns, such as energy use and resource management.

Companies that regularly measure, document, monitor, and communicate their circularity efforts mainly assess product/service aspects, waste and emissions, and material resources -core dimensions also covered by UNI/TS 11820. These responses suggest that such companies are aligned with the standard and potentially ready for adoption or certification.

The most commonly cited measurement tools are life cycle assessment (LCA), material flow analysis (incoming, outgoing, reused materials), and internally developed KPIs. On the contrary, indicators included in UNI/TS 11820 and ISO 59020 documents rank among the least frequently utilized.

The third section explored general attitudes toward the circular economy, regardless of current practices. Key disincentives included the need for high-quality inputs, difficulties in obtaining data for performance monitoring (a concern also underscored by Dr. Cutaia), and consumers' reluctance to pay premium prices for circular solutions.

[2] 34 out of 72 did not complete the form, 3 of which with a completion status of 24%, 18 of 29%, 8 of 67% and 5 of 81%. Anyways, these partial answers were considered.

Interestingly, political instability and resistance to innovation were not seen as major barriers.

The main drivers identified were brand reputation and customer loyalty, increased organizations' awareness of their environmental impact, reduction of waste (therefore, improved efficiency), and leadership commitment to circularity. Proximity to partners or customers, along with resource price volatility, were not viewed as significant triggers.

Coming to the final section, over 50% of respondents were familiar with the UNI/TS 11820 through professional networks, official UNI documents, or collaboration with industry associations. Nevertheless, its adoption does not appear to be a medium to long-term priority. Despite potential benefits such as improved corporate reputation and transparency, barriers include implementation and certification costs, limited funding, technical complexity, and the absence of regulatory requirements - all of which especially impact SMEs (Figure 1 and Table 1).

Figure 19_ Companies' strategic view on UNI/TS 11820

Table 6. Constraints to companies' adoption of UNI/TS 11820

What are the main barriers to UNI/TS 11820 adoption?	Average (Min=1, Max=7)
Implementation and certification costs	4.00
Scarce accessibilty to funds to cover implementation costs	3.71
Absence of regulatory obligations	3.55
Technical complexity for implementation	3.45
Lack of information about the standard	3.24
Lack of technology for implementation	3.11
Lack of resources and technical expertise	3.11
Lack of external support (e.g., advisory)	3.05
Internal resistance to change	2.71

Discussion/Conclusion

Circular economy standards serve as a hub of knowledge, leading the global shift toward change by reducing the fragmentation of perspectives surrounding the CE. They help unify a concept often diluted by the proliferation of schemes, combat greenwashing, stimulate demand for circular markets, add value to the economy, level the playing field, and guide citizens toward more sustainable choices.

As the CE paradigm continues to evolve, standardization plays a crucial role in clarifying concepts, guiding implementation, defining boundaries, and enabling comparability. In essence, it aligns countries under shared criteria—acting metaphorically as the oil that keeps gears turning smoothly or the railway tracks guiding all trains to the same destination.

What standard developers have emphasized (as emerged during the first-hand interview with Dr. Cutaia) is echoed by both current and prospective adopters: for these technical standards to gain broader adoption, they must address the specific needs of small and medium-sized enterprises (SMEs), whose uptake is often hindered by financial limitations and a lack of time, personnel, or expertise.

Looking ahead, the development of a standard for a "management system for the circular economy" may represent the natural next phase of standardization efforts.

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Sustainability and corporate accountability process: Pingue Supermercati Srl case study

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Abstract

In a global context characterized by the urgency of mitigating the impacts of climate change, this research aims to explore the fundamental role companies play in the transition to a circular and sustainable economy. The purpose of the thesis is to demonstrate how the adoption of sustainable practices, and especially their reporting, can generate a range of benefits both internally, for the company, and externally, for all stakeholders. Companies engaging in sustainability reporting for the first time must activate a process of analysis and data collection, through which the most critical aspects can be clearly visualized. The progressive updating of the data makes it possible to highlight and track any improvements due to the activation of sustainable practices. Reporting, therefore, allows benefits for internal management, but also is a contribution to the resolution of global challenges.

Keywords: Sustainability reporting; Circular economy; Sustainable practices; Internal Management; Global challenges

Introduction

In recent years, sustainability has emerged as a central issue in the discussion about the future of businesses and societies. Companies are being called upon to redefine their role and demonstrate a concrete commitment to sustainability by promoting transparency and compliance with current regulations. Sustainability reporting serves as a tool for companies to measure, account for, and communicate their non-financial performance as well as their commitment to sustainability. The future of reporting looks integrated and sophisticated, with a gradual convergence toward uniform and rigorous standards. The trend is moving toward the integration of financial and non-financial information, toward truly holistic reporting that considers all dimensions of corporate performance. This thesis aims to investigate how sustainable reporting can act as a catalyst for a more responsible and resilient business model. The study seeks to demonstrate how transparency and accountability are key elements in engaging stakeholders of a business to build a sustainable future. When these elements are put into action, Corporate Social Responsibility (CSR) emerges, or the voluntary commitment of a company to contribute to sustainable economic development, considering the social and environmental aspects of its activities. In other words, it is the voluntary integration of social and environmental concerns into business activities and relations with stakeholders [1]. Consequently, these concepts were applied to a real-world case study: a small-to-medium enterprise operating in the trade sector. This involved producing the first version of a sustainability report, which allowed for the analysis of challenges and opportunities associated with implementing sustainability reporting in a small business context

Methods

In order to be able to prepare a sustainability report, it is first necessary to know and learn more about the more recent Directive 2022/2464/EU, Corporate Sustainability Reporting Directive (CSRD), which came into force in 2023 promoted by the European Union and which provides for broadening the scope of organizations and companies involved compulsorily in sustainability reporting of their activities. The main purpose is to increase transparency and comparability of information regarding companies' environmental, social and governance (ESG) performance [2]. The introduction of reporting tools and specific reporting standards aims to make the documents produced uniform and comparable. According to the survey "*PMI italiane e rendicontazione di sostenibilità*" conducted in 2021 by the FFS (Forum per la Finanza Sostenibile) among the different reporting models, the most popular one is the sustainability report especially for small and medium-sized companies, including those not yet subject to mandatory reporting requirements [3]. Reporting standards adopted to produce financial statements are a set of rules and guidelines that define how companies should communicate their information related to sustainability. According to the survey presented above, more than two-thirds of companies that prepare a sustainability report adopt GRI (Global Reporting Initiative) which in fact represents the most widely used reporting standard internationally [4]. The sustainability report for the above thesis project was prepared in accordance with the 2021 version of the Global Reporting Initiative Sustainability Standards (GRI Standards), and the reporting scope refers to the fiscal year 2023 (January 1 to December 31) of Pingue Supermercati Srl. Standards-based sustainability reporting provides information on an organization's positive or negative contributions to sustainable development. The first stage for the realization of the sustainability report is characterized by the construction of the materiality matrix. To obtain the matrix, a materiality analysis is carried out, which aims to identify material themes in relation to the most significant current and potential, negative and positive impacts generated by the organization throughout the entire value chain [5]. Once the material themes were identified, they were linked with one or more GRI Topic Standards, where applicable. The materiality matrix, resulting from the analysis, is a two-dimensional chart that identifies the key themes in the company's sustainability action and assesses their importance and impact on internal and external stakeholders and for the company itself (Figure 1).

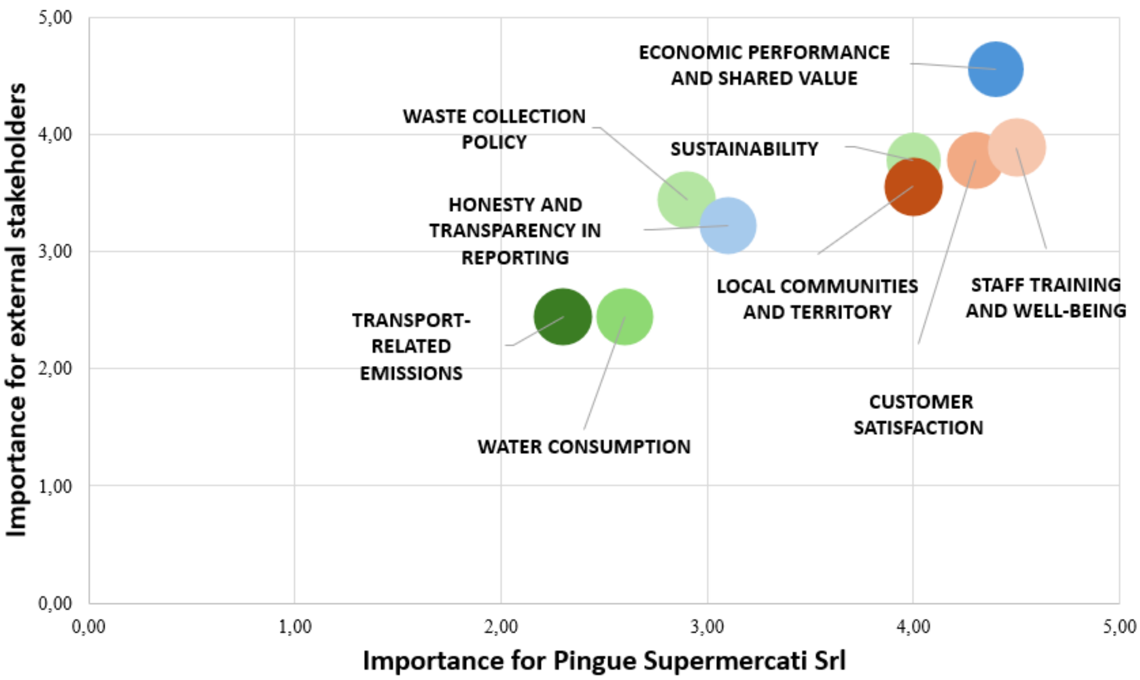

Figure 1_Materiality matrix Pingue Supermercati Srl [5]

The second phase involves interviewing one or more functions for each material topic identified in the matrix, in order to design the document's content and define its index. The report has been structured into three main sections corresponding to the ESG factors (Governance, Social, and Environmental); within each section, data related to the identified material topics are presented and analyzed. Once the index is defined, the data collection sheets for the three sections are prepared. Clearly, to collect the data, statistical-quantitative methodologies, qualitative survey methodologies, or specific indicators are adopted. The data package related to governance is predominantly characterized by qualitative data, aiming to describe in detail the organizational management and control model adopted by the company. As for the social section, the policies and strategies adopted for human resources, suppliers, and partners are reported in detail. Finally, the environmental data packages, also predominantly quantitative, describe the company's environmental and energy management. Specifically, energy, water, and natural gas consumption were calculated, and the kilograms of waste produced from all Pingue Supermercati Srl retail locations and the administrative headquarters were determined, totaling approximately 7053 m² divided into nine consumption centers [5]. To identify consumption figures, various service providers were consulted. Once the section dedicated to data collection and analysis is completed, a purely economic analysis related to value added can be performed. The research methodology was linked to a reclassification of the income statement, which allowed highlighting the company's value added, reflecting not only the company's ability to generate wealth but also to distribute it equitably among the various stakeholders involved. In summary, the report offers an integrated and articulated view of the interconnections between the company and its operating context, emphasizing its economic and social responsibility.

Findings

Once the consumption figures were determined, the company's total CO_2 emissions for 2022 and 2023 were examined, broken down by energy sources. The total obtained is the sum of Scope 1 emissions, which are direct GHG (greenhouse gas) emissions, and Scope 2 emissions, which are indirect GHG emissions. The greenhouse gas emission sources identified in Scope 1 relate to the combustion of diesel and petrol, and the refill of refrigerant gases. Regarding refrigerant gases, three types were purchased: R-404A, R-410A, and R-448A [5]. Each of these is characterized by a specific emission factor for the calculation of CO2eq tons (Table 1).

Table 1. Scope 1 Emission Factors [5]

Report	Unite of Measure	Emission Factor	Source
Fuels			
Diesel	$kgCO_{2eq}$/liter	2,51206	DEFRA [6]
Petrol	$kgCO_{2eq}$/liter	2,09747	DEFRA [6]
Refrigerant Gases			
R404A	$KgCO_{2eq}$/Kg	4.147,00	IPCC [7]
R410A	$KgCO_{2eq}$/Kg	2.255,50	IPCC [7]
R448A	$KgCO_{2eq}$/Kg	1.387,00	IPCC [7]

Emissions resulting from the procurement of electricity or thermal energy consumed by the organization, on the other hand, are identified as Scope 2. This category includes only GHG emissions due to energy production, excluding all emissions related to fuels, the construction of energy plans, and transportation and distribution losses. The two commonly used methodologies for calculating CO_2 emissions are location-based and market-based. The location-based approach is based on the average greenhouse gas emission intensity of the local electricity grid from which energy is drawn. CO_2 emissions are calculated by multiplying electricity consumption (kWh) by a specific emission factor (kg CO_2/kWh) reported in the following Table 2.

Table 2. Scope 2 Emission Factors [5]

Report	Unite of Measure	Emission Factor	Source
Electricity (Location-based)	$kgCO_{2eq}/kWh$	0,257	ISPRA [8]
Electricity (Market-based)	$kgCO_{2eq}/kWh$	0,331	AIB [9]

Finally, the economic analysis conducted relates to the three-year period 2021-2023 through a reclassification of the income statement using the value-added approach. The analysis revealed that, given the company's nature, operating in the agri-food and large-scale retail (GDO) sector, the highest percentage of generated value accrues to suppliers. To better represent this stakeholder category, a map of the Italian peninsula was created, illustrating the diverse distribution of value added per supplier in 2023.

Figure 2_Value added distributed to Italy suppliers by Pingue Supermercati Srl [5]

Once all qualitative and quantitative data have been collected and analyzed, the first version of the document is drafted, followed by its verification, revision, and final approval.

Discussion/Conclusion

The collaboration with the Pingue group not only led to the building of the first version of the company's sustainability report but, more importantly, triggered a broader internal reflection process within the organization, oriented towards the continuous improvement of sustainability practices. In the specific case of the Pingue company under examination, the sustainability report produced had not only an external communication value but also an internal one in terms of management. Therefore, it is possible to identify two distinct, highly relevant functions: a communicative function and an operational function. The communicative function is characterized by a broad scope, reaching not only external stakeholders for communicating achieved results but also internal stakeholders; in fact, the creation of the report contributed to greater awareness among the entire management on the topic of sustainability. Publicizing the company's commitment to sustainability can attract further investors and clients; thus, in this case, the report represents a communication strategy that enhances ethical and social choices. The operational function was never more impactful. Through the reporting process, the company was able to organize and systematize existing data-previously scattered or unstructured-into a coherent framework. The implementation of databases and monitoring systems enabled the company to track progress and identify areas for improvement over time. These systems covered both quantitative indicators and broader sustainability strategies and actions. The operational function, in general, refers not only to numerical or quantitative data but also to strategies and actions that, thanks to this document, could be brought within the scope of sustainability. Through the thesis process, the operational function was therefore implemented within the company and is intended to represent a legacy for subsequent years. In summary, the creation of the first version of the report generated future innovation within the company by activating a reflection process with a view to improvement. The company, in fact, following the results obtained in the report, decided to appoint a sustainability manager in each sales point of Pingue Supermercati Srl. This manager's objective is to guide the employees of the sales point, first and foremost, towards adopting more sustainable practices, but also to monitor and evaluate progress through the introduced databases. This further initiative highlights how accountability can become a basis for management and is not solely aimed at fulfilling directives.

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The Transition to Sustainability and the Implementation of ESRS in the Tourism Sector: The CDSHotels case and an Innovative Framework

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Abstract

The study explores the challenges and opportunities related to the adoption of the European Sustainability Reporting Standards (ESRS) in the tourism sector, focusing on the hotel group CDSHotels as a case study. It assesses the company's readiness to comply with sustainability reporting requirements under the Corporate Sustainability Reporting Directive (CSRD), identifying key strategic and operational issues. A dedicated CSRD reporting software was used to support the analysis, alongside the development of an innovative framework to guide companies in the transition toward ESRS-compliant reporting. The results contribute to reflecting on the transformative role of the ESRS in promoting innovation, change, and a sustainable vision within the tourism sector, offering insights to the ongoing debate on the circular economy and sustainable transformation.

Keywords: ESRS; CSRD; sustainability reporting; circular economy; tourism sector

Introduction

In recent years, increasing regulatory pressure and growing demands for transparency in environmental, social, and economic sustainability have pushed companies to rethink their business models. In a global context that is increasingly focused on sustainability and circularity - marked by climate instability, heightened ethical awareness, and the transition toward a circular economy - ESG (Environmental, Social, Governance) reporting has become essential for ensuring competitiveness and access to capital 1,2.

Various European and international initiatives have aimed to steer a shift toward sustainability, including the 2015 Paris Climate Agreement, the 2030 Agenda and the Green Deal 3. Particularly relevant to this study is also the Corporate Sustainability Reporting Directive (CSRD), which introduced new reporting obligations that will gradually apply to an increasing number of companies 4,5. The CSRD aims to provide clarity and consistency, enabling investors, analysts, consumers, and other stakeholders to better assess the sustainability performance of EU companies, as well as their impacts and associated risks.

To support the directive, the European Commission tasked EFRAG (European Financial Reporting Advisory Group) with developing the European Sustainability Reporting Standards (ESRS), which define the requirements companies must meet when preparing and disclosing sustainability-related information under the CSRD 6,7. The ESRS, which came into force in 2024, also aim to combat greenwashing - misleading communication about a company's environmental or social commitments - which undermines public trust and hinders progress toward genuine sustainability 8,9. With the ESRS, the EU intends to mandate *clear, detailed, and verifiable reporting* to strengthen stakeholder and market confidence in corporate sustainability disclosures 10.

The academic literature has extensively addressed the concept of the circular economy, especially the transition from a linear to a circular economic model 11. However, less attention has been given to how this transition directly impacts corporate reporting in the tourism sector, particularly regarding the ESRS and their integration into corporate strategies 12. In many cases, companies remain unprepared, organizationally and strategically, to implement structured ESG reporting systems.

In this context, the present study aims to explore a sector with a high environmental impact: tourism, which accounts for approximately 8% of global greenhouse gas emissions and is projected to triple by 2050 13. Within this industry, the hospitality sector plays a central role, both in terms of the scale of its offerings and its contribution to environmental impact, being responsible for about 20% of tourism-related emissions 14. Given these factors, the study explores how hospitality companies are approaching the challenge of ESRS compliance, using CDSHotels - a leading hotel group in the Mediterranean, operating in Apulia and Sicily - as a case study. The company, currently undergoing expansion, will be required to publish a sustainability report in accordance with the ESRS starting in 2026, based on 2025 data, due to having exceeded the size thresholds set by EU regulations 15.

The first *question of research* aims to assess level of readiness of CDSHotels to adopt the ESRS by examining its current structure and organizational mechanisms, while identifying the main operational, strategic, and informational challenges encountered in the process. The second question explores the potential support provided by technological solutions - specifically specialized software - in managing and optimizing reporting activities. The objective is to evaluate whether and how these tools can facilitate the integration of the standards into business processes, enhancing both efficiency and reporting reliability. In parallel, the study examines the broader challenges companies face in implementing the standards.

Through the CDSHotels case, the study highlights the need for businesses to rethink their models by integrating principles of sustainability and circularity to create lasting and responsible value, thereby contributing to a more innovative and future-oriented economy.

Methods

The methodology adopted in this research is based on a qualitative approach, with the aim of analyzing the readiness level of CDSHotels in relation to the new sustainability reporting obligations introduced by the Corporate Sustainability Reporting Directive (CSRD).

The initial desk research phase (Table 1) involved an in-depth analysis of institutional sources, including the Commission Delegated Regulation (EU) 2023/2772 of 31 July 2023, the Legislative Decree No. 125/2024, documents and guidelines issued by EFRAG. Scientific articles and contributions from consulting firms (EY, KPMG, Deloitte) were also reviewed to clarify the technical complexities of the ESRS 16,17,18,19. In parallel, the analysis of the company's website and internal reports provided an overview of the sustainability practices already implemented within CDSHotels' facilities.

Table 1. Sources of information in desk research. Source: personal elaboration

Type of Source	Information obtained	Role in Methodology
Normative and Regulatory Sources	- Delegated Regulation (EU) 2023/2772 - CSRD Directive 2022/2464/EU -Legislative Decree 6 September 2024, no. 125	They provide the legal framework and principles for understanding the sustainability reporting obligations required of companies.
EFRAG Technical Documentation	- EFRAG IG 1: Materiality Assessment - EFRAG IG 2: Value Chain - EFRAG IG 3: List of ESRS Datapoints -Technical explanations of EFRAG	They offer practical insights into the implementation of ESRS, such as materiality assessment and value chain management.
International Sources	-EC publications and FAQs -Institutional sites of European and global authorities and consultancy companies	They ensure consistency between corporate standards and global directives, supporting adherence to regulatory obligations and technical compliance.
Corporate Sources	- CDSHotels corporate website-Internal documents and reports - Internal documents	They provide specific data on the company's structure and history, indispensable for assessing the applicability of the standards to the company in question.

The *second phase* involved conducting semi-structured interviews with key figures within the hotel chain, selected based on their direct expertise on the topics under investigation. Specifically, interviews were held with the Director of the Grand Hotel Riviera, the Head of Procurement, the Head of Innovation, and the Energy Manager, with the aim of collecting specific data on management practices, energy consumption, procurement, innovation, and energy policies. The triangulation of these diverse roles ensured an integrated and multi-level perspective of the company's internal dynamics.

To support the qualitative investigation, a structured questionnaire composed of 30 questions was developed and administered to the company's managers. The questions, inspired by the requirements set out in the ESRS, allowed for the mapping of available data relevant to the preparation of the sustainability report.

The research process was enriched by a direct internship experience carried out by the author within one of the group's facilities. This allowed for a participant observation of daily practices and privileged access to operational data and information. This immersive experience provided critical insights for assessing the implementation of sustainability principles.

Given the complexity of understanding and managing the ESRS, as well as the challenges related to data collection and processing for report drafting, it was deemed valuable to integrate the analysis with the use of dedicated sustainability reporting software. The decision to adopt a digital tool allowed the author to conduct a practical experimentation aimed at assessing its potential in supporting the company in organizing and managing the data required for reporting purposes. This approach proved particularly appropriate, considering the company was preparing for its first mandatory sustainability reporting process. An exploratory web search and introductory calls with several software providers were carried out to identify the most suitable CSRD-compliant software.

The integration of these various sources provided a clear, detailed, and multi-level overview, useful for assessing CDSHotels' readiness for the adoption of the ESRS.

Findings

To process the data collected, a preliminary comparison was conducted between the use of a traditional spreadsheet and that of specialized ESG software, in order to assess their respective advantages and limitations. Although widely used, spreadsheets often proved to be ineffective tools for structured sustainability reporting, being prone to errors, difficult to manage over the long term, and lacking in traceability. In contrast, companies that have invested in digital ESG software have reported significant improvements: stronger risk management, greater reporting accuracy, enhanced operational efficiency, and a strengthened corporate reputation.

The adoption of dedicated software facilitated the collection and processing of data, improving its quality and traceability, and helping to reduce errors and information loss. However, the analysis revealed that the ESG software market remains fragmented. According to a KPMG survey, only 37% of companies use specialized ESG tools, while 47% still rely on spreadsheets 20. Moreover, there is a limited availability of tools fully integrated with the ESRS standards, due to their recent introduction and inherent complexity. Notably, none of the analyzed solutions were developed in Italy, highlighting a technological gap in the country.

Following a comparative analysis of different software available on the market—based on criteria such as user-friendliness, customization, automation, security, and regulatory compliance—the Falcony software emerged as the most suitable for the needs of CDSHotels in terms of data processing and sustainability reporting.

The software was customized to compare each ESRS standard with its corresponding level of implementation across the 12 facilities of the hotel group. Each facility and standard was assigned a score, based on *five criteria* defined for CDSHotels: internal knowledge, data availability, ongoing actions, strategic alignment, and implementation capacity. Each criterion contributed to the total score, up to a maximum of 100 points per standard.

The results revealed an medium level of readiness in relation to the ESRS, with variations across the facilities, reflecting a sustainability journey that has begun but is still evolving. Falcony proved to be a valuable ally in providing integrated, structured, and adaptable analyses tailored to the company's specific context.

The study led to the awareness that, from this point forward, companies will face significant challenges, such as: adapting to new regulations, high initial costs for training and data collection systems, managing regulatory and data complexity, staff training, technological implementation difficulties, initial operational risks, and lack of available data.

In response to these challenges, an operational framework was developed to support companies in the complex process of reporting in accordance with the ESRS standards. This model, illustrated in Figure 1, is structured into *four main phases*: Input, Data Collection, Data Processing, and Output, representing the complete flow of the reporting process, with a transversal focus on the selection of technological tools.

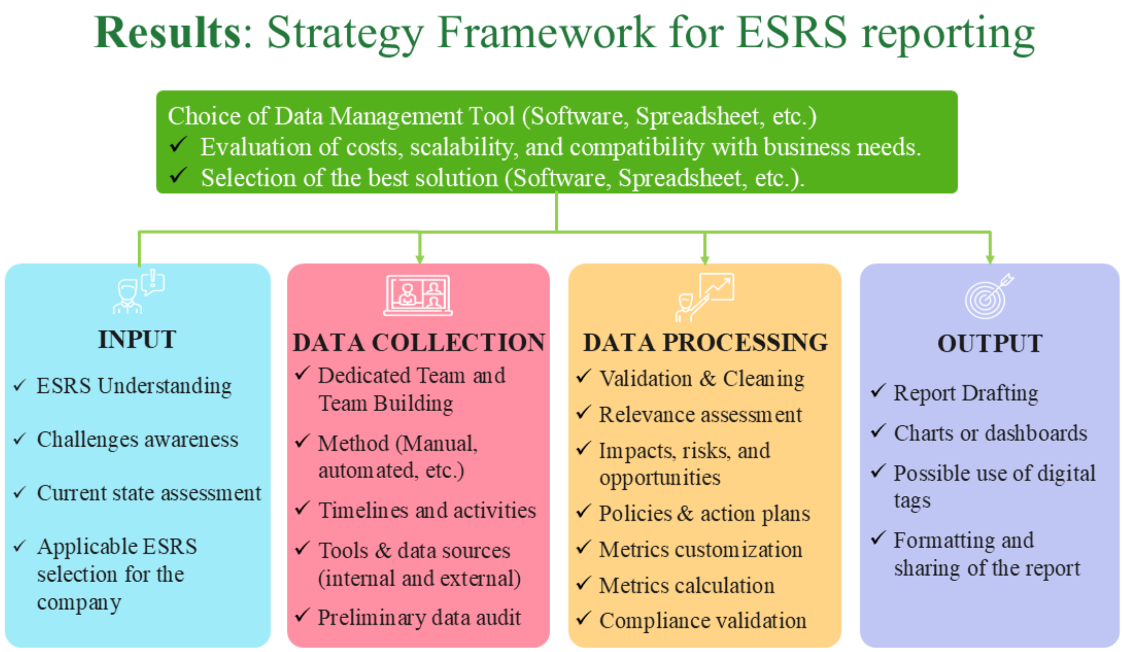

Figure 1_Framework for companies. Source: personal elaboration

The proposed framework stands out for its simplicity, adaptability, and ability to meet the needs of companies of all sizes, offering a logical and functional structure to guide the sustainability reporting process. To make the process more efficient, scalable, and compliant with regulatory standards such as the ESRS, it is essential to integrate the sustainability reporting framework with technological solutions. This framework aims to transform sustainability from a regulatory obligation into a strategic pillar for businesses. Its implementation represents not only a practical innovation but also a step toward a more conscious and responsible corporate culture.

Discussion/Conclusion

The study highlights how the introduction of the European Sustainability Reporting Standards (ESRS) marks a turning point in corporate reporting, signaling a shift from a voluntary approach to a regulated, structured, and integrated model. Although the adoption of these standards entails significant challenges, it offers companies a tangible opportunity to innovate their business models and enhance relationships with stakeholders.

The proposed framework has proven to be a valuable tool to support companies—particularly SMEs—in understanding and implementing the ESRS, facilitating the transition toward effective and transparent reporting. Its application to the CDSHotels case study made it possible to identify both strengths—such as already initiated environmental initiatives—and areas for improvement, especially regarding data systematization and the dissemination of sustainable practices across all facilities.

In conclusion, the ESRS should not be seen merely as a set of obligations, but rather as an opportunity to create long-term value. Companies that approach this path with responsibility can strengthen their competitiveness while contributing to the transition toward a more sustainable and resilient economy.

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The Disclosure on Technologies: An Empirical Analysis on the Tourism Sector

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Abstract

This paper investigates the role of technological disclosure in the tourism sector, with an emphasis on sustainability and smart technology adoption. An empirical analysis was conducted on 55 tourism firms (Appendix) through their annual and sustainability reports from 2018 to 2022. Results highlight how structured governance and the presence of a technology manager are associated with greater voluntary communication regarding innovation strategies. Companies adopting advanced technologies such as smart grids, IoT sensors, and precision agriculture exhibit higher transparency. The study confirms that technological disclosure enhances stakeholder engagement and strengthens competitive positioning within the framework of sustainable tourism.

Keywords: Technological disclosure; smart tourism; sustainability; corporate transparency; IoT; corporate governance

Introduction

Technological innovation [1] and sustainability [2] are reshaping the tourism industry. In this context, corporate disclosure [3]—particularly the voluntary communication of digital innovation strategies—has become a strategic tool. It improves transparency, enhances stakeholder trust, and supports ecological transition [4] objectives. As the tourism sector faces increasing pressure to demonstrate sustainable practice [5], disclosing information related to smart technologies and resource efficiency becomes crucial for attracting investors and differentiating in a competitive market [6].

This study aims to explore how technological disclosure is applied across tourism companies (Figure 1), which factors influence it, and how it contributes to sustainable performance. The paper builds on existing literature on corporate disclosure and smart [7] tourism, offering an empirical contribution through the analysis of real-world data.

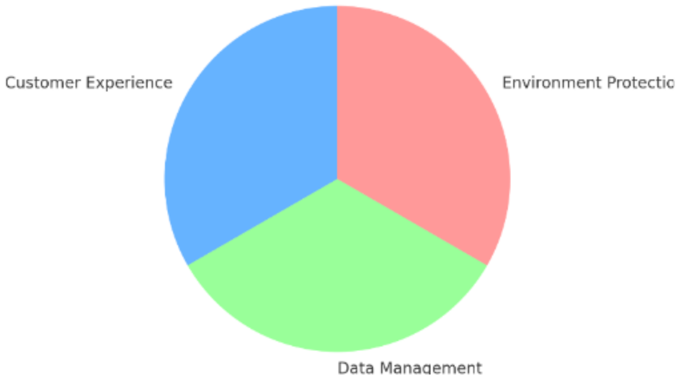

Figure 1_Types of Smart Technologies in Sample companies

Methods

The research is based on a quantitative content analysis of corporate and sustainability reports from 55 tourism firms, including multinational and medium-sized enterprises, over the period 2018–2022. Reports were collected from official databases and company websites.

The study focused on identifying information related to technology, sustainability [8], CSR initiatives [9], innovation [10], diversity, and risk management. Additional variables considered include board composition, presence of a technology manager, company size, and financial performance.

Regression models were applied (Table 1) to identify correlations between governance structures and the extent of voluntary disclosure. The regression analysis yielded a statistically significant positive p-value for the presence of a technology manager, indicating that companies with a dedicated technology manager tend to have higher levels of technological disclosure compared to those without such a manager. This suggests that the presence of a technology manager plays a crucial role in driving transparency and communication regarding technology-related matters within tourism companies.

Table 1: regression results

Indipendent Variable	***Coefficient***	***Standard Error***	***P-Value***	***LCI (95%)***	***UCI (95%)***
Intercept	*59,1536*	*71,3019*	*0,4079*	*-81,6475*	*199,9548*
IT Manager	***28,7823***	***10,2221***	***0,0054****	***8,5964***	***48,9682***
Board Size	*8,9163*	*8,52486*	*0,2971*	*-7,9178*	*25,7505*
Women in the Board	*-19,1847*	*17,2363*	*0,2673*	*-53,2217*	*14,8521*
Location tech disclosure	*13,2282*	*11,657*	*0,258*	*-9,791*	*36,2475*
ROE	*-0,54056*	*0,3198*	*0,0929***	*-1,1722*	*0,091*
Number of Employees	*0,0017*	*0,0004*	*0,0005****	*0,0007*	*0,0026*
Observations	*168*	*168*	*168*	*168*	*168*

Findings

The analysis revealed several key findings:

- Companies with structured governance [11], especially those with a dedicated technology manager, showed significantly higher levels of technological disclosure (Figure 2).
- Large enterprises tend to include detailed sections on innovation, smart technologies, and sustainability strategies.
- Smaller firms focused more narrowly on operational sustainability, with less emphasis on digital transformation.
- Technologies such as IoT sensors, smart grids, and precision agriculture were frequently disclosed by the most innovative companies.
- Voluntary disclosure was positively correlated with firm size, board diversity, and profitability.

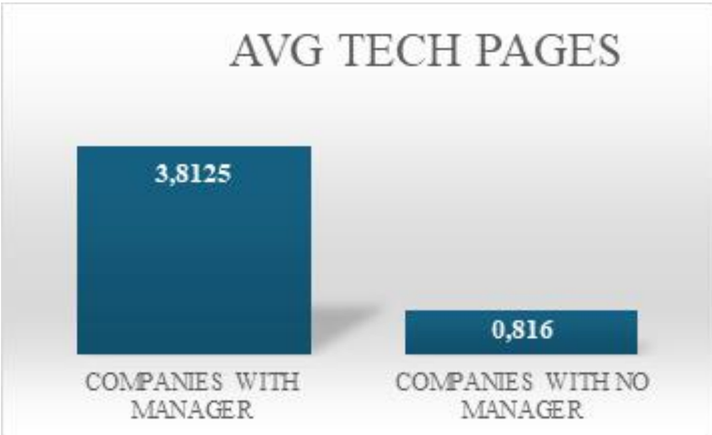

Figure 2_Differences in disclosure with the presence of a manager. Avg tech pages are the number of technologies related pages in the companies's financial and sustainability reports.

Discussion/Conclusion

The results support the hypothesis that technological transparency plays a dual role in modern tourism companies: it acts as both a competitive asset and a tool for responsible management. Firms that adopt advanced technologies and communicate their strategies openly are better positioned to meet stakeholder expectations and navigate the sustainability transition.

This study contributes to a deeper understanding of how corporate governance and technological innovation influence disclosure practices. While larger firms lead in transparency, the findings also suggest opportunities for smaller enterprises to improve stakeholder engagement through more strategic communication.

Further research could explore longitudinal trends or examine the role of digital platforms in enhancing real-time transparency in tourism services.

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Circularity Passport for Tribological Devices: A Framework and Algorithm Proposal

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Abstract

This paper proposes a methodological framework and an algorithm designed to address the lack of sustainability certifications in the tribology sector. While circularity passports are increasingly being applied in various industrial fields, tribological devices (such as bearings and seals) still lack structured tools for assessing and communicating their environmental impact. The research presented here proposes a framework that considers the three fundamental life cycle phases—production, use, and end-of-life—integrated with an algorithm for quantifying sustainability and assigning an eco-label. The methodology aims to ensure transparency, reduce the risk of greenwashing, and guide companies toward more circular practices. Although still at a conceptual level, the model lays the foundation for future operational applications.

Keywords: Circular economy; Tribology; Green tribology; Ecolabelling; Circularity passport; Sustainability algorithm

Introduction

The transition from a linear economic model, based on the "take-make-dispose" paradigm, to a circular economy has become a strategic priority to ensure sustainability and the efficient use of resources. The circular economy aims to keep products, materials and resources in use for as long as possible, reducing waste and valorising discarded materials [1].

In this context, the Circularity Passports (CPs)They are fundamental tools: real digital documents that accompany products throughout their life cycle, describing their composition, performance, potential for reuse and recycling [2].

Despite progress in sectors such as construction, electronics and textiles, the tribological devices— mechanical systems in relative motion where friction, wear and lubrication are key aspects — do not yet have dedicated passports [3]. This lack is linked to their particular complexity: during use, performances continuously change due to wear and friction, influencing both energy efficiency and particulate emissions. For this reason, unlike other products, their sustainability must also be assessed during the development phase use [4]. The lack of certification tools in this sector not only limits transparency but also opens the way to greenwashing risks. For this reason, this thesis aims to fill this methodological gap by developing an evaluation framework and of a sustainability algorithm capable of powering a circularity passport for tribological devices.

The research work, developed within the PRIN project"TRIBOSCORE - TRibological modellIng for sustainaBle design Of induStrial friCtiOnal inteRfacEs", in collaboration with the University of Salento and the Italian Institute of Technology (IIT), intends to respond to this gap by proposing framework and an algorithm for the creation of a specific circularity passport for tribological devices.

Methodology

The methodology used is based on two main pillars:

- Methodological framework: an analysis framework that takes into account the entire life cycle of tribological devices, divided into its three main phases.
- Sustainability Algorithm: a computing system that processes data collected by the framework, attributing a weighted score to the variables analyzed. This score allows us to generate an overall assessment of the device's sustainability level.

The combination of the two tools allows you to outline a circularity passport, capable of providing transparent and comparable information.

Methodological framework

The framework developed structures the sustainability assessment of tribological devices along three phases of the life cycle:

- *Production*: choice of materials, embodied energy, CO2 emissions and manufacturing processes.
- *Use:* monitoring of the friction coefficient, wear rate, lubrication efficiency, energy consumption and particulate emissions during operation.
- *End of life*: recycling potential, recovery of secondary raw materials, energy recovery and impacts related to disposal.

This matrix structure, as shown in Figure 1, organized in three columns (production, use, end of life) and associated variables, allows to have a full view, with particular attention to the usage phase, which is crucial for devices in relative motion.

		PHASES		
		PRODUCTION	USE	END OF LIFE
VARIABLES	ENVIRONMENTAL IMPACT (Person / Planet)	CO2 emissions and energy consumption, critical materials	Emissions during use (wear); Tribo-chemical reactions	Recyclability of materials and waste management
	TRIBO-EFFICIENCY	Optimized, energy efficient production processes	Reduction of energy losses (friction, dissipation); Tribo performances (product dependent)	Energy recovery during material recycling
	DURABILITY / WEAR	Selection of durable and resistant materials	Monitoring wear and tear and performance degradation	Reuse and recyclability of main components;

Figure 1_Framework matrix for sustainability assessment in the production, use and end-of-life phases

The Sustainability Algorithm

To make the framework operational, a sustainability algorithm which processes the data collected in the three phases and returns a weighted sustainability score. The algorithm is divided into three main steps:

- *Data collection*→ information from the three phases of the framework (production, use and end-of-life), entered into a dedicated digital database or existing platforms.
- *Weight assignment*→ Each variable receives a specific weight based on the type of device (for example, a polymer seal or a bearing). This weighting allows the methodology to be versatile and applicable to different industrial contexts.
- *Sustainability score calculation*→ the overall value is determined as a weighted average of the variables, providing an immediately interpretable numerical result. The weighted sum produces a final score on a scale of 0–100. The score is associated with a color label (scale A–E, from green to red), to ensure comprehensibility and transparency for businesses and consumers.

LEVEL	SCORE	COLOUR	DESCRIPTION	
A	85-100	Dark green	Excellent	
B	70-84	Light green	Good	
C	55-69	Yellow	Middle	
D	40-54	Orange	Low	
E	0-39	Red	Very low	

Figure 2_Sustainability labeling system with color scale

The output of the algorithm is in fact an "environmental license": a classification that associates the calculated score with achromatic scale (Figure 2), from green (high level of sustainability) to red (low level). This visual system allows the results to be easily accessible and understandable not only for industrial operators, but also for consumers, promoting transparency and counteracting the risk of greenwashing [4].

To provide a visual representation of the described process, Figure 3 shows the diagram illustrating the data flow between the three phases of the product life cycle, the centralized database and the sustainability algorithm.

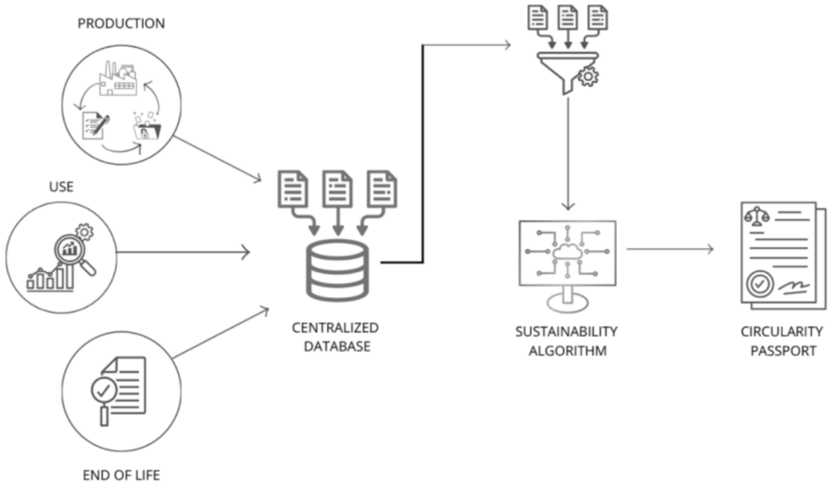

Figure 3_Diagram of the data flow for the generation of the circularity passport

Discussion

The developed model represents a first conceptual and methodological contribution to the topic of sustainability applied to tribology, a sector that, unlike others, does not yet have consolidated tools for assessing the circularity of products.

The main innovation lies in two elements:

- *The inclusion of the use phase* Tribological devices undergo progressive performance degradation due to friction and wear, and monitoring this phase allows for a more realistic picture of their environmental impact.
- *The versatility of the model*: the possibility of assigning different weights to the variables based on the device being analyzed makes the methodology flexible and adaptable to different types of products (e.g. bearings, brakes, polymer seals).

An additional added value is represented by the communication of results. The colour scale associated with the sustainability score allows for the translation of complex technical information into an accessible language, facilitating the transparency towards consumers and countering practices of greenwashing.

Finally, the model opens the way to a possible integration with digital platforms Companies could record their product data in dedicated databases, which the algorithm would automatically use to calculate the "environmental license." This would make the system scalable and standardizable, facilitating the spread of eco-design practices.

Conclusions

The work highlighted a significant gap in the tribology sector: the lack of circularity passports and specific environmental assessment tools. Starting from this criticality, a model composed of a methodological framework and from a sustainability algorithm, designed to generate a circularity passport of mechanical devices in relative motion.

The main contributions of the research can be summarized as follows:

- introduction of an integrated approach that considers production, use and end-of-life;
- development of an algorithm adaptable to different tribological devices;
- proposal for a color system that simplifies the communication of the level of sustainability;
- enhancing transparency and traceability as tools to reduce the risk of greenwashing.

Although this is still a theoretical model, not yet experimentally validated, it provides a solid foundation for future developments. Research opportunities include:

- the empirical validation of framework and algorithm on different tribological devices;
- the implementation in digital data collection tools usable by businesses;
- the definition of ecolabelling standards specific for the tribology sector.

In summary, the work represents a preliminary but significant step towards defining an environmental evaluation and certification system dedicated to tribology, contributing to progress towards a more sustainable economy circular, transparent and sustainable.

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INFORMATION & TRAINING

School education on environmental sustainability aimed at the Alpha generation: the international, Italian and Marche Region context

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Abstract

The growing focus on environmental sustainability has made it necessary to integrate this topic into school curricula. This study investigates environmental sustainability education targeting Generation Alpha, with a particular focus on the international, Italian and Marche Region contexts. Using both direct research (through a survey distributed to preschools, primary, and lower secondary schools in the Marche Region), and comparative analysis across different territorial levels, the study explores teaching methods, existing initiatives, and key challenges related to embedding environmental sustainability into school curricula. The findings highlight the importance of a holistic, community-based approach that actively involves students, teachers, institutions and local stakeholders. The thesis underscores the need for stronger educational policies, innovative teaching resources, and experiential learning strategies to better prepare future generations to face global environmental challenges.

Keywords: environmental sustainability; environmental sustainability education; school curricula

Introduction

Environmental sustainability refers to the responsible use of natural resources to meet current needs without compromising the well-being of future generations. According to the planetary boundaries framework proposed by Steffen and Rockström, sustainability entails living well within Earth's limits [1]. The United Nations' Agenda 2030 outlines 17 Sustainable Development Goals (SDGs), which aim to eliminate poverty, reduce inequality, combat climate change, and promote peace and education. Among these, SDG 4 ("Quality Education") plays a pivotal role by fostering awareness, innovation, inclusion, and informed decision-making. Environmental education serves as a bridge between awareness and action. A 2024 study demonstrates that well-structured environmental programs can enhance civic engagement and encourage sustainable behavior [2]. Ocean literacy also plays a critical role: targeted initiatives have been shown to significantly improve students' understanding of marine environments, underscoring the importance of early environmental education [3]. Digital tools (such as mobile apps, simulations, and virtual reality) further enrich sustainability education by making it more interactive and engaging [4]. However, persistent challenges remain, including limited teacher training and access to resources. Globally, countries take varied approaches to sustainability education. The G20 has prioritized inclusive growth and environmental responsibility, while UNESCO supports inclusive policies and investments to incorporate sustainability into education systems [5]. Programs like Eco-Schools and Green Flag provide frameworks for schools to adopt sustainable practices, demonstrating measurable impacts on student behavior and community involvement. In Africa, despite limited resources, initiatives such as school gardens and recycling projects support sustainability education. Collaboration with Civil Society Organizations (CSO) has proven key for teacher training and policy development [6]. In Asia and the Pacific, countries address diverse challenges through community-based projects and the use of mobile apps to raise awareness, particularly in countries Malaysia [7] and India [8], where education is essential in tackling growing environmental threats. North America's EcoSchools USA program helps schools adopt structured sustainability practices with strong student engagement. Latin American countries are incorporating sustainability into curricula and building green infrastructure, often with NGO and international support. In Australia, projects like the Victorian Science in Schools Research Project have effectively integrated environmental education, focusing on teacher development and school-wide participation [9]. The European Union advances sustainability through the European Green Deal and the GreenComp framework, aiming to embed sustainability competences in all learners. Erasmus+ and other EU initiatives support teacher training, curriculum innovation, and cross-school collaboration. This study aims to analyze the state of environmental sustainability education in nursery, primary, and lower secondary schools in the Marche Region (Italy), comparing it with international practices. The Marche Region supports various initiatives, including "Sustainability Week" and locally funded customized educational programs. Schools also participate in national and European programs such as “Eco-Schools” and the “2030 Agenda for Sustainable Development”. Many local associations further contribute to education and sustainability efforts.

Methods

SURVEY: ENVIRONMENTAL SUSTAINABILITY EDUCATION

1. Has your institution addressed the topic of environmental sustainability"?
   □ NO (survey ends here) □ YES (please answer the following questions).
2. In which school levels has environmental sustainability been addressed?
   □ Nursery school, children aged: □ 3 □ 4 □ 5
   □ Primary school, grades: □ I □ II □ III □ IV □ V
   □ Lower secondary school: □ I □ II □ III
3. Has the topic been included in school projects?
   □ NO □ YES – Please specify: project title; grades involved; duration; school year; topics covered. (Repeat for multiple projects.)
4. Has environmental sustainability been incorporated into the curriculum?
   □ NO □ YES – Please specify: subject(s) and grade(s): ___________
5. Have expert-led sessions been organized?
   □ Public bodies (e.g.); □ Private companies (e.g.); □ Forestry Police; □ Other: ____
6. Is the topic emphasized during environmental awareness days?
   □ World Day for Energy Saving and Sustainable Lifestyles (February 18); □ World Water Day (March 22); □ Earth Day (April 22); □ Other: ____________

Figure 1_The questionnaire

To assess how environmental sustainability education is being implemented for Generation Alpha in the Marche Region, a six-question survey—featuring both multiple-choice and open-ended questions—was sent to all public and private nursery, primary, and lower secondary schools in the Region (Figure 1).

Findings

Responses were received from 85 schools (both public and private). The majority (96.6%) reported addressing environmental sustainability at all school levels—nursery, primary, and lower secondary—with even distribution. Only 3.4% stated that the topic was not included in their school programming (as illustrated in the second chart). Approximately 75% of the schools have developed one or more educational projects focused on sustainability, covering a wide range of themes, such as "Healthy Nutrition and a Healthy Environment" and many others (Figure 2).

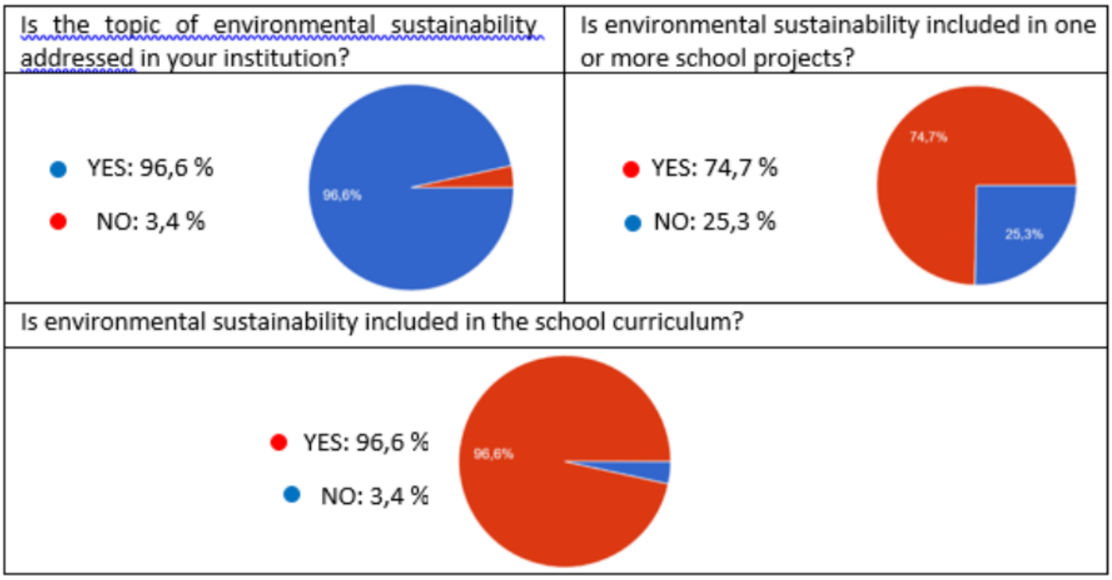

Figure 2_Some questions from the questionnaire and answers

In preschools, where subjects are not compartmentalized, sustainability is approached holistically through everyday activities like drawing, storytelling, and practical life skills. In primary schools, the topic is explored transversally, while in lower secondary schools, it is more closely integrated with Science and Technology. Civic Education plays a unifying role across all levels, reinforcing sustainability as a cross-disciplinary theme. STEM subjects (Science, Technology, Engineering, and Mathematics) are particularly emphasized, as they provide essential tools for understanding environmental issues and fostering analytical, critical thinking. Schools conduct labs in science, mathematics, languages, English, and physical education with a sustainability focus. Educational excursions are also used to contextualize learning. Schools often collaborate with local institutions and organizations to enhance their educational offerings. Survey data revealed partnerships with public bodies, private companies, forestry police, and experts from various fields, including: National/regional/local associations, NGOs, Agricultural and beekeeping enterprises, Vocational training centers, Environmental education centers, Universities (e.g. Polytechnic University of Marche), Waste management firms and public utility companies, environmental departments, fire brigades, and civic organizations. Many schools actively engage in major environmental awareness days, including World Days for Energy Saving (Feb 16–18), World Wildlife Day (March 3), World Water Day (March 22), Earth Day (April 22), World Bee Day (May 20), Biodiversity Day (May 22), European Mobility Week (Sept 16–22), National Tree Day (Nov 21).

Discussion/Conclusion

Environmental sustainability seeks to reconcile human development with the preservation of natural resources. Among the 17 Sustainable Development Goals (SDGs) of the UN 2030 Agenda, SDG 4 recognizes the transformative power of education in fostering sustainable, inclusive, and innovative citizenship. The integration of sustainable skills is essential to address global challenges. Educational approaches to sustainability often involve practical and interdisciplinary experiences. However, limited resources, gaps in teacher training, and cultural barriers hinder full implementation. Nonetheless, digital tools and interactive methods can significantly enhance environmental education. Global initiatives, such as UNESCO's "Decade of Education for Sustainable Development" (DESD), catalyzed initiatives worldwide. Africa has launched Eco-Schools despite infrastructural constraints. Japan and South Korea promote innovative educational policies, "green schools" and interactive technologies [10]. North America's Eco-Schools USA uses a seven-step model integrating sustainability into school curricula [11] to embed sustainability in school life. Latin America's "Escuelas Sustentables" promote environmental certifications and green buildings. The European Commission supports sustainability education through the Green Deal and GreenComp, which define core sustainability competences such as systemic thinking, and sustainable action, supported by programs like Erasmus+, which prepares teachers and schools to face climate challenges. European projects include workshops, school garden management, and community engagement initiatives. While practical projects abound, many countries lack mechanisms to monitor their impact. Italy promotes interdisciplinary environmental education through ministerial guidelines and local collaborations. In the Marche Region, schools implement thematic workshops and interdisciplinary initiatives on recycling, energy efficiency, and waste reduction. Sustainability is integrated into subjects such as science, geography, and technology, providing a comprehensive view of human environmental impact. Schools implement recycling systems, promote creative recycling, and engage students in creating objects from recycled materials. Some schools manage organic gardens. Days dedicated to cleaning parks, beaches, or urban areas are also organized. Partnerships with local associations and other organizations provide valuable materials and support. Exhibitions, shows, and public meetings are used to raise awareness among families and citizens. Digital tools, simulations, educational apps, and training videos help students grasp concepts like ecological footprint and climate change. Some schools even install photovoltaic panels and energy-monitoring systems as hands-on learning tools. Comparing international, European, national, and regional practices reveals a strong alignment in methodology and. The Marche Region is well-positioned within global trends, showing growing commitment to sustainability education. The importance of sustainability education is widely acknowledged as a vital tool for addressing environmental and social challenges, preparing new generations for a more equitable and resilient future, and fostering the cultural change necessary for planet protection. To enhance impact, curricula should encourage critical thinking through real-world case studies to enhance a clearer understanding. By exploring case studies, identifying effective strategies, and generating innovative solutions, students can develop critical thinking skills to address sustainability challenges. Teachers can leverage online resources like scientific journals, research archives, and environmental organization websites. Engaging students in a multi-phase process involving videos, readings, and group discussions is crucial for knowledge acquisition. Documentaries or video reports about local environmental issues can foster emotional connection. Guided discussions allow students to analyze, reflect, and share insights. Environmental and sustainability education should be taught as a cross-cutting theme across various disciplines rather than an isolated subject. Integrating sustainability across subjects promotes a systemic understanding of reality. Increased collaboration among schools, local communities, and non-governmental organizations will promote effective and lasting sustainable education. Policies should include financial incentives and resources to support schools and teachers in implementing sustainability programs. This study significantly emphasizes the need for continuous training, retraining, and empowerment initiatives to keep the public and stakeholders informed and aware of the ongoing environmental crisis. Teachers are pivotal in promoting sustainability education in schools, responsible for imparting the knowledge, skills, and values needed to address global challenges. Prioritizing specific teacher training is essential, enabling them to integrate environmental sustainability into their teaching practices. Education and awareness are the most effective strategies to address environmental concerns. Increasing awareness, building capacity, and fostering a sense of responsibility among teachers can significantly contribute to collective action and the adoption of sustainable practices. Schools are the primary source of sustainability knowledge, followed by social media. Online platforms can be leveraged to spread awareness. Resources like Eco-Schools' climate change teaching kit and FAO's learning resources on food security and sustainable agriculture provide free, engaging materials for teachers and students of all ages. The use of digital tools in schools, as seen in Malaysia's successful integration of a dedicated app to boost ecological awareness among young students, is highly recommended. This approach, which uses interactive activities to maintain engagement and enhance concept assimilation, can inspire similar initiatives in regions like Marche. The urgency of raising resilient future citizens is reflected in SDG 13.3, which calls for improving education, awareness, and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning. Education instills a sense of urgency, motivates proactive engagement, and nurtures critical thinking and problem-solving skills. Adequate support for school education on environmental sustainability, including resources and a conducive environment for promoting Education for Sustainable Development, requires the involvement of municipal, provincial, and regional public bodies active in environmental issues. Valuing local contexts and using the territory as an educational resource makes students aware of their impact. A holistic approach is recommended, integrating sustainability not only into the curriculum but also into school management and local environmental policies.

Equipping students with necessary resources and experiential education is paramount. Environmental sustainability education contributes to making people more aware of human impact on Earth, influencing behavior and stimulating action. Environmental education programs can be adapted to engage individuals of all ages and backgrounds, promoting a collective commitment to sustainability. An inclusive approach allows every social group to contribute, addressing environmental challenges through collective cooperation. Finally, better monitoring and evaluation tools are needed to measure the impact of sustainability education and ensure its effectiveness. While progress has been made in integrating sustainability into early childhood, primary, and lower secondary education, numerous challenges persist, requiring coordinated commitment from governments, schools, and civil society. Environmental sustainability education needs further structural support, economic resources, and inter-sectoral coordination to be fully effective and transformative.

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Fostering sustainability culture in Public Administrations: actors, strategies, and training impact

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Abstract

The integration of sustainability into public administration is a critical lever for promoting systemic, cultural, and organisational change. This study explores how Italian public institutions - through strategies, actors, and training initiatives - contribute to shaping a shared sustainability culture. Drawing on the revised National Sustainable Development Strategy (SNSvS), the paper investigates the enabling role of institutional training, focusing on the Scuola Nazionale dell'Amministrazione (SNA) and the Agenzia delle Entrate (AdE), as case studies. Through qualitative analysis, including document review and expert interviews, the research shows how sustainability-oriented training acts as both a vector for innovation and a driver of institutional coherence. The result highlights the strategic potential of educational pathways in supporting long-term cultural, organisational, and institutional transformation in public governance.

Keywords: Sustainability; Public Administration; Lifelong Learning; Sustainable Development; Organisational Change

Introduction

Sustainability is no longer a theoretical ideal, but a practical and ethical imperative for institutions, organisations, and societies. As articulated in the UN 2030 Agenda [1], the sustainable development paradigm urges a systemic response to complex challenges such as climate change, social inequality, and institutional inertia. Within this framework, the sociological perspective contributes by analysing the interdependencies that exist between social organisation and sustainable transformation [2].

In Italy, the implementation of the National Sustainable Development Strategy (SNSvS) represents a key step in aligning public policy with the Sustainable Development Goals (SDGs) [3]. Among the three strategic vectors of the SNSvS, the second - *Culture for Sustainability* - emphasises education, training, and communication as enablers of systemic change [4]. This vector incorporates principles of lifelong and transformative learning, recognising the role of public institutions as key actors in fostering sustainable mindsets [5]. This paper investigates how public administrations contribute to promoting sustainability culture through targeted training initiatives, with a focus on two institutions: the Scuola Nazionale dell'Amministrazione (SNA) and the Agenzia delle Entrate (AdE). The analysis aims to understand how education can function as a transformative tool for embedding sustainability into the administrative fabric, fostering not only the development of new skills and knowledge but also enabling a cultural shift that aligns institutional practices, core values, and decision-making processes with the principles of sustainable development [6].

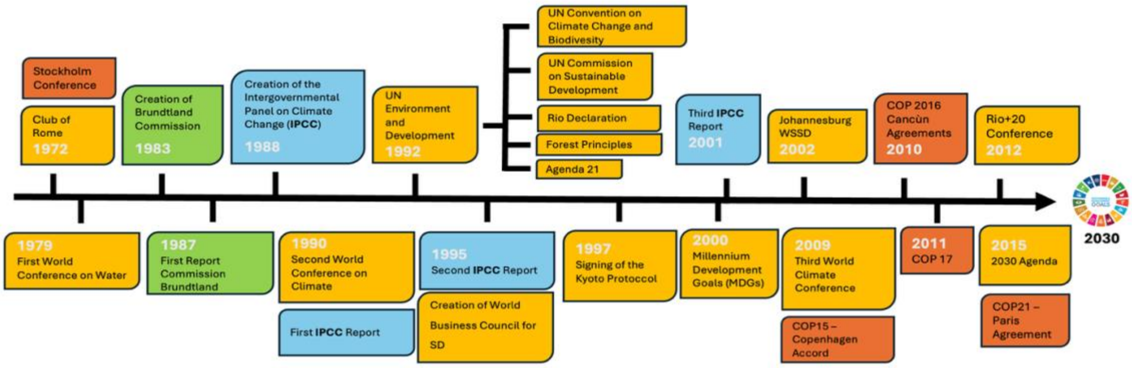

Figure 1_ The stages of approach towards sustainable development (ASviS)

Methods

The research follows a qualitative design, combining document analysis and semi-structured expert interviews. Primary sources include strategic policy documents such as the SNSvS 2017 and 2022 versions, the National Recovery and Resilience Plan (PNRR), and materials related to the Green Public Procurement (GPP) system. These documents were analysed in order to trace the evolution of institutional discourse and training priorities.

The empirical component of the study focuses on two key case studies. The first is the Scuola Nazionale dell'Amministrazione (SNA), which serves as the institutional hub for the training of public managers and officials. The second is the Agenzia delle Entrate (AdE), a central public agency that has integrated sustainability into its internal operations through targeted training initiatives.

To gain a more in-depth understanding of these cases, two targeted interviews were conducted with key informants identified as institutional witnesses, given their institutional roles and direct involvement in training-related activities. Specifically:

- Professor Andrea Lippi, Head of the Public Policies and Governance Department at the Scuola Nazionale dell'Amministrazione (SNA), who holds the highest responsibility within the institution for the design and oversight of training initiatives;
- Dr. Salvatore Lazzara, Director of Training Office at the Agenzia delle Entrate (AdE), the leading figure in charge of planning and coordinating the Agency's internal training strategies.

A thematic coding approach was applied to the interview transcripts and documentary sources to identify recurring themes. Particular attention was given to concepts such as institutional coherence, innovation in public administration, and the role of lifelong learning in embedding sustainability across the public sector.

Findings

The analysis of the revised National Sustainable Development Strategy (SNSvS 2022) underscores the increasing relevance of education and training as strategic enablers of sustainability [7]. In particular, the vector 'Culture for Sustainability' emphasises the importance of fostering a shared vision through systemic education and institutional learning. Within this framework, public administrations are called to act not only as policy implementers but also as cultural agents capable of promoting value-based change across the administrative system [8].

The case study of the Scuola Nazionale dell'Amministrazione (SNA) reveals a structured and evolving training provision aligned with the Agenda 2030 goals. The SNA plays a dual role both as a centre of excellence for the training of public managers and as a promoter of integrated thinking. Its programmes aim to build competences such as foresight, policy coherence, and environmental responsibility, while supporting a culture of continuous learning and institutional transformation.

Similarly, the Agenzia delle Entrate (AdE) has integrated sustainability principles into its internal training model, based on the long-standing adoption of new public management (NPM) approaches [9]. Training programmes developed by AdE focus not only on behavioural aspects - such as energy saving and sustainable procurement - but also on a broader awareness of sustainability as a public governance value. Through targeted educational interventions, the Agency encourages both top-down alignment with overarching strategic objectives and bottom-up engagement of personnel [10].

Complementary insights are provided by national survey data, such as the FPA 2019 report, which indicates a gradual yet uneven institutionalisation of sustainability practices across public administrations. While awareness and commitment are growing, especially in relation to green public procurement, many administrations still lack structure frameworks for training and monitoring. Fragmentation and limited coordination remain barriers to systemic progress.

Table 1.Training and awareness programmes on GPP issues (FPA 2019 report)

Tab. 1 – In your opinion, should a Public Administration define a training and awareness programmes on Green Public Procurement issues aimed at	(Val%):	
	2019	2017

The directors	9,7	11,5
The staff involved in the purchasing process	6,2	5,8
All the staff of the institution	84,1	82,7
Grand total	100,0	100,0

Overall, the findings suggest that sustainability-oriented training is emerging as a catalyst for public innovation [11]. When linked to coherent strategies and supported by specialised public institutions like SNA and AdE, educational initiatives can activate cultural change, align practices with long-term objectives, and contribute to the development of a more sustainable and resilient public sector [12].

An important consideration is to approach the transition to sustainability with a holistic perspective, capable of capturing all the facets of sustainable development. Public administration, thanks to its institutional autonomy, can act as a lever for both organisational and cultural change.

Discussion/Conclusion

This study confirms the essential role of training in fostering a culture of sustainability culture within public administrations. When institutional education is aligned with strategic policy, it acts as a key enabler of coherence, innovation, and inclusion. The cases of SNA and AdE show how targeted training can catalyse not only operational change, but also a transformation in organisational mindset.

Yet, important challenges persist. Sustainability is still too often regarded as an add-on rather than a core principle governance. Embedding training practices into the institutional fabric requires addressing fragmentation, ensuring committed leadership, and promoting intersectoral collaboration supported by robust evaluation frameworks.

Future research could assess the impact of specific training modules and extend the analysis to local administrations. For now, this study highlights that sustainability training is not merely about skill development, it is a strategic asset for transforming public governance towards long-term, systemic change.

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