Premi di Tesi di Laurea ENEA-CONAI
Atti delle tesi presentate

ENEA-CONAI Master Thesis Awards
Proceedings of the selected thesis

Edited by
Erika Mancuso, Tiziana Beltrani,
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Master Thesis on Circular Economy and Sustainability

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Introduzione

Con grande soddisfazione presentiamo la terza edizione degli *Atti delle tesi presentate nell'ambito del Premio di Tesi di Laurea ENEA-CONAI 2025 e 2026*, iniziativa nata dalla collaborazione tra ENEA e CONAI per valorizzare la ricerca universitaria sui temi dell'economia circolare, della sostenibilità e dell'innovazione.

Il Premio si conferma uno strumento efficace di visibilità in quanto offre ai giovani laureati l'opportunità di promuovere i loro contributi alla transizione ecologica e a modelli di sviluppo più sostenibili. L'edizione 2025-2026 ha inoltre ricevuto il patrocinio dalla Rete delle Università per lo Sviluppo Sostenibile (RUS) e dalla Piattaforma Italiana degli Stakeholder per l'Economia Circolare (ICESP), ulteriore riconoscimento del valore scientifico e istituzionale dell'iniziativa. Il volume raccoglie una selezione delle tesi premiate per qualità scientifica, originalità e rilevanza applicativa. Gli elaborati affrontano temi strategici quali ecodesign, gestione sostenibile delle risorse, valutazione degli impatti ambientali, tecnologie per il riciclo e modelli di produzione e consumo circolari.

L'esperienza maturata nelle precedenti edizioni ha poi evidenziato come il Premio non rappresenti soltanto un riconoscimento per il merito accademico, ma costituisca anche un osservatorio sulle tendenze emergenti della ricerca italiana in materia di economia circolare. Attraverso la pubblicazione degli extended abstract e la loro valutazione da parte di un Comitato Tecnico Scientifico, CONAI ed ENEA intendono favorire la diffusione e la condivisione delle buone pratiche con il sistema produttivo e la società. Questa edizione si colloca in un momento particolarmente significativo per le politiche europee, segnato dall'attuazione del nuovo Regolamento sugli imballaggi e i rifiuti di imballaggio (PPWR) e dall'avvio del futuro *Circular Economy Act*, iniziative che rafforzano il ruolo dell'economia circolare nella decarbonizzazione e nella creazione di un mercato unico delle materie prime seconde. E la crescente partecipazione al Premio testimonia l'impegno delle nuove generazioni nell'affrontare le sfide ambientali e climatiche del nostro tempo. Le tesi raccolte nella pubblicazione dimostrano infatti come creatività e interdisciplinarità possano tradursi in proposte e soluzioni concrete per il raggiungimento degli obiettivi europei e nazionali di economia circolare.

Ringraziamo tutti i partecipanti, i relatori, le università e i componenti del Comitato Tecnico Scientifico per il contributo offerto. Un ringraziamento speciale va ai giovani ricercatori e ricercatrici che, con il loro impegno e le loro competenze, rappresentano una risorsa essenziale per costruire un futuro più sostenibile.

Simona Fontana, Direttore Generale CONAI

Claudia Brunori, Direttore Dipartimento Sostenibilità ENEA

Introduction

We are pleased to present the third edition of the Proceedings of the theses submitted for the *ENEA-CONAI 2025-2026 Degree Thesis Award*, an initiative born from the collaboration between ENEA and CONAI to promote university research on topics related to the circular economy, sustainability, and innovation.

The Award continues to be an effective visibility tool, offering young graduates the opportunity to showcase their contributions to the ecological transition and to more sustainable development models. The 2025-2026 edition has also received the patronage of the *Italian University Network for Sustainable Development (RUS)* and the *Italian Stakeholder Platform for the Circular Economy (ICESP)*, further recognition of the initiative's scientific and institutional value. This volume brings together a selection of theses awarded for their scientific quality, originality, and practical relevance. The works address strategic topics such as Ecodesign, sustainable resource management, environmental impact assessment, recycling technologies, and circular production and consumption models.

Experience gained through previous editions has shown that the Award is not only a recognition of academic excellence but also serves as an observatory of emerging trends in Italian research on the circular economy. Through the publication of extended abstracts and their evaluation by a Scientific and Technical Committee, CONAI and ENEA aim to promote the dissemination and sharing of best practices with industry and society. This edition takes place at a particularly significant moment for European policies, marked by the implementation of the new *Packaging and Packaging Waste Regulation (PPWR) and the launch of the future Circular Economy Act*. These initiatives reinforce the role of the circular economy in decarbonization efforts and in the creation of a single market for secondary raw materials. The growing participation in the Award demonstrates the commitment of younger generations to addressing the environmental and climate challenges of our time. The theses featured in this publication clearly show how creativity and interdisciplinarity can be translated into concrete proposals and solutions for achieving European and national circular economy objectives.

We would like to thank all participants, supervisors, universities, and members of the Scientific and Technical Committee for their valuable contributions. Special thanks go to the young researchers whose dedication and expertise represent an essential resource for building a more sustainable future.

Simona Fontana, General Director of CONAI.

Claudia Brunori, Director of Department for Sustainability, ENEA.

CLOSING THE LOOP

THE CIRCULAR ECONOMY IN THE AGRI-FOOD SECTOR: CONSUMER PERCEPTIONS OF UPCYCLED PRODUCTS GENERATED FROM FOOD WASTE

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ABSTRACT

Given the environmental impacts of the agri-food sector, the circular economy appears to be the solution for reducing food waste and losses. Recently, the upcycling of food waste has emerged as an innovative practice that repurposes food by-products into higher-value resources, thereby preventing the economic and environmental costs of disposal. Since consumer perceptions of upcycled products remain underexplored, this study adopts the Theory of Planned Behaviour and the Theory of Reasoned Action to investigate consumers' purchase intentions and perceptions by examining their attitudes, subjective norms, and perceived behavioural control. The empirical investigation was conducted using a questionnaire administered to 1,022 adult Italian consumers via Qualify, Altroconsumo's collaborative platform. Results show that, despite limited knowledge of upcycled products, almost the entire sample is willing to purchase them. However, the main barriers limiting their diffusion remain a lack of awareness and product availability in physical retail stores.

Keywords: Circular economy; Upcycled products; Food waste; Consumer perceptions; Theory of Planned Behaviour; Waste-to-value.

1. INTRODUCTION

The current environmental crisis is driven by the traditional linear economic model of 'take-make-use-dispose', an approach historically deemed acceptable only as long as resources were considered abundant and the environmental impacts of industrial production remained unacknowledged [1]. However, as the unsustainability of 'business as usual' practices became undeniable [2], the transition to a circular paradigm became imperative [3]. By adopting the 'cradle-to-cradle' principle, it is possible to achieve more efficient waste management [1], reduce disposal costs [4], improve the management of scarce resources, and minimise overall environmental impacts.

Every year, one-third of the global food production is lost or wasted [5], while food waste (FW) accounts for approximately half of European municipal solid waste [6]. In Italy alone, economic losses related to FW amount to €14 billion annually [7]. Consequently, the global agri-food system – comprising agriculture, processing, packaging, transport, retail, and waste management – represents one of the key

challenges to achieving zero-waste objectives. Aligned with the 2030 Agenda for Sustainable Development and the European Green Deal's Farm to Fork strategy, the circular economy (CE) framework is increasingly integrated into this system. This approach aims to valorise all Food Loss and Waste (FLW) and surpluses generated across the supply chain, converting materials intended for human consumption that would otherwise be discarded into valuable resources.

As highlighted by the Environmental Protection Agency's Wasted Food Scale [8], upcycling represents the preferred method for managing FLW, second only to direct FW prevention. Specifically, food upcycling constitutes a distinct sub-category of the 'Recovery and Recycling' business model. Through this approach, FLW is transformed into valuable inputs, thereby mitigating the environmental and economic costs of disposal while generating higher-value finished products. Indeed, the distinction between recycling and upcycling lies precisely in this value creation: rather than merely reclaiming a material, upcycling processes secondary inputs to deliver enhanced functionality and superior quality [9]. Extant research focuses predominantly on upcycled products for human consumption, while applications within the pet food sector remain an emerging segment. These are variously defined as 'waste-to-value' (WTV), 'upcycled foods', or 'value-added surplus products' (VASP) [10], [11]. Such products – made from FW, by-products, or surpluses that are entirely safe [11] yet deemed unsaleable by producers, retailers, and the hospitality sector [12] not only divert waste from disposal but also exhibit enhanced nutritional value [10]. Beyond widely investigated food-to-food applications, such as Biova Project, which transforms surplus retail bread into craft beer, the Italian entrepreneurial ecosystem increasingly applies upcycling across diverse industries. Cross-sector examples include NASTE Beauty in cosmetics (utilising agricultural by-products), ID.EIGHT in fashion (producing apple and grape-based bio-leather footwear), Krillmat in interior design (developing a patented biopolymer derived from organic by-products for 3D printing), and Relicta in sustainable packaging (engineering a water-soluble bioplastic sourced from industrial fish processing waste).

While firms fundamentally exist to generate value for their stakeholders, and despite the well-documented social, economic, and environmental benefits of food upcycling [13], the consumer ultimately acts as the primary decision-maker in operationalising this specific form of CE. It therefore becomes critical to investigate consumers' attitudes towards upcycled offerings [14]. Although this topic has recently gained prominence in the scientific literature [15], empirical evidence indicates a persistent lack of public awareness regarding upcycled products made from FW [16]. A literature review on consumer perceptions of upcycled products derived from FW, comprising 41 scientific articles, revealed that these attitudes are influenced by factors classified into two main categories: individual-related variables, including demographic and psychographic characteristics, and product-related variables (Table 1). This analysis highlights a critical empirical disconnect: while scholarly research

remains predominantly focused on human food, identified studies on non-food applications (only two papers examining cosmetics and bioplastics) or pet food (only one article) remain extremely scarce. Consequently, consumer perceptions in these emerging domains remain largely unexplored [17]. To bridge this gap, an empirical investigation was conducted to examine consumer responses towards upcycled offerings beyond traditional human food applications.

Table 1: *Factors influencing consumer perception of upcycled products made from food waste*

Individual-level variables
• ***Demographic variables***: gender; age; education; income.
• ***Psychographic variables***: environmental and social sustainability awareness; awareness of upcycled product benefits; food waste prevention awareness; preceived quality and safety of upcycled products; status-seeking, frugality, and convenience; preference for organic, eco-friendly, and plant-based foods.
Product-level variables
Price; brand; packaging and labeling; product origin and nutritional value; perceived product novelty; communication.

Source: *Author's elaboration.*

2. METHODS

2.1 Research design

The present study adopts a research design grounded in the Theory of Reasoned Action (TRA) [18] and the Theory of Planned Behaviour (TPB) [19]. These models were selected as they represent well-established theoretical frameworks for analysing and predicting sustainable consumer behaviour. Specifically, the TPB extends the TRA by incorporating the variable of Perceived Behavioural Control (PBC), which accounts for an individual's perception of possessing the necessary resources, opportunities, and skills to perform a given behaviour. This extension allows the model to explain not only behaviours under complete volitional control but also those – originally excluded from the TRA framework – that are not fully under the individual's voluntary control. According to Ajzen [19], behaviour is directly influenced by intention, which is in turn co-determined by attitude, subjective norm, and PBC; these three antecedents are respectively conditioned by behavioural, normative, and control beliefs (Figure 1). Consequently, the questionnaire was structured based on Ajzen's [19] framework, the variables examined in the extant literature, and supplementary informative elements. These include prior knowledge, past purchase experience with upcycled products, interest in environmental sustainability and upcycling, alongside individual demographic variables.

2.2 Data collection

To explore consumers' perceptions of upcycled products made from FW, an empirical survey was carried out on 8 January 2026 on a sample of 1,022 adult Italian consumers (Figure 2). Data collection was

performed in collaboration with Altroconsumo, using a structured questionnaire distributed via their collaborative platform, Qualify. Participants were recruited through a non-probability, voluntary self-selection sampling approach using an opt-in consumer panel. The predefined inclusion criteria required participants to be Italian residents aged 18 or older enrolled in the platform. Data collection was conducted on a first-come, first-served basis and was automatically closed once the target size of 1,022 completed responses was reached. The questionnaire comprised five sections (Figure 3): the first measured the core TRA and TPB constructs (purchase intention, attitude, subjective norm, and PBC), while the remaining four explored respondents' past purchasing experience, additional literature-backed variables, general knowledge of upcycled products, environmental interest, and demographics.

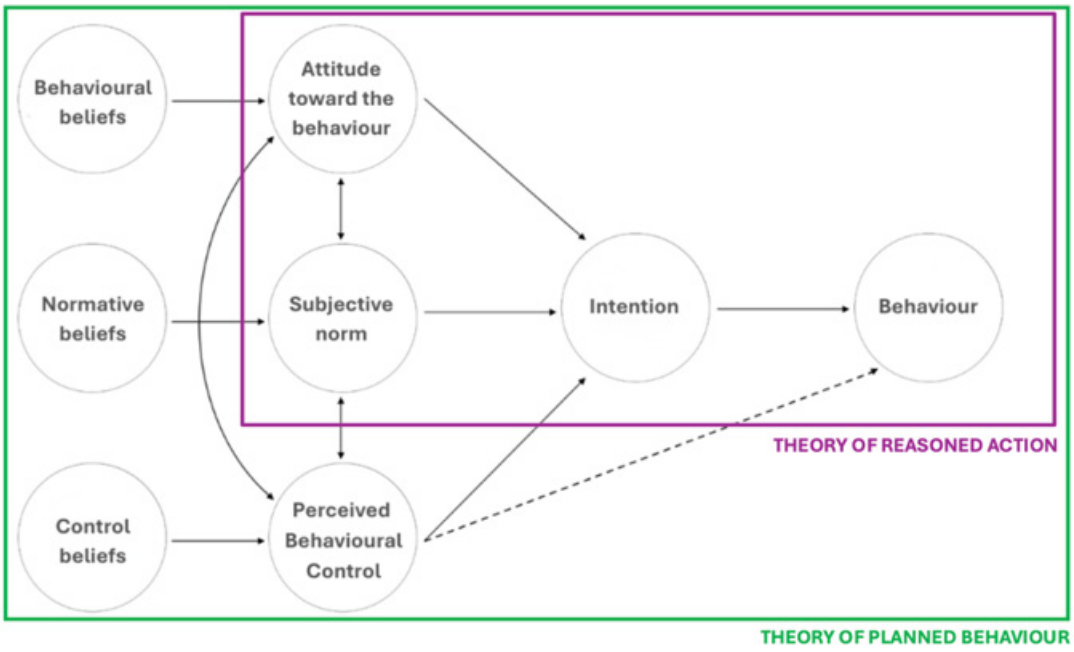


Figure 1: *The reference framework.* ***Source:*** *Author's elaboration based on Ajzen's model [19].*

Variable	Frequency (n)	Percentage (%)
Gender		
Male	543	53,13%
Female	473	46,28%
Prefer not to say	6	0,59%
Age Group		
18–29	51	4,99%
30–45	289	28,28%
46–61	441	43,15%
62–80	237	23,19%
>80	4	0,39%

Variable	Frequency (n)	Percentage (%)
Education Level		
Lower secondary education or less	62	6,07%
Upper secondary education (High school)	478	46,77%
Bachelor's Degree	118	11,55%
Master's Degree	275	26,91%
Postgraduate Degree (Master, PhD)	89	8,71%
Education		
Up to €15.000	82	8,02%
€15.001 – €28.000	231	22,60%
€28.001 – €50.000	366	35,81%
€50.001 – €75.000	151	14,77%
Over €75.000	34	3,33%
Prefer not to say	158	15,46%

Figure 2: *Demographic profile of the respondents (N = 1,022)*

Source: *Author's elaboration based on empirical data.*

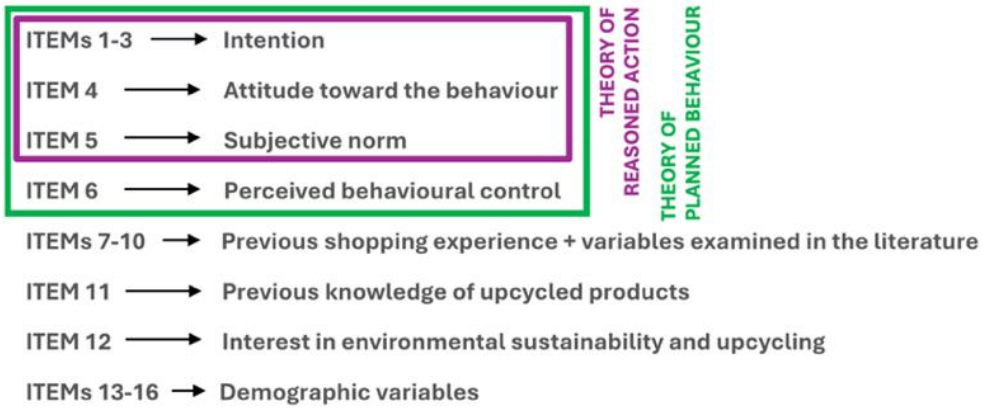


Figure 3: *Structure of the questionnaire Source: Author's elaboration.*

3. FINDINGS

The survey results show a particularly high level of purchase intention for upcycled products made from FW, with 92.27% of the sample willing to buy them [20]. Respondents' product preferences were primarily concentrated in sustainable packaging, home furnishings, and personal care. While participants demonstrated a strong willingness to invest cognitive and learning effort in adopting upcycled solutions, this propensity significantly decreased when considering transactional and economic efforts. Turning to the core intention antecedents, consumers' attitude toward the target behaviour is positive. Conversely, both subjective norm and PBC exhibit a neutral trend, reflecting a perceived lack of social pressure and lower volitional control over the purchase.

Regarding past purchase experience, 14.68% of respondents reported having previously purchased upcycled products made from FW, with packaging, food for human consumption, and

cosmetics/personal care products emerging as the most frequently cited categories. Among these past buyers, 58.00% were moderately satisfied with their purchase, 17.33% remained neutral, and 17.33% were highly satisfied, while minor proportions expressed moderate (3.33%) or high (4.00%) dissatisfaction. In contrast, for the remaining 85.32% of the sample who had never purchased upcycled products, the most frequently reported barriers to adoption included a fundamental lack of awareness and limited availability in physical retail stores. Alongside these factors, other obstacles included higher purchase costs compared to conventional alternatives, low quality perception, food neophobia, safety concerns, and a limited recognition of direct environmental benefits. Furthermore, resistance was driven by low trust in non-leader brands, reluctance to alter lifestyle habits, and aversion to innovative packaging or novel offerings. Indeed, this limited familiarity is reflected in the finding that, before completing the survey, more than half of the respondents (53.06%) were unfamiliar with the concept of upcycling. The sample nonetheless exhibited, on average, a high general interest in environmental sustainability and upcycling practices, with the majority stating they routinely engaged in pro-environmental behaviours.

4. DISCUSSION/CONCLUSION

4.1 Theoretical discussion and managerial implications

The market for upcycled products derived from FW represents a potential blue ocean, an uncontested market space characterized by low direct competition and significant growth opportunities. However, its full realization remains strictly contingent upon consumer acceptance. Interestingly, although respondents exhibited a profound lack of awareness regarding FW-derived upcycled products (a finding also reported in the literature by [21], they expressed a near-unanimous intention to purchase them. This paradox (also documented by [22] underscores the critical importance of implementing effective corporate and institutional communication strategies capable of reaching the public and fostering the adoption of these innovative solutions. Concurrently, it signals a substantial opportunity for firms currently operating in this sector or planning to enter it soon. The existence of highly receptive consumer segments (consistent with findings by [23] and our finding that consumers are willing to exert cognitive and learning effort) suggests that this nascent market could expand rapidly, particularly if supported by targeted public awareness campaigns aimed at conveying the added value of upcycled products. However, account must also be taken of consumers' low willingness to pay a premium price compared to conventional alternatives, as well as their reluctance to incur additional transactional effort. Beyond these limits, substantial barriers to adoption persist, including limited product availability in physical retail stores, price competition from conventional alternatives (cf. [21]), skepticism toward novel items or innovative production techniques, lower value perception, and the lack of awareness. Consequently, brands operating within this novel sustainable product category must actively overcome these obstacles to strategically position themselves in the consumer's mind. Transparent labelling strategies,

informational campaigns highlighting environmental benefits, trade marketing initiatives designed to facilitate entry into large-scale retailing, and competitive pricing relative to conventional alternatives constitute primary actionable solutions.

4.2 Limitations and future research

The empirical study relies on a non-probability, voluntary self-selection sample of 1,022 Italian citizens who are registered members of Altroconsumo recruited through its opt-in consumer panel. These respondents likely reflect active and informed consumers who may be more attentive to environmental sustainability issues than the average Italian population. Furthermore, using the Qualify online platform introduced inherent platform-related limitations, including self-selection and digital coverage biases, as the sample is restricted to digitally active consumers who voluntarily participate in online panels. Additionally, completing a questionnaire on a portal known for its focus on consumer protection may slightly heighten the social desirability bias regarding sustainable purchasing intentions. Consequently, while the findings provide valuable insights into engaged consumer segments, caution should be exercised when generalising the results to the broader population or to less digitally proficient demographics. To cross-validate and generalise the findings, future research should employ representative sampling methods on the general population, as well as comparative studies involving culturally and geographically diverse consumer segments from different countries. Finally, while this study provides robust descriptive insights into intention antecedents, future research should employ multivariate statistical techniques, such as structural equation modelling (SEM). This would formally test the predictive power and causal relationships between the three TPB antecedents and the purchase intention regarding upcycled products.

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FROM WASTE TO RESOURCE: EFFECT OF CARBONACEOUS ADDITIVES ON THE ANAEROBIC DIGESTION OF CITRUS BY-PRODUCTS

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ABSTRACT

The citrus supply chain generates large quantities of solid by-products (orange peel waste - OPW), whose energy valorisation through anaerobic digestion (AD) represents a strategic opportunity for the circular economy and bioeconomy. This work investigates the effect of adding granular activated carbon (GAC) and biochar (BC) on the AD of ensiled OPW, through batch tests (UNI 16175-5 standard) carried out in two phases: with non-acclimated inoculum and with pre-adapted inoculum containing the same additives. The results show that GAC and BC do not compromise methane yield or process stability, but accelerate its kinetics, particularly biochar at high concentration after microbial acclimation. Biochar, a low-cost pyrolysis by-product with reduced environmental impact, is confirmed as a promising additive for industrial integration between recovery supply chains from a circular economy perspective.

Keywords: Anaerobic digestion; orange peel waste (OPW); biochar; granular activated carbon (GAC); methane potential; reaction kinetics.

1. INTRODUCTION

The citrus supply chain plays a strategic role for the agri-food sector of numerous countries, including the United States, Brazil, Mexico, China and, in the Mediterranean area, Spain, Greece and Italy [1] [2]. Industrial processing generates substantial solid waste, mainly peels, seeds and membranes, which can account for over 50-60% of the processed fruit's weight [2]. Traditional disposal methods, such as incineration and landfilling, are now obsolete due to poor recovery efficiency and the risk of environmental contamination [3]. A widespread option is the direct use of orange peel waste for feed, soil conditioners, compost and fertilisers [4]; more recently, attention has shifted towards integrated biorefinery models, in which the residue becomes a secondary raw material for biofuels, bioactive compounds and high-value intermediates for the chemical and pharmaceutical industry [2], in line with the principles of the circular economy and bioeconomy.

Anaerobic digestion (AD) has been widely proposed as an eco-friendly and economically advantageous alternative to traditional methods of disposing of citrus residues [5] [6]. However, large-scale adoption

is hindered by critical issues such as low hydrolysis rate, substrate inhibition, poor stability and limited electron transfer [7]. Among optimisation strategies, carbon-based additives (nanotubes, graphene, activated carbon, biochar) show considerable potential, selectively adsorbing inhibitory compounds, providing physical support for biofilm formation and promoting direct interspecies electron transfer (DIET), a mechanism further discussed in the Discussion section.

This work investigates the effect of GAC and BC on the anaerobic digestion of ensiled orange peel waste, in two distinct phases: Phase 1, with non-acclimated inoculum, to characterise the methane potential in the presence of the additives; Phase 2, with pre-adapted inoculum (the digestate from Phase 1, containing the same materials), to assess the effect of microbial acclimation on process efficiency.

2. METHODS

The experimental activity was carried out through batch tests according to the UNI 16175-5 technical standard, which describes the standardised procedure for determining the biochemical methane potential (BMP) of organic matrices under mesophilic conditions (35°C).

2.1 Substrate and inoculum

The substrate consists of orange peel waste (OPW), an industrial by-product from a processing plant in the province of Reggio Calabria, subjected to a seven-week ensiling process to ensure its availability throughout the year. The inoculum is the digestate from the "Fattorie della Piana" anaerobic digestion plant (Reggio Calabria), operating under mesophilic conditions on livestock effluents and agri-food residues; prior to use it was sieved (mesh ≤5 mm) and stored at approximately 35 °C.

Preliminary characterisation: inoculum, TS 3.4% ± 0.07%, $VS_{\%TS}$ 69.8% ± 0.76%, pH 7.66; OPW, TS 12.1% ± 0.34%, $VS_{\%TS}$ 94.6% ± 0.19%, pH 3.55.

2.2 Carbonaceous additives

Granular activated carbon (GAC), supplied by NORIT (specific surface area 1100 m^2/g), and biochar (BC), supplied by AquaGreen (Roskilde, Denmark, https://aquagreen.dk/), obtained through steam drying (200 °C) and pyrolysis (650 °C, 20 minutes) of lignocellulosic biomass and sewage sludge (specific surface area ≈50 m^2/g), were used. Preliminary characterisation: Biochar, TS 85.6% ± 2.48%, $VS_{\%TS}$ 44.8% ± 2.10; Activated carbon, TS 96.8% ± 0.15%, $VS_{\%TS}$ 54.2 ± 10.72%.

2.3 Experimental design

Phase 1 (23 days) involved 16 three-neck glass reactors (400 mL working volume, in a thermostatic cabinet at 35 °C), divided into: blank control (inoculum only); positive control with microcrystalline cellulose; OPW alone; OPW+GAC (5 g/L); OPW+BC at low dose (BC1, 5 g/L); OPW+BC at high dose (BC2, 25 g/L), each condition in triplicate, with nutrient solutions dosed according to the UNI 16175-5 standard. At

the end of Phase 1, the digestates were homogenised by condition and reused as pre-adapted inoculum for Phase 2 (24 days), keeping the additive concentrations unchanged and pairing each triplicate of reactors with a corresponding blank control [8].

2.4 Monitored parameters and kinetic models

Cumulative net specific methane production (mL CH_4/ g_{vs}), initial and final pH, volatile fatty acid (VFA) concentration and the FOS/TAC ratio were monitored, determined by acid-base titration. As a quality control of the method, microcrystalline cellulose was used as a reference substrate, with an expected BMP value of 335 NmL CH_4/ g_{vs} ± 25%. Methane production data were interpolated using the first-order and modified Gompertz kinetic models, to estimate the methane potential (B_0 , P), the kinetic constant k, the lag phase λ and the maximum production rate R_m [9].

3. FINDINGS

3.1 Phase 1: methane production and stability

The reactor fed exclusively with OPW showed the highest methane yield (578 ± 59 mL CH_4/ gvs), in line with literature values for ensiled OPW, generally above 500 NmL CH_4/ gvs [10] [11]. The additive-amended systems (OPW-GAC, OPW-BC1, OPW-BC2) showed comparable yields, between 520 and 560 mL CH_4/ gvs, with a maximum deviation of 10% from the OPW control, falling within the physiological variability of the process (Figure 1).

The pH ranged between 7.1-7.4 at the start and 7.4-7.5 at the end of the test in all reactors. Residual VFA concentrations (214.4-480.9 mg/L) and the FOS/TAC ratio (0.07-0.13) — significantly lower than typical values for anaerobic reactors under continuous or semi-continuous operation, generally reported between 0.15 and 0.45 for optimal conditions [12] — indicate effective conversion of fermentation intermediates, with no signs of acid accumulation or significant differences attributable to the carbonaceous materials (Figure 3).

The kinetic parameters B_0 and P were comparable across the tested conditions (0.48-0.60 and 0.45-0.57 NL/ gvs, respectively), with the OPW reactor showing the shortest lag phase (λ). The kinetic constant k was higher for OPW and OPW-BC2 (0.19 1/d); the systems amended with GAC or biochar showed higher maximum production rates (Rm) than OPW alone, indicating an acceleration of reaction kinetics despite the absence of increases in cumulative yield (Figure 2).

3.2 Phase 2: effect of microbial acclimation

With pre-adapted inoculum, all conditions showed an improvement in cumulative yields (OPW: 730 ± 18; OPW-GAC: 595 ± 58; OPW-BC1: 524 ± 36; OPW-BC2: 729 ± 16 mL CH_4/ g_{vs}), an increase not directly

attributable to the additives, since it was also observed in the OPW control, and attributable to the adaptation of the microbiota to the substrate over time [13] (Figure 1). The reactors containing carbonaceous materials nonetheless reached the production plateau more rapidly than OPW alone.

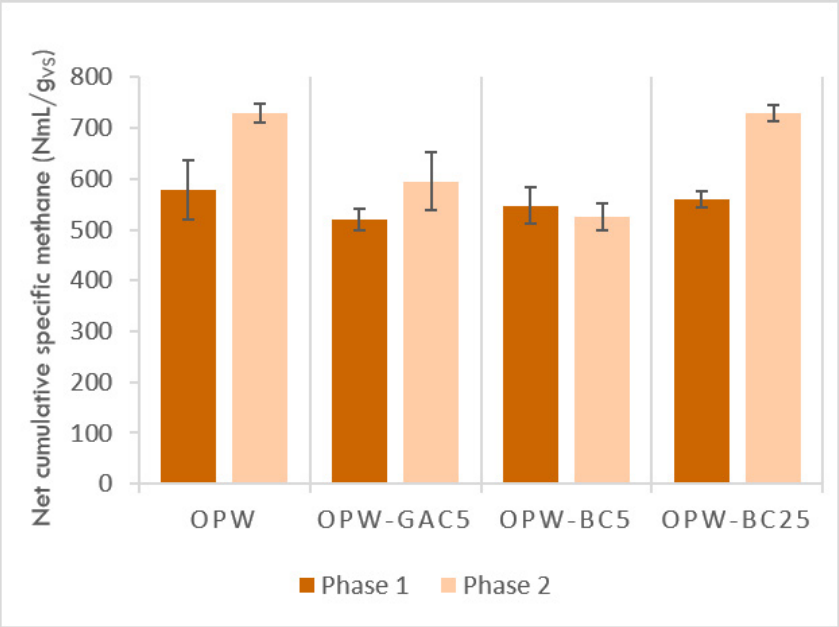


Figure 1. *Net cumulative specific methane production (mL/gvs) over 24 days of BMP testing, Phase 1 and Phase 2.*

The methane potential B_0 increased in all conditions except OPW-BC1, with the most marked increase for OPW-BC2 (from 0.58 to 0.81 NL/ g_{vs}). The maximum production rate Rm improved particularly for OPW-GAC (from 0.071 to 0.121 NL/(g_{vs}·d)) and OPW-BC2 (from 0.063 to 0.077 NL/ (g_{vs} ·d)); no improvement in any kinetic parameter was observed for OPW-BC1 (Figure 2).

The direct comparison between the two phases indicates that microbiota acclimation, rather than the carbonaceous additives themselves, is the main factor behind the increase in overall methane yield, whereas the effect of the carbonaceous materials mainly manifests at the kinetic level, anticipating the production plateau in both experimental phases.

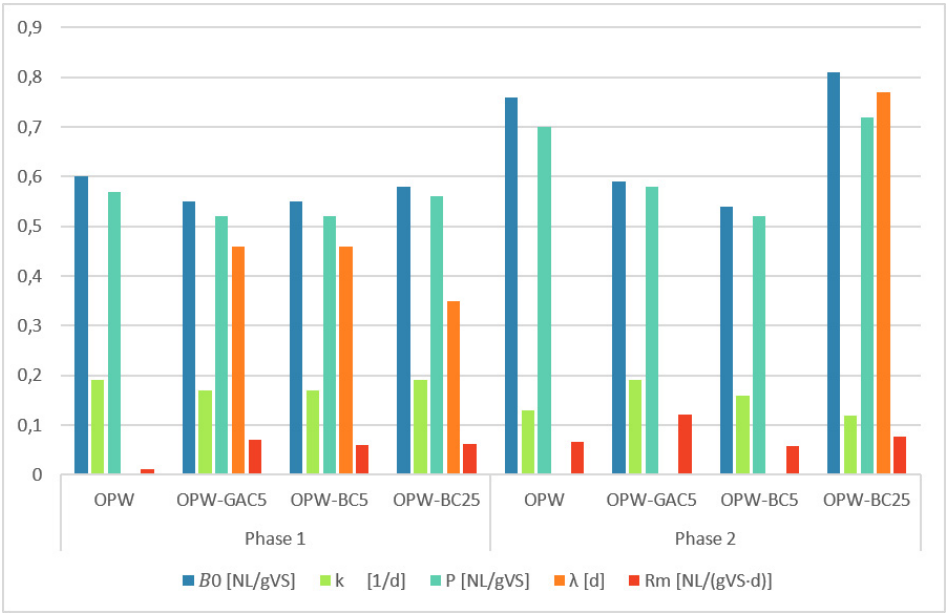


Figure 2. *First-order (B_0 [NL/gVS], k [1/d]) and modified Gompertz (P [NL/ gVS], λ [d], Rm [NL/(gVS ·d)]) kinetic parameters — Phase 1 and Phase 2.*

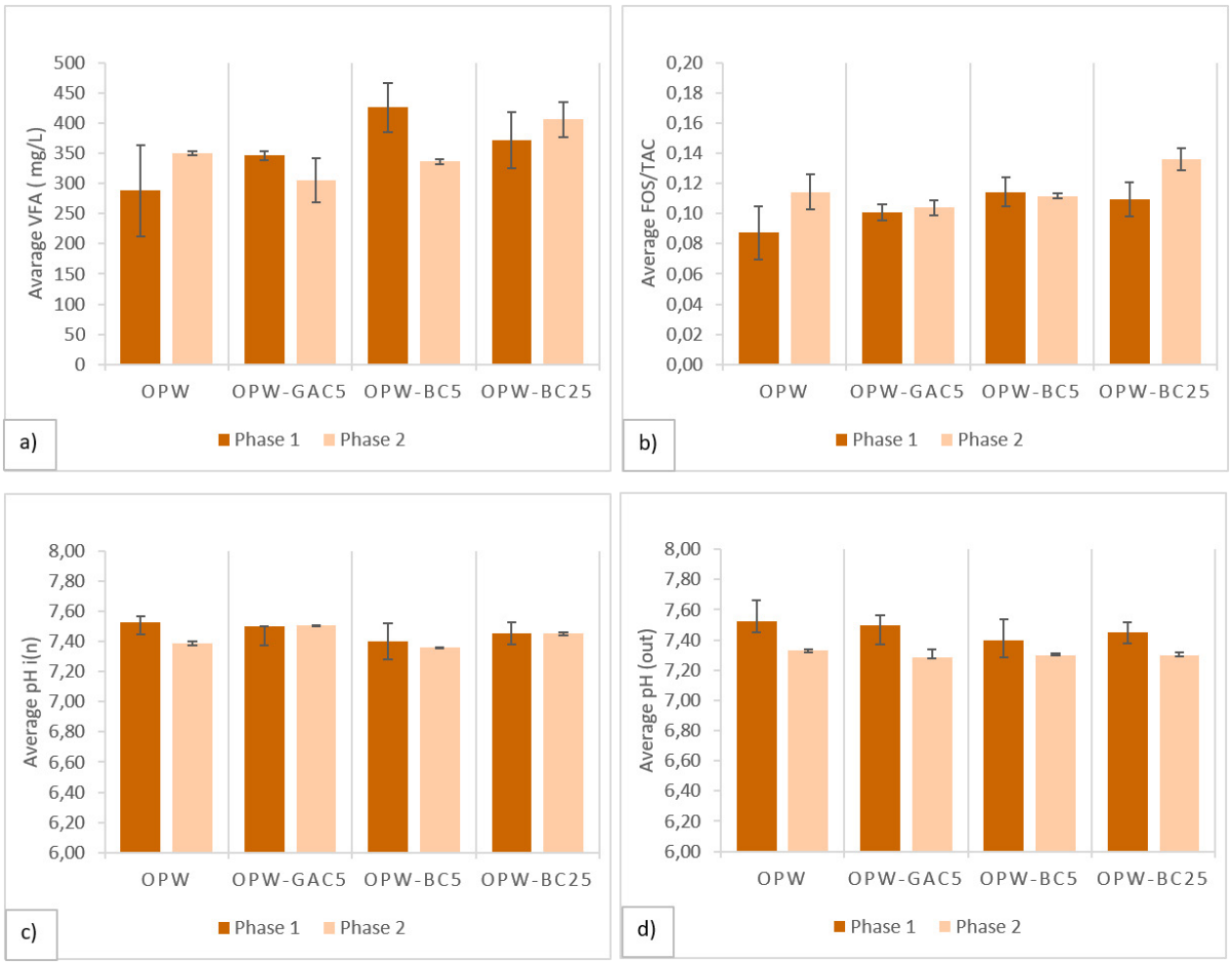


Figure 3. *ak) Average VFA concentration values; b) FOS/TAC values; ,c,d) Average pH values of the reactor mixtures at the start and end of the experiment. (Phase1 and Phase 2).*

4. DISCUSSION/CONCLUSION

From a mechanistic standpoint, the kinetic acceleration observed with GAC and biochar is consistent with their role as a support for microbial adhesion and as mediators of direct interspecies electron transfer (DIET) between syntrophic bacteria and methanogenic archaea — an alternative mechanism to indirect transfer via hydrogen or formate, capable of increasing the resilience of the microbial consortium to pH variations or VFA accumulation, consistent with the process stability observed in both phases.

Consistently with these observations, GAC and biochar do not cause inhibitory effects on the anaerobic digestion of the ensiled orange peel waste, although without significantly increasing cumulative methane yield. Among the materials tested, biochar showed considerable potential in terms of the overall sustainability of the system. Unlike GAC, biochar is not a costly synthetic product but a by-product of residual biomass pyrolysis, one whose use itself calls for dedicated valorisation pathways. Notably, the addition of biochar, even at high concentrations, did not cause inhibitory effects on the anaerobic digestion process.

This evidence points to the possibility of synergistically integrating two recovery supply chains — that of agro-industrial residues and that of carbonaceous materials — within a single biological platform, with potential benefits in terms of reduced operating costs and improved overall environmental impact.

As these results are preliminary, having been obtained through batch tests, they do not allow a full assessment of long-term dynamics or system stabilisation under continuous operating conditions. Future work will involve applying the same conditions to continuous or semi-continuous systems, including at pilot scale, evaluating the biomass degradation rate and the phytocompatibility of the digestate, with a view to agronomic application and an effective industrial scale-up consistent with the circular economy.

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END-OF-LIFE STRATEGIES FOR EV LI-ION BATTERIES: A CHEMISTRY-INFORMED SYSTEM DYNAMICS APPROACH IN THE EU CIRCULAR ECONOMY FRAMEWORK

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ABSTRACT

The rapid expansion of electric vehicles requires sustainable End-of-Life (EoL) strategies for Li-ion batteries. This study develops a System Dynamics model (2015–2035) to quantify future battery flows and material demands within the EU Circular Economy framework, focusing on how specific cell chemistries influence EoL pathways. Results show that over 95% of EoL batteries are suitable for repurposing or remanufacturing rather than immediate recycling. While recycling cannot completely eliminate primary mineral dependency, a combined approach of pyrometallurgical, hydrometallurgical, and mechanical recycling is essential to meet the strict targets of Regulation EU 2023/1542. To validate these theoretical findings, a real-world case study of the innovative mechanical recycling process by the Italian company Seval is integrated. Ultimately, efficient EoL management enhances circularity and reduces reliance on critical raw materials through sustainable supply chain practices.

Keywords: Circular Economy, Sustainability, Batteries End-of-Life, Li-ion Battery Chemistries, System Dynamics Modelling, Real-World Case Study, Electric Vehicle

1. INTRODUCTION

The global surge in the adoption of electric vehicles (EVs) has boosted Li-ion batteries to the forefront of the clean energy transition, simultaneously underlying an urgent imperative: the establishment of comprehensive and sustainable strategies for their End-of-Life (EoL) management. This thesis addresses this critical need by conducting a dynamic and holistic analysis of the entire EV passenger cars' Li-ion battery supply chain, spanning from production through operational use to ultimate end-of-life. The overarching aim is to generate actionable insights for strategic decision-making within a Circular Economy (CE) framework, thereby encouraging a truly sustainable battery ecosystem development. The focus of this research is set on the European context, recognizing the European Union's globally agreed leadership and innovative role in adopting ambitious policies for CE and battery management. With its pioneering Regulation EU 2023/1542 [1], the EU serves as a relevant global case study for developing sustainable strategies in this pivotal sector. This research was structured around several specific, interconnected objectives aimed at driving battery circularity:

- Forecasting flows and material demand and evaluating circular economy strategies: Estimate future volumes of EoL batteries and assess the demand for critical raw materials across the supply chain, analyzing the effectiveness and viability of key circular options, specifically repurposing, remanufacturing, and recycling.
- Understanding chemistry-specific dynamics: Study the lifecycle of batteries based on their specific chemical composition to optimize EoL management and material recovery efficiency.
- Empirical model validation and informing strategic decision-making: Test and validate the theoretical model's assumptions through a real-world industrial case study of battery recycling operations and provide data-driven insights for stakeholders and policymakers to ensure alignment with the EU Battery Regulation and support long-term sustainability.

2. METHODS

This thesis primarily employed a System Dynamics (SD) modeling approach, chosen for its robust capability to analyze complex, interconnected feedback loops and long-term dynamics inherent in the battery lifecycle, from raw material extraction to EoL management. [2] The developed SD model (whose high-level conceptual diagram is reported in Figure 1) enabled:

Comprehensive lifecycle simulation: Simulating the flow of batteries across their entire lifecycle, distinguishing by various chemistries [3], to precisely forecast EoL volumes, assess critical raw material demands for production, and track their recovery from recycling.

Integrated strategy and policy evaluation: Providing a flexible framework to evaluate the effectiveness of different Circular Economy strategies (repurposing, remanufacturing, recycling) and to assess the impact of current and proposed EU regulatory frameworks on achieving sustainability targets.

Scenario testing: Offering the ability to test various future scenarios related to technological advancements and market adoption rates.

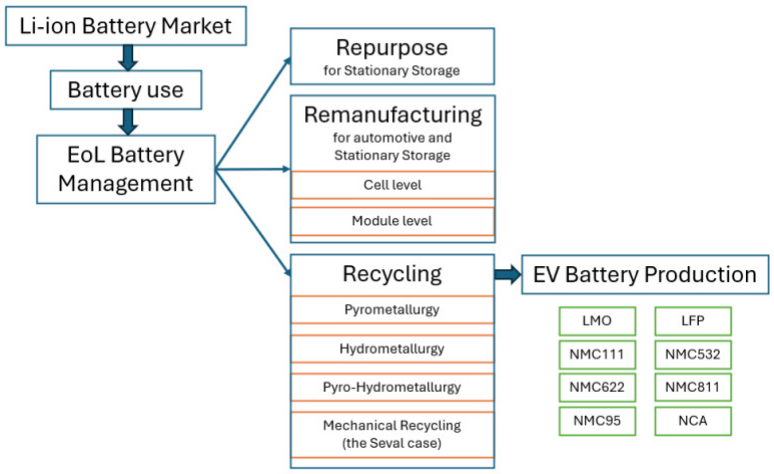


Figure 1: *SD model high level conceptual diagram.*

The theoretical model's insights were further grounded and empirically validated through the integration of a real-world case study involving Seval, a prominent Italian company specializing in innovative mechanical recycling processes for Li-ion batteries. This practical insight provided crucial operational data and contextual understanding, enhancing the model's relevance and applicability.

3. FINDINGS

3.1 Future Battery Flows and Market Dynamics

The model projects significant Li-ion battery flows reaching EoL by 2035. A key finding, based on State of Health (SoH) assessment, is that over 95% of EoL batteries are suitable for more virtuous strategies like repurposing or remanufacturing, rather than immediate recycling. However, there's a current temporal mismatch: EoL volumes are modest compared to the growing demand for these secondary applications, leading to an underutilization of second-life potential. Projections indicate the EU's capability to largely satisfy its internal EV battery requirements, particularly for EV cars. However, due to significant risks, such as production facility scale-up times, investment cancellations, rising costs, or lack of critical raw material access, the actual deployment of projected capacity may face high uncertainty.

3.2 End-of-Life Strategies Evaluation within Circular Economy Paradigm

The study highlights that the promising market for stationary storage is largely unmet by repurposed batteries due to both limited supply of high-SoH EoL batteries and market barriers (e.g., cost-competitiveness, warranty issues). For remanufacturing, particularly in the automotive sector,

demand is consistently unmet, primarily due to consumer reluctance towards reconditioned products and inherent time lags in EoL feedstock availability.

Remanufacturing at the cell level, especially for stationary storage, faces additional constraints related to prismatic cell geometry availability and technological process maturity.

Crucially, the study confirms that recycling alone will not eliminate the necessity for primary mineral supply, but it is set for significant expansion, driven by increasing EoL battery volumes. Importantly, European recycling capacity is anticipated to be sufficient to process these increasing EoL volumes after 2025. The strategic repurpose of EoL EV batteries for stationary storage is identified as a powerful tool for enhancing CE effectiveness and reducing reliance on virgin critical minerals, complementing recycling efforts.

3.3 In-Depth Analysis on Battery Chemistries and Recycling Processes

Battery chemistries play a critical role in recycling processes, far more than for repurposing or remanufacturing. Hydrometallurgical processes demonstrated to exhibit high recovery rates for all key materials (Lithium 95%, Nickel 97%, Cobalt 95%, and Copper (95%), meeting EU target requirements for 2027 and 2031. Similarly, mechanical recycling excels in overall mass recovery and producing "Black Mass" for subsequent refining. In contrast, standard pyrometallurgical processes, while meeting the target requirements for Nickel (98%) and Copper (96%), fall short for Cobalt (86% vs. 90% target by 2027) and generally do not recover Lithium. Despite these process efficiencies, the model projects significant challenges in meeting the recycled content targets for new batteries, particularly for Nickel and Cobalt, which remain substantially below the 2031 and 2036 EU Directive thresholds. This is largely attributed to the exponential growth of the EV market, where even high recycling efficiencies cannot supply sufficient material to meet the demand for recycled content from this sector alone, implying the need for additional recycled materials from other sources. The analysis further demonstrates that a combined approach of pyrometallurgical, hydrometallurgical, and mechanical recycling is essential to meet the ambitious overall EU process recycling targets of 65% by 2025 and 70% by 2030 [2]. As reported in Figure 2, mechanical recycling and combined pyro-hydrometallurgical strategies are the most effective in ensuring compliance with those targets, due to their higher versatility in recovering a wide range of fractions, regardless of the specific chemistry. In contrast, standalone pyrometallurgical and hydrometallurgical processes exhibit fluctuating efficiencies that directly mirror the evolving mix of EoL battery chemistries entering the recycling stream.

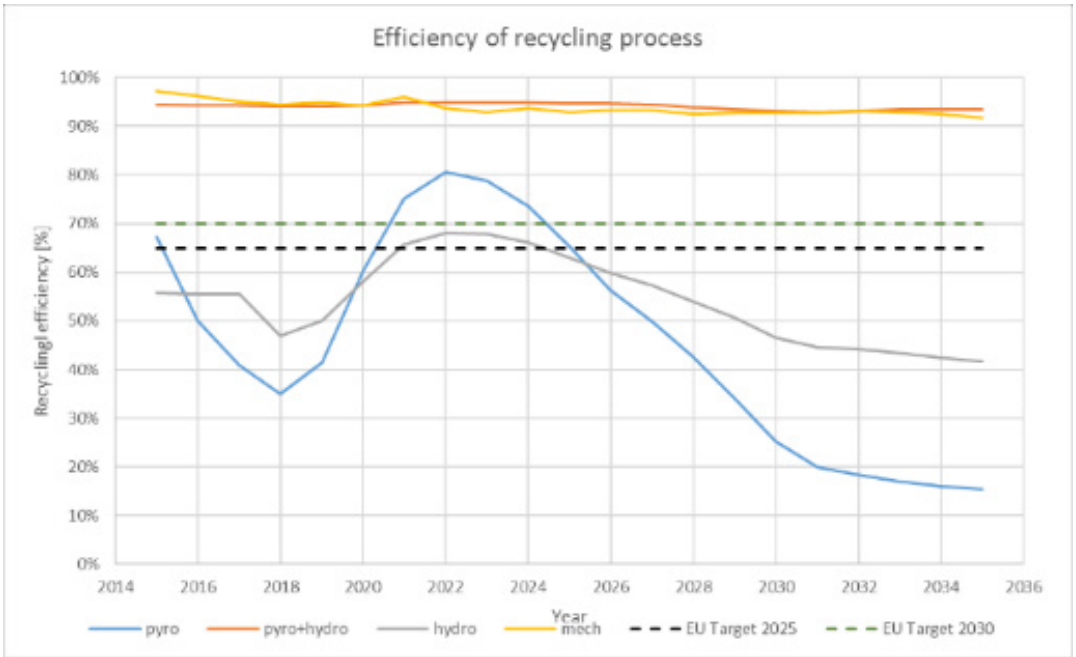


Figure 2: *Efficiency of the recycling process (expressed as a percentage corresponding to the process mass ratio) vs EU Directive (2015-2035).*

3.4 Real-world case study integration: the Seval company

The analysis of Seval, a leading Italian company in WEEE and battery management, provided invaluable practical insights into mechanical recycling processes. Seval's operational capabilities, including their new lithium-ion battery recycling project with a significant annual treatment capacity, grounded the theoretical model in industrial reality. This collaboration empirically validated the challenges and opportunities within the battery circular economy framework, showcasing the tangible contribution of real-world actors to the Italian and European recycling landscape.

3.5 Implications for strategic decision-making and policy

The modeling results and comparative analyses, robustly validated by the Seval case study, offer comprehensive, data-driven support for strategic decision-making across the entire battery value chain. For policymakers, the findings underscore the importance of fostering a diverse portfolio of EoL strategies, recognizing the temporal dynamics of battery flows and the critical need for integrated recycling approaches to meet EU Regulation 2023/1542 targets. The Digital Product Passport (DPP), mandated by this regulation, is identified as a transformative tool for enhancing transparency and traceability throughout the battery lifecycle, crucial for facilitating efficient reuse, repair, and optimal EoL management. However, its successful implementation will require addressing challenges related to initial costs, standardization, and consistent sharing of accurate State of Health data. The study emphasizes that achieving a truly sustainable battery ecosystem necessitates concerted, collaborative efforts from all stakeholders, including governments, manufacturers, recyclers, and

consumers. This involves careful planning, continuous innovation, diversification of critical mineral supply, and the rigorous adoption of sustainable practices across the entire battery supply chain to achieve strategic autonomy and environmental responsibility.

4. DISCUSSION

The future of mobility and green energy in Europe is not merely electric, but profoundly circular. This transformative effort, driven by the EU ambitious commitment, demands innovation, collaboration, and a far-sighted vision to unlock every battery's full potential, building a truly sustainable era.

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INDUSTRIAL SYMBIOSIS PRACTICES IN THE WEST MIDLANDS: THE NISP AND THE INVOLVEMENT OF SMES. ASSESSING OPPORTUNITIES AND CHALLENGES FOR THE ADOPTION OF SUSTAINABLE PRACTICES

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ABSTRACT

This thesis examines industrial symbiosis (IS) best practices adopted by small and medium-sized enterprises (SMEs) in the West Midlands region of the UK through the National Industrial Symbiosis Programme (NISP), the Birmingham & Solihull Industrial Symbiosis (BASIS) programme and other regional IS initiatives. The objective is to assess the benefits and challenges of these practices, as well as their applicability to the Italian economic context. This research adopts an interdisciplinary approach to evaluate the overall value generated by IS processes not only from environmental and social perspectives but also from an economic standpoint and investigates the five key dimensions influencing corporate health and stability: economic, financial, asset and capital structure, organisational and governance and socio-environmental equilibrium. For each of these, the benefits and challenges associated with the implementation of IS practices were identified. Furthermore, the research explores how SMEs address regulatory challenges and overcome operational barriers [1].

Keywords: BASIS; Capital and Asset Sustainability; Circular Economy; Economic Sustainability; Financial Sustainability; Industrial Ecology; Industrial Symbiosis; NISP; Organizational and Governance Sustainability; SMEs; Socio-Environmental Sustainability; Sustainable Development; West Midlands;

1. INTRODUCTION

This dissertation represents the outcome of an extensive process of investigation and methodological development. The study was made possible by an ERASMUS+ mobility period undertaken in Birmingham, a city hosting International Synergies Ltd., a leading organisation in the field of IS. The West Midlands provided a suitable context for this research, being recognised as a benchmark for circular economy strategies and resource efficiency initiatives through programmes such as the NISP, the BASIS programme and other regional initiatives. IS represents the central theme of this research, providing the framework around which the subsequent areas of investigation have been developed. In particular, the thesis focuses on the identification of IS best practices adopted by SMEs, which

represent the backbone of both the UK and Italian productive systems. While existing literature has investigated IS within large industrial clusters and eco-industrial parks, the opportunities and challenges associated with SMEs remain comparatively underexplored. This research aims to contribute to filling this gap by examining how SMEs participate in IS networks, the benefits and barriers associated with their adoption and the conditions required to transfer these practices to similar economic contexts. Through a mixed-method approach, the study evaluates the impact of IS across economic, financial, patrimonial, organizational and governance, and socio-environmental dimensions. The research therefore seeks to assess whether the practices identified in the West Midlands can represent feasible and replicable solutions to support the sustainability and competitiveness of Italian SMEs.

2. METHODS

Regarding data collection, the study initially relied on a structured questionnaire consisting of 110 Delphi-based questions [2] administered to a sample of SMEs operating in the West Midlands. The questionnaire aimed to investigate the adoption of IS best practices and their potential effects on firms' economic, financial, patrimonial, organisational and governance, and socio-environmental performance. To analyse these effects across the economic, financial and patrimonial dimensions, the case-study analysis considered indicators including Total Production Value, Profit/Loss before Tax, ROA, ROE, Total Assets, Total Liabilities, Equity, Tangible Fixed Assets, Current Liabilities, Non-current Liabilities, Reserves and Other Funds, Operating Expenses and Net Profit. Firms were identified through interviews with representatives of public authorities and organisations involved in facilitating IS initiatives and the questionnaires were distributed electronically. Due to a response rate of 0%, the research adopted an alternative methodological approach. Semi-structured interviews with key stakeholders, including representatives of International Synergies Ltd. and the West Midlands Combined Authority, were combined with a financial statement analysis of two SME case-study companies, Crick Gardens I.C.I. and Glue Collective Ltd., using Moody's Orbis database. For each case-study company, a peer-group sample of ten SMEs was identified through advanced database filters, while Student's t-test was employed to assess whether observed changes in the two prioritised economic indicators, Total Production Value and Profit/Loss before Tax, were statistically significant.

3. FINDINGS

The publication trend of IS research exhibits some fluctuations over the period 1999–2025 but reveals a clear upward trajectory. While the early years were characterized by very low publication levels, often with fewer than ten articles per year, scientific output increased from the late 2000s onwards. A marked acceleration can be observed after 2015, with annual production exceeding previous levels and reaching more than 100 publications in both 2022 and 2025. This pattern reflects the growing interest

in IS as a key strategy for improving resource efficiency, promoting sustainable development and advancing circular economy objectives [3]. The dataset was retrieved from Scopus using the search query TITLE-ABS-KEY ("industrial symbiosis"), which identifies publications containing the term “industrial symbiosis” in the title, abstract or keywords. Only documents classified as articles were included in the analysis, while other document types, such as books, book chapters, conference papers, editorials, and reviews were excluded. The resulting dataset comprises 984 articles published between 1999 and 2025 in 14 different languages, with English representing the predominant publication language. Furthermore, China emerged as the most productive country in terms of scientific output on IS. The data also indicate that the Journal of Cleaner Production is the leading publication outlet in the field, accounting for 178 articles out of the 984 included in the dataset. This finding highlights the journal's central role in disseminating research on IS, circular economy practices, resource efficiency and sustainable industrial development.

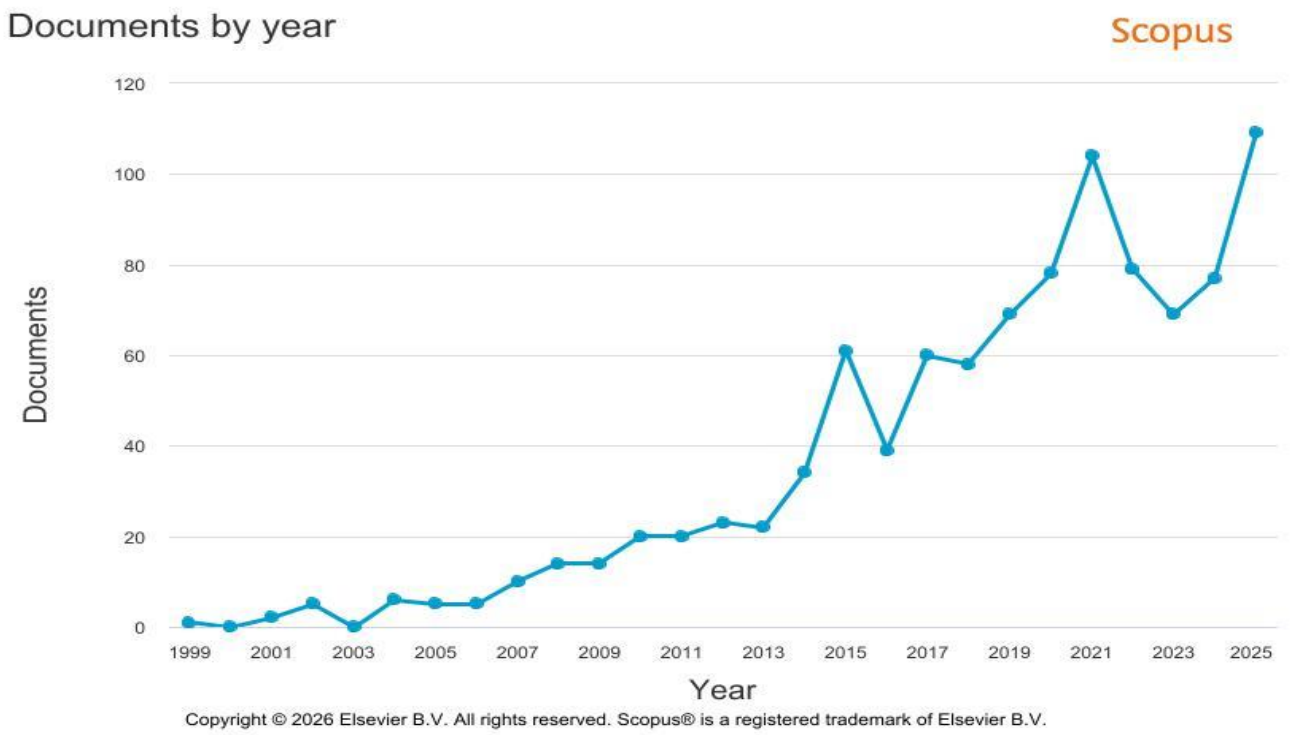


Figure 1: *Annual scientific output. Source: Scopus.*

In the analysis of the most relevant keywords, terms such as "Industrial Symbiosis Practices" and "Symbiotic Relationships" were treated as synonymous concepts, as were "Sustainable Development" and "Sustainability". To improve the consistency of the analysis, conceptually equivalent terms were consolidated whenever they conveyed the same meaning. Conversely, the terms "Waste" and "Waste Materials" were kept distinct, as the former refers to the broader concept of waste generation and management, while the latter emphasizes material residues that can potentially be recovered, exchanged or reintegrated into production processes. Fig. 2 highlights "Industrial Symbiosis Practices", "SMEs", "West Midlands", "Waste", "Raw Material", "Sustainable Development" and "By-product" as the most prominent keywords. The selection of the most relevant terms was performed using Biblioshiny, considering the frequency of occurrence of keywords composed of one, two and three words. The prominence of these keywords reflects the central role of IS practices within the circular economy framework, particularly in the West Midlands context, where SMEs' involvement in the exchange of waste materials and by-products contributes to resource efficiency and sustainable development through the valorisation of industrial resources [4]. Other relevant keywords, such as "Waste Material", "Disposal Processes" and "Production Processes" suggest a growing interest in the relationship between waste management practices and industrial production systems, highlighting the potential of IS to replace conventional disposal approaches with resource recovery strategies and more efficient production processes.

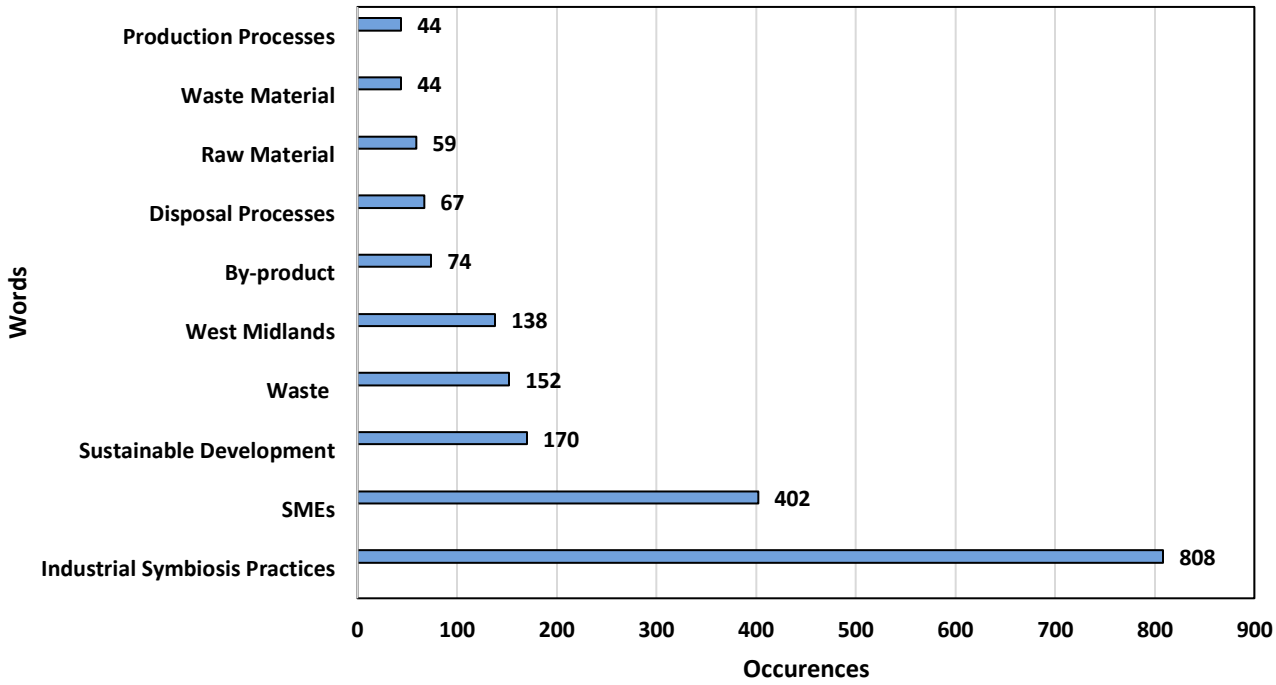


Figure 2: *Relevant keywords. Source: authors' elaboration based on Biblioshiny data.*

The Thematic Map (Fig.3), generated using the Walktrap algorithm, highlights the following clusters: "Industrial Symbiosis Practices", "SMEs", "Resource Exchange", "By-product", "Facilitation Programmes" and "Business Performance" as Motor Themes (central and well developed); "Circular Economy", "Industrial Ecology", "Sustainable Development", "Waste Materials", "Secondary Raw Materials", "Production Processes" and "Waste Disposal Processes" as Basic Themes (a consolidated yet less explored methodology); "Collaboration Networks", "Governance" and "Public Institutions" as Niche Themes (specialized within specific domains); and "Decarbonization" as an Emerging Theme (peripheral themes with potential for future development).

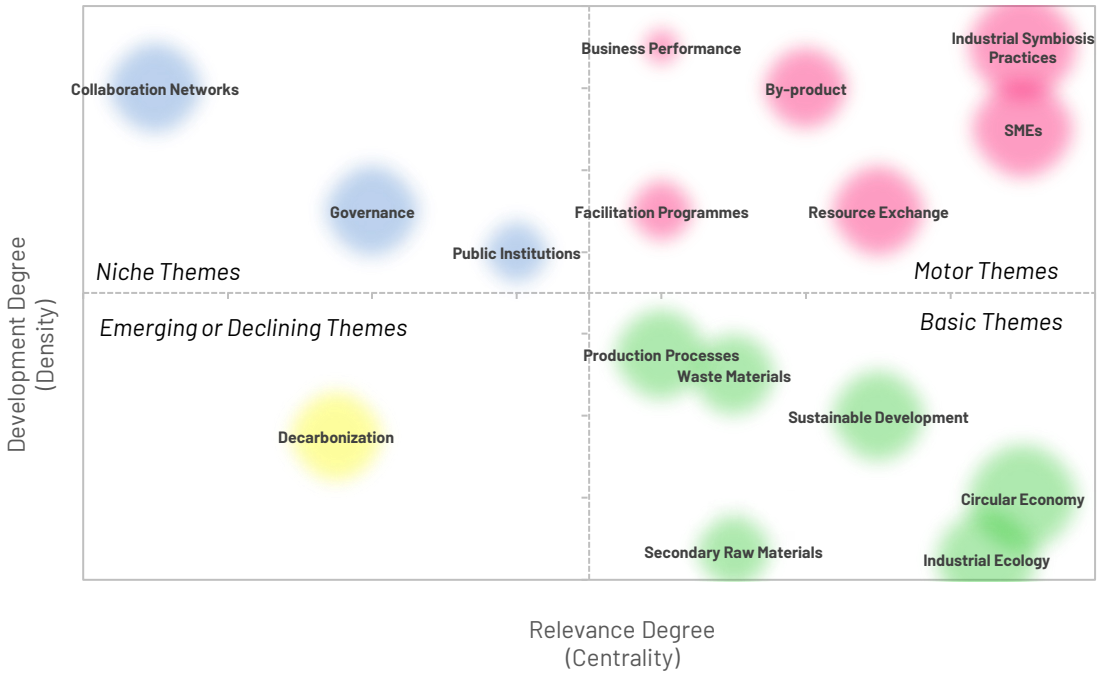


Figure 3: *Relevant keywords – Thematic map. Source: authors' elaboration based on Biblioshiny data.*

3.1 Content Analysis

The content analysis highlights the potential of IS to improve the sustainability and competitiveness of SMEs through best practices implemented in the West Midlands under the NISP and BASIS programmes [5]. The study adopts a mixed-method approach, combining a Delphi-based questionnaire, semi-structured interviews with IS facilitators and a financial statement analysis of selected SMEs using Moody's Orbis database and Student's t-test.

The analysis evaluates the impacts of IS across economic, financial, patrimonial, organizational and governance, and socio-environmental dimensions, while also assessing the feasibility of transferring these best practices to the Italian economic and productive context.

4. DISCUSSION/CONCLUSION

The strong structural similarity between the economic and industrial systems of the West Midlands and Italy, both largely based on SMEs development and characterised by comparable sectoral compositions,

suggests that the best practices developed within IS facilitation programmes such as the NISP, the Centre for Circular Economy and Sustainability (CEBAS) and the BASIS programme could potentially be transferred in the Italian context. The analysis of the case studies highlighted that the productive sectors involved require waste streams like those largely generated by Italian production chains, thereby ensuring the continuous availability of recoverable resources. However, the results obtained through the t-test calculation revealed a non-statistically significant relationship between the implementation of IS practices and improvements in the financial statement items of the companies analysed. This finding suggests that, although IS may represent a promising model in terms of resource efficiency, its direct economic benefits for firms may not be immediately evident or may be influenced by other factors, such as the macroeconomic context, market dynamics and the level of regulatory support. Consequently, the assumptions developed throughout this research remain primarily theoretical and hypothetical and require further investigation. In particular, future research could explore more thoroughly the role of factors such as economies of scale, the availability of public incentives and access to collaborative networks, in order to understand the extent to which these elements may enhance (or, conversely, constrain) the economic benefits that is expected to generate.

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VALORIZATION OF GRAPE POMACE THROUGH BIOREFINERY: AN ANALYSIS OF ECONOMIC SUSTAINABILITY

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ABSTRACT

Grape pomace, the main solid by-product of winemaking, represents 20-30% of processed grapes and is generated in Italy in millions of tonnes each year, yet it is still largely disposed of or distilled. This study assesses its valorization through the biorefinery model, combining a literature review that maps the main extraction technologies against the Technology Readiness Level (TRL) scale with an ad-hoc survey of 31 Italian wineries and 18 researchers. Findings show a spectrum from mature technologies (solid–liquid and supercritical-CO_2 extraction, TRL 7–9) to emerging green methods (microwave-, ultrasound- and enzyme-assisted extraction, TRL 4–7), while integrated biorefineries remain at TRL 3–7. A marked awareness–practice gap emerges: 90% of wineries know of bioactive compounds but 68.8% still sell pomace to distilleries and only 10% consider valorization already profitable. Economic sustainability, targeted incentives, regulatory simplification and research–industry collaboration, rather than technical maturity alone, prove decisive.

Keywords: Grape pomace; Biorefinery; Circular economy; Technology Readiness Level; Wine by-products.

1. INTRODUCTION

The transition from a linear "take–make–dispose" economy to a circular model is a strategic priority for the agro-industrial sector, where reusing, recycling and regenerating materials reduces waste and keeps resources in use for as long as possible [1], [2]. Within this framework, biomass (renewable organic matter of vegetal or animal origin) is a key resource, since agricultural and agro-industrial residues that are commonly treated as waste can be valorized into high-value products [3].

The wine sector is emblematic of this challenge. Grape pomace, the solid residue left after pressing and fermentation, accounts for roughly 20–30% of the weight of processed grapes and is composed mainly of

skins, seeds and stalks [4]. As one of the world's leading wine producers, Italy generates millions of tonnes of this by-product every year, historically destined to distillation for grappa, composting, animal feed or energy, none of which fully exploits its chemical value [5].

Pomace is, in fact, rich in bioactive compounds (polyphenols such as anthocyanins, tannins and resveratrol, together with tartaric acid and seed oils) with recognized antioxidant, antimicrobial and colouring properties of interest to the food, nutraceutical, cosmetic and pigment industries [6], [7]. The biorefinery concept provides an integrated model to convert this biomass comprehensively into multiple marketable products, combining physical, thermochemical, chemical and biological processes within a circular, near zero-waste logic [8], [9].

This paper synthesizes a broader study on the economic valorization of grape pomace. Its aim is twofold: to map the maturity of the main valorization technologies using the Technology Readiness Level (TRL) framework, and to assess the technical, economic and regulatory barriers to their adoption as perceived directly by the two categories of actors involved (wineries and researchers).

2. METHODS

The study adopted a two-phase: in a preliminary phase, a review of the scientific literature was carried out on the composition of pomace, the extractable bioactive compounds and the available biorefinery technologies, with particular attention to innovative green methods. The search drew on the main scientific databases and publisher platforms as Scopus, ScienceDirect (Elsevier), MDPI, Wiley Online Library and SpringerLink, complemented by Google Scholar and by institutional repositories (IRIS), together with grey literature from institutional and sector sources (e.g. FAO, ENEA and the European Commission): priority was given to peer-reviewed articles and reviews published in the last decade, and around 170 sources were consulted overall. Each technology thus identified was then positioned on the Technology Readiness Level (TRL) scale (1–9) in order to describe its degree of maturity.

In a second phase, two ad-hoc questionnaires were designed and distributed to collect primary data from complementary stakeholders: wineries, as producers of the raw material, and researchers, as developers of new transformation technologies. The survey was administered to a sample of 31 Italian wineries (mainly located in the Apulia region) and 18 researchers from the University of Foggia (chiefly the DAFNE and Social Sciences departments). The questionnaires investigated current management practices, awareness and adoption of valorization technologies, perceived economic sustainability, and the critical issues and opportunities of the sector. This qualitative approach was chosen to surface not only objective data but also expectations, doubts and resistance among the actors involved.

3. FINDINGS

3.1 Literature review on technological maturity of valorization routes

The industrial landscape of pomace valorization is dominated by well-established extraction technologies. Solid–liquid extraction (SLE), widely used for recovering bioactive compounds from plant materials, can be placed at TRL 7–9, being ready for full commercial deployment thanks to its low capital cost and operational simplicity. Supercritical fluid extraction (SFE), particularly with supercritical carbon dioxide (SC-CO2), has also reached TRL 7–9, supported by existing industrial plants and scale-up and economic feasibility studies [11].

Emerging green methods, as microwave-assisted (MAE), ultrasound-assisted (UAE) and enzyme-assisted extraction (EAE), have shown promising laboratory results and are validated in relevant environments, but their large-scale deployment is still limited, placing them at TRL 4–7 [12]. Integrated biorefineries, which aim to obtain several products (e.g. seed oil, polyphenols and biochar) from the same feedstock, remain at an overall TRL 3–7, with some process combinations more mature than others [10] (Fig. 1).

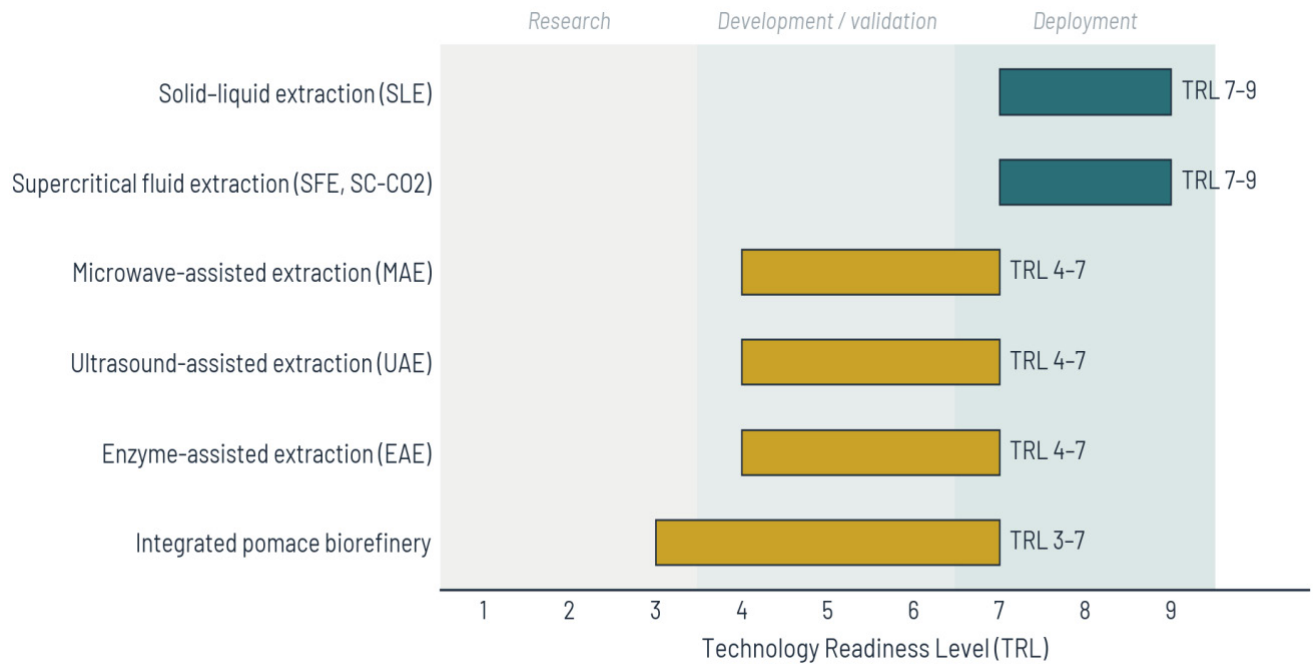


Figure 1. *Technology Readiness Level (TRL) of the main grape-pomace valorization technologies.*

Technical readiness alone, however, does not guarantee market uptake. TRL captures whether a technology works, not whether a viable market and business model exist; for this reason, the combined Market and Technology Readiness Level perspective is increasingly used to identify where an innovation risks stalling in the so-called "Death Valley" between laboratory and market.

3.2 Survey on practices and perceptions of wineries

All surveyed wineries operate in wine production and vary in size, with annual outputs between 1,000 and

over 20,000 hectolitres. Their by-product management is still overwhelmingly conventional: 68.8% sell pomace to third parties, chiefly distilleries, and 28.1% rely on on-farm composting, while internal valorization remains a sporadic practice (Fig. 2a). The reasons given converge on the lack of real alternatives, cost-effectiveness of current solutions, management simplicity and the absence of suitable in-house infrastructure.

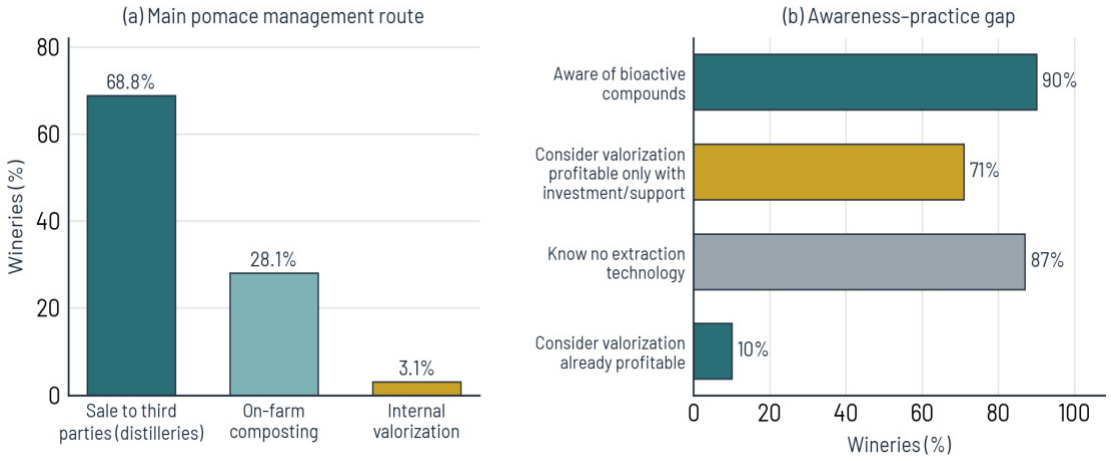


Figure 2. *Survey of 31 Italian wineries: (a) main pomace management route; (b) awareness–practice gap.*

A clear awareness–practice gap emerges (Fig. 2b). While 90% of respondents are aware that bioactive compounds can be extracted from pomace (citing mainly polyphenols and resveratrol) 87% know of no specific extraction technology, signalling a marked information mismatch between research and production. Economically, only about 10% consider valorization already profitable, whereas 71% believe it could become so only with significant initial investment and concrete public support. The main barriers reported are high investment costs, lack of information, the absence of a structured supply chain and poor communication among the actors of the chain.

3.3 The research perspective and mirrored barriers

The 18 researchers span food and agricultural technologies, chemistry of natural products, and economics and bioeconomy, reflecting the interdisciplinary nature of the topic. In their projects the most common techniques are SLE, MAE, UAE, EAE and SC-CO2 extraction, occasionally integrated within biorefinery or membrane-based schemes. Asked about the obstacles to transferring results to the market, they identified the lack of funding for the transition from laboratory to pilot/industrial scale, the scarcity of industrial partners willing to invest in experimental technologies, weak communication channels between research and industry, and market uncertainty for the resulting products.

These barriers mirror those reported by companies: the lack of industrial partners lamented by researchers corresponds to the lack of investment and internal skills felt by (especially small) wineries, generating a vicious circle in which innovations remain confined to laboratories.

The shared shortage of intermediate financial instruments and the weakness of research–industry communication emerge as the most systemic obstacles. Encouragingly, half of the researchers have already collaborated with wineries or processing centres, indicating a genuine willingness to co-design solutions.

4. DISCUSSION

The analysis outlines a sector with considerable potential but a clear bottleneck: the decisive constraint is not technical feasibility (several extraction routes are already mature) but the demonstration of economic sustainability, particularly in the scale-up from laboratory or pilot to industrial level.

The mirrored barriers reported by wineries and researchers reveal a systemic block rooted in insufficient funding for intermediate stages, a fragmented and logistically demanding supply chain, and weak communication between the two worlds.

Several levers can unlock this potential. First, targeted research and innovation (R&D) investment should improve extraction efficiency and reduce operating costs, prioritizing projects with a credible path towards higher TRLs [13]. Second, economic and fiscal incentives (tax credits for green technologies, direct support for pilot and demonstration plants, and improved access to credit) can bridge the gap between upfront costs and long-term benefits. Third, a simpler and harmonized regulatory framework, with unequivocal end-of-waste criteria aligned at national and European level, would reduce uncertainty. Fourth, structured collaboration among wineries, biorefineries, research institutes, start-ups, investors and policymakers, through public–private partnerships, is essential to overcome the transfer gap. Finally, developing solid markets for bio-based products and coupling process design with Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) would strengthen both credibility and reliability [14], [15].

A more fundamental determinant underlies all these levers: the firm's absorptive capacity (the ability to recognise, assimilate and commercially apply external knowledge, built cumulatively on prior internal knowledge) [16]. It is structurally weak in the agri-food SMEs of the sector, where scarce internal R&D and few qualified human resources limit the uptake of external knowledge and collaboration with universities and technology-transfer intermediaries [17]. Incentives, regulation and partnerships therefore pay off only if matched by investment in human capital (qualified personnel, including post-doctoral researchers, and continuous workforce training).

In conclusion, grape pomace can shift from a disposal cost to a strategic resource for a more circular wine sector, provided that technological progress is matched by economic viability, coherent policy and multi-stakeholder cooperation. Integrating advanced modelling and validation tools within a combined technical–economic perspective appears the most promising way to guide this transition.

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GLYCOLYSIS OF TEXTILE PET RESIDUES UNDER UPERCRITICAL CO_2 CONDITIONS: STATISTICAL STUDY, KINETICS AND REUTILIZATION INSIGHTS

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ABSTRACT

The textile industry is one of the most polluting industrial sectors, generating high resource consumption and large amounts of waste, with polyethylene terephthalate (PET) being one of its most widely used polymers. Although PET can be mechanically recycled, chemical recycling offers a more sustainable long-term solution by depolymerizing the polymer into valuable products such as bis(2-hydroxyethyl) terephthalate (BHET), which in turn can be used to produce PET, thereby supporting a circular economy. However, textile PET is more difficult to depolymerize than bottle-grade PET because of its fibrous structure and the presence of additives. Therefore, developing efficient and environmentally friendly catalytic systems is essential. Ionic liquids, particularly 2-hydroxyethylammonium acetate (2-HEAA), have emerged as promising non-toxic catalysts, while supercritical CO2 (sCO2) can enhance the process by providing a green reaction medium and reducing solvent consumption. This study investigates the combined use of 2-HEAA and sCO2 for the glycolytic depolymerization of textile PET, focusing on process optimization, reaction kinetics, and catalyst reusability.

Keywords: circular economy; ionic liquids catalysis; statistical study; chemical recycling; textile polyethylene terephthalate waste.

1. INTRODUCTION

The textile industry is among the most resource-intensive industrial sectors, generating significant environmental impacts through water consumption, energy demand, greenhouse gas emissions and waste generation [1]–[3]. It is estimated that to produce a single cotton T-shirt, around 2,700 liters of fresh water are needed, enough to sustain one person's drinking needs for 2.5 years [4]. Polyesters fibers, particularly polyethylene terephthalate (PET), dominate global fiber production and are widely employed in fast-fashion applications [5]. Approximately 57% of the global fiber production in 2023 was accounted to polyesters; considering all its applications, poly(ethylene terephthalate) (PET) reached a global production

of 83 million metric tons per year, in 2023 [6]. While mechanical recycling remains the most established end-of-life strategy, repeated processing can reduce material quality and often requires blending with virgin polymers [7]. In contrast, chemical recycling offers a more sustainable long-term solution by converting the polymer into valuable products. Various methodologies can be approached to obtain different degradation products, such as glycolysis, hydrolysis, methanolysis, aminolysis and ammonolysis. Glycolysis, as seen in Fig. 1, is the most established, and most of the current methods studied for PET degradation rely on this reaction. The reaction is a transesterification between the polyester and the both solvent and co-reagent, ethylene glycol (EG) to produce Bis(2-hydroxyethyl) terephthalate (BHET), a useful monomer for PET synthesis, supporting a circular economy [8].

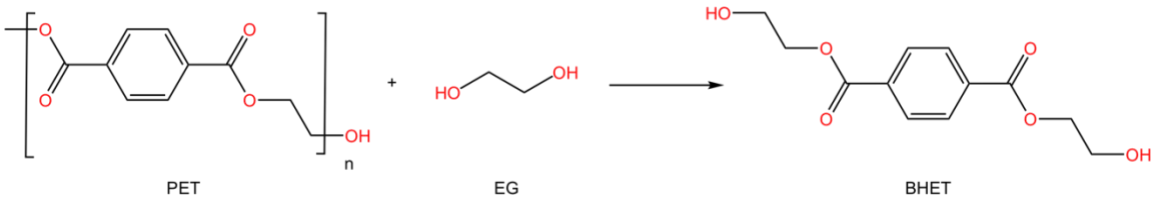


***Figure 1**. PET glycolysis.*

However, textile PET is generally more resistant to depolymerization than bottle-grade PET because of its fibrous structure, higher crystallinity and the presence of additives. Therefore, developing efficient and environmentally friendly catalytic systems is essential. Ionic liquids have emerged as promising catalysts because of their tunable properties, low volatility and potential recyclability [9]. Among them, 2-hydroxyethylammonium acetate (2-HEAA), has demonstrated encouraging performance in bottle-grade PET glycolysis [10]. Furthermore, although supercritical CO_2 (sCO_2) has been successfully employed in several polymer-processing technologies, its influence on the glycolytic depolymerization of textile PET has not yet been investigated. Supercritical carbon dioxide ($scCO_2$) and ionic liquids can operate synergically by forming a biphasic reaction system, thereby reducing the use of toxic and expensive solvents. The present work evaluates the combined use of 2-HEAA and supercritical CO_2 for textile PET glycolysis, focusing on process optimization, reaction kinetics, product selectivity and catalyst reusability.

2. METHODS

Micronized poly(ethylene terephthalate) (PET) textile fibers (average particle size of 0.5 mm), supplied by Area de Tintura S.L. (Valencia, Spain), were used as feedstock. Ethylene glycol (EG, >99%, VWR Chemicals) served as the depolymerization solvent, while 2-hydroxyethylammonium acetate (2-HEAA), synthesized via equimolar neutralization of 2-hydroxyethylamine and acetic acid followed by vacuum drying (60 °C, 24 h), was employed as the catalyst. Glycolysis reactions were performed in a 50 mL high-pressure Parr reactor under supercritical CO_2 at a constant pressure of 120 bar for 15 min, according to preliminary optimization studies. The effects of reaction temperature (183–217 °C), PET/ionic liquid ratio (1.7–6.0 g g^{-1}), and PET/EG ratio (14.1–33.0 g g^{-1}) were investigated through a full factorial experimental design, with each

condition performed in duplicate. At the end of each experiment, the reaction mixture was cooled, depressurized, and vacuum filtered. The recovered solid residue was dried at 60 °C until constant weight, and PET conversion was determined gravimetrically from the mass difference between the initial polymer and the residual solid. Statistical analysis of the experimental data was performed by ANalysis Of VAriance (ANOVA) to evaluate the significance of the investigated factors and their interactions. Reaction products were subsequently characterized by gas chromatography (GC) for BHET determination.

Kinetic experiments were conducted under the optimized PET/EG and PET/IL ratios by varying the reaction temperature (180–210 °C) and reaction time (10–25 min). Apparent first-order rate constants and activation energy were determined using the Arrhenius approach. Catalyst recyclability was evaluated over five consecutive cycles using two different solvent/catalyst recovery strategies. PET feedstock and reaction products were characterized by thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), gel permeation chromatography (GPC), Fourier-transform infrared spectroscopy (FTIR), and gas chromatography (GC) for BHET quantification.

3. FINDINGS

The depolymerization of textile polyethylene terephthalate (PET) through glycolysis using 2-hydroxyethylammonium acetate (2-HEAA) as catalyst and co-solvent was investigated to assess its potential within a circular economy approach. The study included optimization of the reaction conditions, kinetic analysis, statistical evaluation of the main process parameters, maximization of PET conversion, and catalyst reusability.

The PET textile waste exhibited the typical thermal and structural properties of a semicrystalline polyester, with a glass transition temperature of 81.6 °C, melting temperature of 251.2 °C, and crystallinity of 33.7%. GPC analysis yielded a number-average molar mass (Mn) of 2321 ± 386 g·mol^{-1} and a weight-average molar mass (Mw) of 6253 ± 913 g·mol^{-1}, values consistent with recycled PET. TGA confirmed high thermal stability, with degradation starting around 400 °C.

A factorial design was used to evaluate the effects of temperature (183–217 °C), textile-to-ionic liquid ratio (TEX/IL), and textile-to-solvent ratio (TEX/S). Fig. 2 shows the main effect plot (MEF). According to MEF, temperature is the dominant factor affecting PET conversion, with an optimum value around 210 °C. TEX/IL had a moderate but significant influence, whereas TEX/S showed no statistical significance.

Interaction analysis identified an optimum operating region centered at approximately 210 °C and TEX/IL = 1:16.5, in excellent agreement with the experimental validation. The response surface confirmed the dominant influence of temperature and its synergistic interaction with the catalyst loading.

Under optimized conditions, GC-FID confirmed almost complete conversion to BHET. Notably, the crude depolymerization product contained more than 99 wt.% BHET without further purification, demonstrating the exceptional selectivity of the catalytic system.

Operating under supercritical CO_2 significantly enhanced the process. At the optimized conditions (210 °C, TEX/IL = 1:16.5, TEX/S = 1:7.0, 15 min), PET conversion increased from 84.8% at atmospheric pressure to 97.0% under sCO_2. The enhancement provided by supercritical CO_2 can be attributed to improved mass transfer, better penetration of the glycolytic medium into the semicrystalline PET fibers, and enhanced contact between PET, ethylene glycol and the ionic liquid catalyst.

The glycolysis followed a first-order kinetic model, with reaction rate increasing with temperature. Arrhenius analysis yielded an apparent activation energy of 137.0 kJ mol^{-1}. Although higher than values reported for bottle-grade PET, this is consistent with the greater resistance of textile fibers to depolymerization and remains lower than that reported for other catalysts applied to textile PET [11].

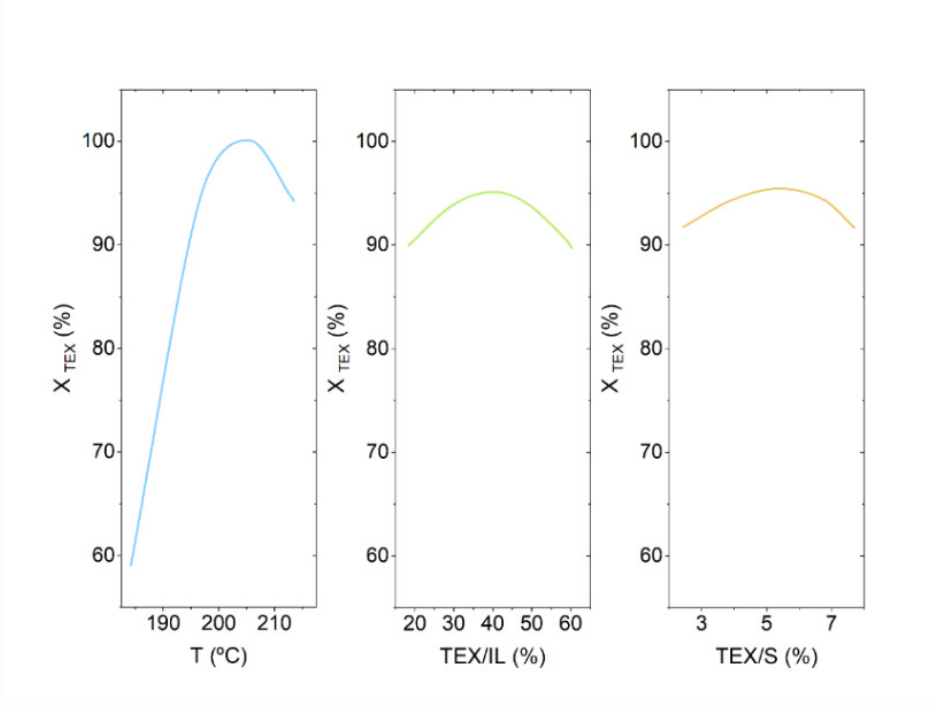


Figure 2. *Main effects plot showing the impact of T, TEX/IL and TEX/S on the PET conversion.*

Interestingly, the 2-HEAA/ethylene glycol system was successfully reused over five cycles with only a limited decrease in conversion when solvent and catalyst losses were compensated, maintaining values above 87%. Without replenishment, conversion decreased more markedly due to volume losses during recovery. Compared with previous studies using the same or different ionic liquids, the catalyst showed excellent stability despite the considerably shorter reaction time. FTIR analysis of the recovered reaction mixtures confirmed the preservation of the catalytic system and showed progressive accumulation of BHET and other oxygenated products during repeated cycles, particularly when fresh solvent and catalyst were added to compensate for processing losses.

4. DISCUSSION/CONCLUSION

This study demonstrates that the glycolysis of textile PET can be effectively enhanced by combining 2-hydroxyethylammonium acetate (2-HEAA) with supercritical CO_2. The statistical analysis highlighted the

key role of temperature in governing depolymerization performance, while the PET/ionic liquid ratio provided an additional leverage for process optimization. The limited influence of the PET/ethylene glycol ratio suggests that efficient conversion can be achieved without excessive solvent consumption, improving the overall sustainability of the process.

The beneficial effect of the supercritical medium indicates that mass transfer and reaction efficiency can be substantially improved under these conditions, enabling rapid depolymerization and high selectivity toward BHET. The kinetic results further support the suitability of 2-HEAA for textile PET recycling, confirming its ability to promote ester bond cleavage despite the intrinsic resistance of textile fibers compared with bottle-grade PET.

An additional advantage of the proposed system is its recyclability. The catalyst/solvent mixture retained good performance over multiple reuse cycles, and spectroscopic analyses confirmed the preservation of the catalytic environment throughout the recycling tests. These findings highlight the robustness of the process and its potential for repeated operation with limited performance losses.

Overall, the combination of 2-HEAA and supercritical CO_2 represents a promising approach for the chemical recycling of textile PET, offering a balance between conversion efficiency, product selectivity, and catalyst reusability. The proposed strategy contributes to the development of more sustainable routes for textile waste valorization within a circular economy framework.

Overall, the results demonstrate that combining 2-HEAA with supercritical CO_2 provides a rapid, highly selective, and recyclable process for the chemical recycling of textile PET, representing a promising route for sustainable textile waste valorization.

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DYNAMIC CIRCULAR PRODUCTIVITY IN EUROPEAN PRODUCTION SYSTEMS

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ABSTRACT

This study provides a dynamic assessment of circular productivity across 27 European countries over the period 2010–2024. Building on a conceptual representation of circular production, the analysis combines a Directional Distance Function with the Malmquist–Luenberger productivity index to jointly account for desirable outputs and material-related environmental pressures. The framework distinguishes between efficiency improvements and shifts in the production frontier, enabling the identification of heterogeneous circular transition pathways across European production systems. The findings indicate that productivity dynamics are primarily driven by technological change rather than by efficiency gains. Moreover, substantial territorial disparities emerge, with Western and Northern European countries operating closer to the frontier, while Southern and Eastern economies exhibit more persistent inefficiencies and slower adjustment processes. These results highlight the need for differentiated policy strategies aimed at fostering circular innovation and reducing structural gaps in the transition towards more resource-efficient production systems.

Keywords: Circular Economy; Productivity; Malmquist-Luenberger index; Directional distance function; Technological Change.

1. INTRODUCTION

The transition towards circular production systems represents one of the major challenges facing European economies. Beyond improving economic performance, circularity requires a progressive reduction in dependence on virgin resources and a greater reliance on secondary materials. Accordingly, productivity can no longer be interpreted exclusively as the efficient transformation of inputs into outputs but must also reflect the environmental implications embedded within production processes and the extent to which production systems are able to preserve material value over time [4–6]. Measuring productivity under these conditions remains challenging. Existing circular economy indicators mainly provide static assessments of resource efficiency and material use [4,5], often overlooking the dynamic interactions between technological progress, productivity improvements and changes in material composition. In particular, traditional productivity measures generally fail to account simultaneously for

desirable and undesirable outputs and to distinguish between efficiency gains and shifts in the production frontier [1–3]. This limitation is particularly relevant within the circular economy context, where technological innovation may facilitate the substitution of virgin materials with secondary resources and support the transition towards more sustainable production systems [6,8,10]. To address this gap, this study combines a conceptual representation of circular production with a dynamic Malmquist–Luenberger framework. Using Eurostat and AMECO data for 27 European countries over the period 2010–2024, the paper investigates how circular productivity evolves over time and whether heterogeneous transition pathways emerge across European production systems.

2. METHODS

Circular productivity is assessed using the Directional Distance Function (DDF) framework proposed by Chung et al. [1] and the Malmquist–Luenberger (ML) productivity index introduced by Pastor and Lovell [2] and subsequently extended by Oh [3]. This approach enables the simultaneous consideration of economic performance and environmental pressures by accounting for both desirable and undesirable outputs within the production process. The ML framework makes it possible to distinguish between changes associated with improvements in technical efficiency and those attributable to technological progress. In this way, productivity dynamics can be interpreted not only in terms of a country's ability to move closer to the existing production frontier, but also in terms of shifts in the frontier itself resulting from innovation and technological development. The empirical analysis relies on a balanced panel of 27 European countries observed over the period 2010–2024 using Eurostat and AMECO data. Capital and labour are considered productive inputs, while economic output and recycled materials represent desirable outputs. Virgin material use is treated as an undesirable output, allowing productivity changes to be evaluated consistently with circular economy objectives. Recent studies have increasingly adopted productivity-based approaches to assess environmental and circular performance at the national level [7,9]. Building on this literature, the proposed framework provides a dynamic perspective on the evolution of circular productivity across European production systems.

3. FINDINGS

3.1 Circular intensity across Europe

Figure 1 illustrates the spatial distribution of the average recycled-to-virgin material ratio (R/V) across European countries over the period 2010–2024. Higher values indicate production systems characterised by a stronger integration of secondary materials and, consequently, a greater degree of circular intensity.

The evidence reveals marked heterogeneity across Europe. Countries such as France, Italy and Estonia belong to the highest quartile of the distribution, suggesting a relatively stronger capacity to substitute virgin resources with recycled materials. A second group, including Spain, Germany, Austria and Denmark,

displays medium-to-high levels of circular intensity. By contrast, several Eastern European countries and some Northern economies remain in the lower quartiles, indicating a greater reliance on virgin materials within their production systems.These findings suggest that the adoption of circular practices does not follow a simple geographical pattern. Rather, circular intensity appears to reflect differences in technological capabilities, material management strategies and the maturity of national circular economy policies. Such disparities highlight the existence of uneven starting conditions in the European transition towards more resource-efficient production systems.

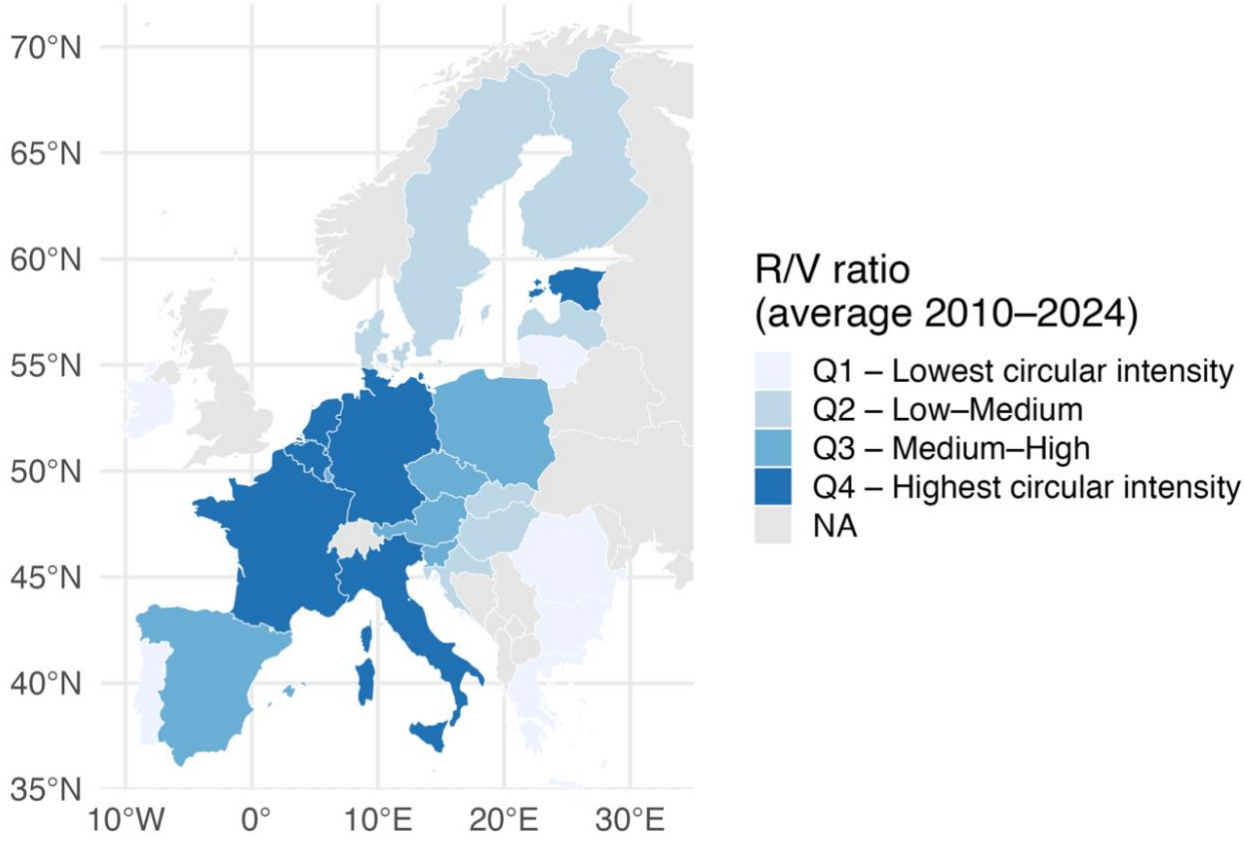


Figure 1. *Spatial distribution of the average recycled-to-virgin material ratio across European countries (2010–2024). Higher values indicate stronger circular intensity. Source: Authors' elaboration based on Eurostat data.*

3.2 Circular adjustment potential across European regions

Figure 2 reports the evolution of the average directional distance values (Mean Dv) across four European macro-regions over the period 2010–2024. Unlike productivity indices, directional distance values capture the potential for simultaneously expanding desirable outputs and reducing undesirable outputs, thereby reflecting the scope for improving circular performance.

Southern European countries exhibit the highest values throughout most of the period, suggesting greater room for adjustment towards more circular production configurations. Eastern and Northern Europe display intermediate and more volatile patterns, while Western Europe records consistently lower values, indicating more limited adjustment potential.

These results suggest that European regions entered the circular transition from markedly different starting positions. Regions characterised by larger directional distances may possess greater opportunities for improvement, whereas lower values may reflect production systems already operating closer to their attainable circular frontier.

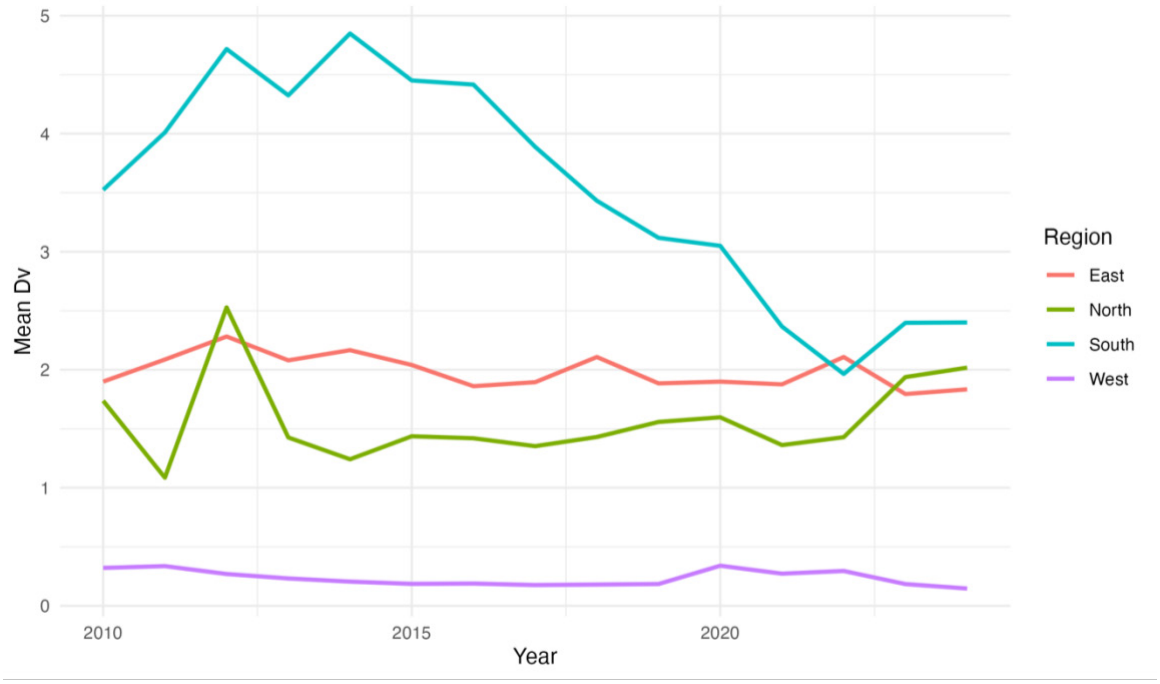


Figure 2. *Average dynamics of circular productivity and its decomposition across European countries. Source: Authors' elaboration.*

3.3 Productivity decomposition and regional heterogeneity

Figure 3 presents the decomposition of circular productivity change into technological change (TECH), technical efficiency change (TECCH) and total factor productivity change (TFPCH) across European macro-regions. The results reveal heterogeneous productivity dynamics. In most regions, fluctuations in total factor productivity closely mirror changes in the technological component, suggesting that frontier shifts associated with innovation constitute the primary driver of circular productivity dynamics. By contrast, technical efficiency changes remain comparatively modest and stable over time. Southern Europe exhibits episodes of pronounced productivity growth followed by subsequent corrections, whereas Eastern and Northern Europe experience more volatile trajectories. Western Europe displays comparatively smoother dynamics characterised by smaller variations in both efficiency and technological change. Overall, these findings indicate that the European circular transition has been shaped predominantly by technological progress rather than by improvements in the ability of countries to catch up with the existing frontier.

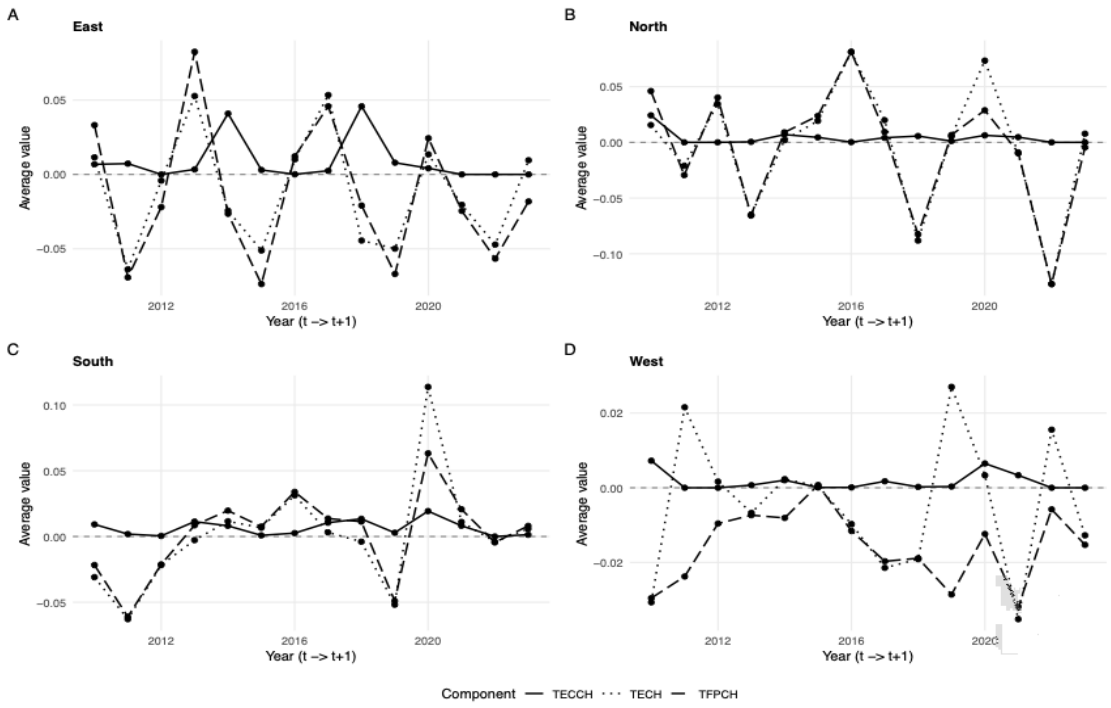


Figure 3. *Regional dynamics of circular productivity and its components across European macro-regions. Source: Authors' elaboration.*

4. DISCUSSION AND CONCLUSION

This study provides a dynamic evaluation of circular productivity across European production systems, showing that the transition towards more resource-efficient configurations has unfolded along structurally heterogeneous trajectories. The empirical evidence reveals substantial cross-country differences in material use patterns, technological capabilities and productive structures, which translate into uneven distances from the attainable circular frontier. Some economies already operate in proximity to their potential circular configuration, whereas others retain significant adjustment margins, reflecting differentiated initial conditions and distinct capacities to internalise circular practices within production processes.

The decomposition of productivity dynamics indicates that technological progress is the predominant driver of circular productivity change, while improvements in technical efficiency play a comparatively limited and more stable role. This pattern suggests that advances in circular performance depend primarily on the ability of production systems to incorporate innovations that expand the feasible production set and facilitate the substitution of virgin materials with secondary resources. Such evidence is consistent with recent contributions emphasising the centrality of technological substitutability and innovation in enhancing circular performance, particularly in relation to the integration of recycled materials, as discussed in the literature on material substitutability.

From a policy perspective, the results underscore that a uniform approach to the circular transition is unlikely to be effective in a context characterised by structural heterogeneity. Countries operating closer to the frontier may benefit from policies aimed at sustaining frontier-enhancing innovation and accelerating the diffusion of advanced circular technologies. Conversely, economies with wider adjustment gaps require interventions oriented towards strengthening productive capabilities, improving material management systems and reducing barriers to the adoption of circular technologies. Differentiated policy strategies are therefore essential to align interventions with the specific structural and technological conditions of each production system.

Overall, the analytical framework adopted in this study offers a coherent tool for monitoring the evolution of circular productivity and for identifying policy priorities consistent with the heterogeneous nature of European production systems. By capturing both the magnitude and direction of changes in circular performance, the dynamic perspective contributes to a more refined understanding of the circular transition and provides a robust basis for designing policies capable of supporting a more inclusive and resource-efficient development trajectory across Europe. Future extensions may further explore sectoral heterogeneity or incorporate additional dimensions of circular performance, such as the role of frontier shifts in shaping long-run circular dynamics.

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PRODUCT-SERVICE SYSTEMS AS A COMPLEMENTARY STRATEGY TO THE RIGHT TO REPAIR

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ABSTRACT

Recently, sustainability and resource use have become central in economic and policy debate, challenging the linear consumption model due to its environmental impacts and limits. Attention is therefore shifting towards circular economy approaches, where repair plays a key role in extending product lifespan, reducing waste and supporting the transition toward a "repair society". The evolution of Right to Repair within the European context suggests that, while representing a necessary step, it may remain insufficient due to structural limitations that subordinate public repair interest to private incentives. The study investigates Product-Service Systems (PSS) as complementary use-oriented models embedding repair into business design. An exploratory survey identifies the main determinants of PSS adoption, showing how business model innovation may complement regulation by making repair a systemic practice.

Keywords: right to repair, circular economy, product-service systems, consumer behavior, repair.

1. INTRODUCTION

In recent years, sustainability, circularity and resource management have played an increasingly prominent role in the economic landscape. The linear consumption model that has defined economic growth over the last century is increasingly being questioned due to its well-documented environmental impact, which highlights the biophysical limits of the current system. As a result, growing attention is being directed towards the circular economy. Within this framework, repair plays a central role in extending product lifespans and reducing waste, emerging as both a legislative and social response to the declining relevance of repair practices in industrial economies. In a context characterized by products that are increasingly fragile, prone to malfunctioning and difficult to repair, the generation of growing e-waste streams is inevitable. On a global scale, e-waste emissions increased by more than 50% between 2014 and 2020 [1]. Although developed countries achieve high scores in terms of the Human Development Index, patterns of overconsumption in these contexts are widely recognized as key drivers of planetary boundaries transgression and environmental degradation [2]. Consequently, several governments have introduced legislation aimed at facilitating access to repair practices. These efforts culminated in Directive (EU) 2024/1799 ("Right to Repair").

The aim of this work is to examine the relationship between repair practices and use-oriented models from a multidisciplinary perspective that encompasses legislative, infrastructural and behavioral dimensions. It explores the intersection between regulatory frameworks, business model innovations and consumers' attitudes. This study investigates whether and under which conditions use-oriented models can support the systemic integration of repair throughout product life cycles.

2. METHODS

Sustainable behavior adoption may be hindered by the presence of economic, behavioral and cognitive barriers that prevent consumers from translating favorable attitudes into actual behavior. This phenomenon, commonly referred to as the "intention-behavior gap", may limit the effectiveness of the Right to Repair if the existing barriers to repair are not adequately addressed.

Within this context, the literature has increasingly explored alternative consumption models to traditional ownership, such as Product-Service Systems (PSS). These models represent promising pathways for reorganizing repair practices, as they structurally integrate maintenance and product longevity into the value creation process in business models. From the consumer's perspective, use-oriented business models shift the evaluation of an offering from ownership-related to functional aspects such as perceived value, perceived risk and convenience.

To empirically test the proposed research model, the theoretical constructs were operationalized through a structured questionnaire. Specifically:

- Perceived value was defined as the consumer's overall assessment of the utility of a product or a service, based on the perceived trade-off between benefits received and the sacrifices required to obtain them [3]. The selected items assess perceived quality, reliability and economic convenience of the service, while specifically comparing the use-oriented model with the traditional ownership model.
- Perceived risk was defined as the consumer's subjective perception of uncertainty regarding the potential adverse consequences associated with adopting the service [4]. The measurement items cover concerns related to service performance, availability and the perceived discomfort associated with using a pre-owned product.
- Convenience was operationalized according to the SERVCON framework (Seiders et al. [5]), encompassing decision, access, transaction, benefit and post-benefit convenience. The construct reflects perceived behavioural control by capturing the time and effort required to access and manage the service.
- Adoption intention refers to the consumer's willingness to adopt the rental service as an alternative to traditional ownership.

The measurement items were adapted from previously validated scales: Kim et al. [6] for perceived value, Hazée et al. [7] for perceived risk, and Berry et al. [8] for convenience. The empirical setting selected is the rental of a domestic washing machine. This appliance was selected because it is explicitly covered by the EU Right to Repair Directive, requires regular maintenance, and has low symbolic value, making it a suitable context for testing use-oriented circular models [9]. Constructs have been measured by a 7 points Likert scale, with values between 1 (strongly disagree) and 7 (strongly agree).

To estimate the effect of the selected constructs on adoption intention, a multiple linear regression model was specified, with adoption intention as the dependent variable and perceived value, convenience and perceived risk as independent variables ($AI = a + b_1 \cdot Value + b_2 \cdot Convenience + b_3 \cdot Risk$). The unstandardized coefficients (b) therefore express the expected change in adoption intention, measured on the 7-point scale, associated with a one-point increase in the corresponding predictor, holding the other predictors constant. The intercept (a) is not estimated independently: it derives from the coefficients and the sample means ($a = \bar{Y} - \Sigma b_i \cdot X_i$), so that the regression plane passes through the mean values of all variables. It represents the predicted intention when all predictors equal zero and has no substantive interpretation, since the scale starts at 1. Because the unstandardized coefficients depend on the measurement units and variability of each construct, standardized coefficients (β) were also computed as $\beta = b \cdot (SD_x / SD_y)$, where SD_x and SD_y are the standard deviations of the predictor and of adoption intention, respectively. These are the coefficients reported in Figure 1: they derive directly from those of the estimated equation and allow the relative weight of the three predictors to be compared on a common scale. Finally, multicollinearity among predictors was assessed through the Variance Inflation Factor (VIF).

3. FINDINGS

Data were collected through a structured online questionnaire administered over a four-week period, resulting in 257 valid responses.

To assess measurement reliability, internal consistency was evaluated through the calculation of Cronbach's alpha coefficient, with satisfactory results obtained for all constructs. The sample presents a clear gender imbalance, with 69% of respondents being female and 30% male. Most participants were aged between 25 and 34 years and reported a medium-to-high education level.

The average perceived value of 3.71 (SD = 1.17) suggests a moderate evaluation of the utility offered by the proposed model. Perceived risk presents a higher average value of 4.56 (SD = 1.32), indicating the presence of relevant uncertainty. The average convenience score is 4.04 (SD = 1.08). Finally, adoption intention shows a relatively low average value of 3.10 (SD = 1.68), suggesting limited willingness among respondents to adopt the proposed service model. Pearson correlations confirmed positive associations between value and adoption intention (r = 0.66) and between convenience and adoption intention (r = 0,41), whereas perceived risk was negatively associated (r = –0.20).

To investigate the effect of the selected constructs on adoption intention, a multiple linear regression model (Figure 1) was estimated according to the following equation:

$$\textbf{\textit{Adoption intention} = -0.105 + 0.847 \cdot \textit{Value} + 0.225 \cdot \textit{Convenience} - 0.186 \cdot \textit{Risk}}$$

The standardized coefficients in Figure 1 derive from the coefficients of this equation (e.g., for perceived value, 0.847 × 1.17 / 1.68 = 0.59).

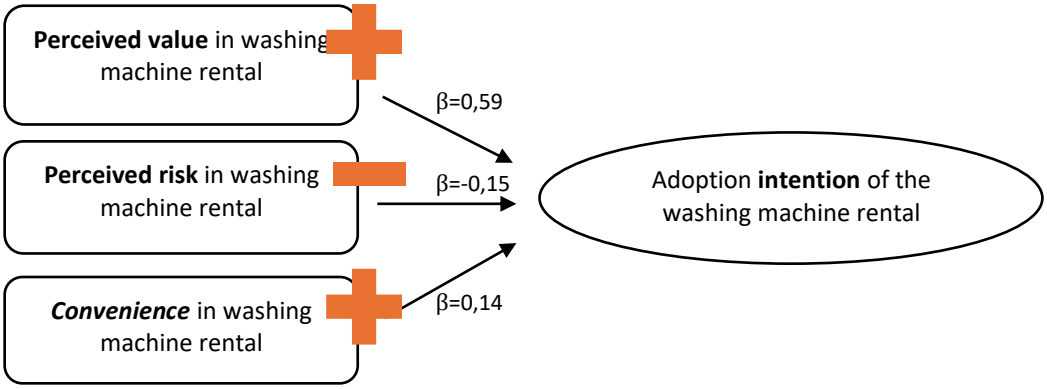


***Figure** 1: the figure reports the standardized regression coefficients. Perceived value is the strongest predictor of adoption intention, whereas convenience has a weaker positive effect and perceived risk a limited negative effect. The regression model is statistically significant ($F = 75.9$, $p < 0.0001$) and explains approximately 47% of the variance in adoption intention ($R^2 = 0.47$). No evidence of multicollinearity was detected. Source: authors' elaboration based on collected data.*

The exploratory analysis highlights some additional patterns within the sample. Female respondents report higher perceived risk compared with male respondents (M = 3.97; F = 4.82). Furthermore, a significant difference emerges between respondents who had previously purchased a washing machine and those who had not: individuals with previous ownership experience show lower willingness to adopt the rental service (Cohen's d = -0.27).

The median willingness to pay (€22.50) was considerably lower than the mean (€44.58), indicating a skewed distribution. This suggests a psychological price threshold of approximately €20 and confirms that respondents continue to benchmark the service against the purchase price of a new washing machine.

4. DISCUSSION/CONCLUSIONS

The findings indicate that perceived value is the primary driver of consumers' intention to adopt Product-Service Systems (PSS), highlighting the central role of tangible benefits and functional utility in the evaluation process [10]. In this context, utilitarian considerations appear to outweigh normative or moral motivations. The adoption of circular consumption practices therefore emerges not primarily as the outcome of environmental awareness, but rather as the consequence of a value proposition perceived as superior to traditional ownership. The relatively modest effect of perceived risk suggests that uncertainty

does not constitute a deterministic barrier to adoption. Instead, its influence appears to depend on the overall value proposition, interacting with consumers' expectations regarding the benefits generated by the service [11].

These findings give rise to several managerial and policy implications. The dominant role of perceived value suggests that the design of use-oriented services should focus on delivering clear and tangible benefits capable of overcoming consumers' psychological barriers.

Under business models in which producers retain product ownership, the responsibility and economic risk associated with product failure shift from consumers to producers, thereby realigning incentives. In such a context, product durability, reliability, and ease of repair become direct sources of economic value for manufacturers rather than external constraints.

This transition, commonly referred to as “servitization”, requires firms to compete not only on price but also on the cognitive framework through which consumers evaluate competing alternatives. Emphasizing the total cost of ownership over the entire product life cycle, rather than the initial purchase price alone, may enable consumers to make more informed comparisons and better appreciate the value generated by service-based solutions.

From an operational perspective, firms should implement structured monitoring systems and, where feasible, Internet of Things (IoT) technologies to anticipate product failures, optimize maintenance scheduling, and improve spare-parts management. These capabilities can increase service reliability while reducing maintenance costs and extending product lifetimes. From a policy perspective, the transition towards a "repair society" cannot rely solely on regulatory interventions. Rather, it requires a broader process of cultural, technological, and infrastructural transformation capable of simultaneously reshaping the roles of both producers and consumers within the circular economy. Nevertheless, some limitations should be acknowledged. For energy-intensive products, extending product lifespans may not always lead to lower overall environmental impacts if newer technologies provide substantially greater energy efficiency. In such cases, the environmental trade-off between product longevity and technological replacement should be carefully evaluated [12]. Furthermore, repair obligations imposed on manufacturers may unintentionally distort market competition by disadvantaging independent repair providers [13]. Consequently, appropriate regulatory mechanisms should be developed to preserve competition and prevent the exclusion of independent repair actors from the repair ecosystem.

In conclusion, while Directive (EU) 2024/1799 represents an important step towards promoting repair, its effectiveness ultimately depends on consumers' willingness to exercise this right. The findings suggest that use-oriented business models can complement regulatory interventions by embedding repair and maintenance into firms' value creation processes. By shifting ownership from consumers to providers, these models have the potential to transform repair from an individual choice into an embedded feature of consumption, thereby supporting the transition towards a more circular economy.

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FROM WASTE MANAGEMENT TO CLEAN ENERGY: NEW PERSPECTIVES IN INDUSTRIAL SYMBIOSIS

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ABSTRACT

This study aims to demonstrate a circular economy strategy that combines municipal waste management and industrial wastewater from electroplating processes, in order to develop potential applications in the field of green chemistry. Spent activated carbons were recovered from landfill leachate treatment plants and pretreated to remove accumulated organic pollutants, then simulated galvanic rinse waters, containing precious metals, were introduced to provide valuable metals. Thanks to a purification and adsorption process, the spent activated carbons were converted back into potentially useful catalysts for fuel cells. The focus was on the oxygen reduction reaction (ORR) in an alkaline environment, which is the reaction that occurs at the cathode of an alkaline fuel cell. Structural analysis of carbonaceous supports demonstrated the effectiveness of pretreatments in obtaining a material capable of adsorbing palladium from waste solutions, generating a possible catalyst. Moreover, electrochemical analyses indicate that the palladium-enriched carbon system lowers reaction barriers by favoring a four-electron pathway, thus offering a possible model for a new circular process based on industrial waste, prior to more detailed investigations in the future.

Keywords: Industrial Symbiosis; Circular Economy; Waste Valorization; Functional Carbon Materials; Clean Energy Conversion.

1. INTRODUCTION

The transition to sustainable industrial systems requires a fundamental shift from linear production models to closed-loop systems, where the combination of industrial flow waste would allow to use the waste from one process to directly feed another [1]. This choice significantly reduces the use of virgin raw materials and limits the environmental impact associated with conventional disposal methods. In municipal waste management, landfills produce variable volumes of leachate, an extremely polluting fluid being rich in organic substances and heavy metals [2, 10]. To ensure safe disposal in the environment of the leachate, plants such as landfills use purifiers which use activated carbon as the final filtration step, where these porous materials progressively accumulate organic pollutants, gradually losing their adsorbent capacity while purifying the liquid [3, 10].

In parallel, considering another industrial flow, metallurgical surface treatment processes (such as electroplating and decorative electroplating finishes) generate large flows of rinse water containing residual quantities of valuable transition metal and noble metal ions [4, 6, 8]. Metals such as palladium and nickel are industrial components characterized by great geopolitical interest and a significant carbon footprint associated with their primary extraction.

In this preliminary study, spent carbonaceous materials from landfill operations are used as supports to recover the precious metals mentioned above [7, 15]. In this way, this application involves their combined recycling by generating an enriched catalytic material [5, 14] and specifically oriented to the oxygen reduction reaction (ORR) for alkaline fuel cells [9, 12, 13].

2. METHODS

The carbonaceous support was obtained from granular activated carbon used for the filtration of leachate at the Belvedere SpA plant in Peccioli (Italy). The material was ground and subjected to an alkaline washing protocol using a 0.1 M KOH solution mixed with a 50% (v/v) ethanol and water formulation, keeping the mixture under continuous stirring for 40 hours [15]. This procedure was chosen to remove the organic contaminants derived by the leachate from the internal surface, without altering the physical stability of the carbon granules.

The regenerated carbon powders were exposed to two distinct simulating galvanic rinse solutions: a multimetallic matrix bearing coordinated nickel-palladium complexes ("Nipal" solution) and a monometallic fluid containing exclusively palladium species [8]. The interaction was maintained again for 40 hours under ambient conditions, in order to promote metal adsorption.

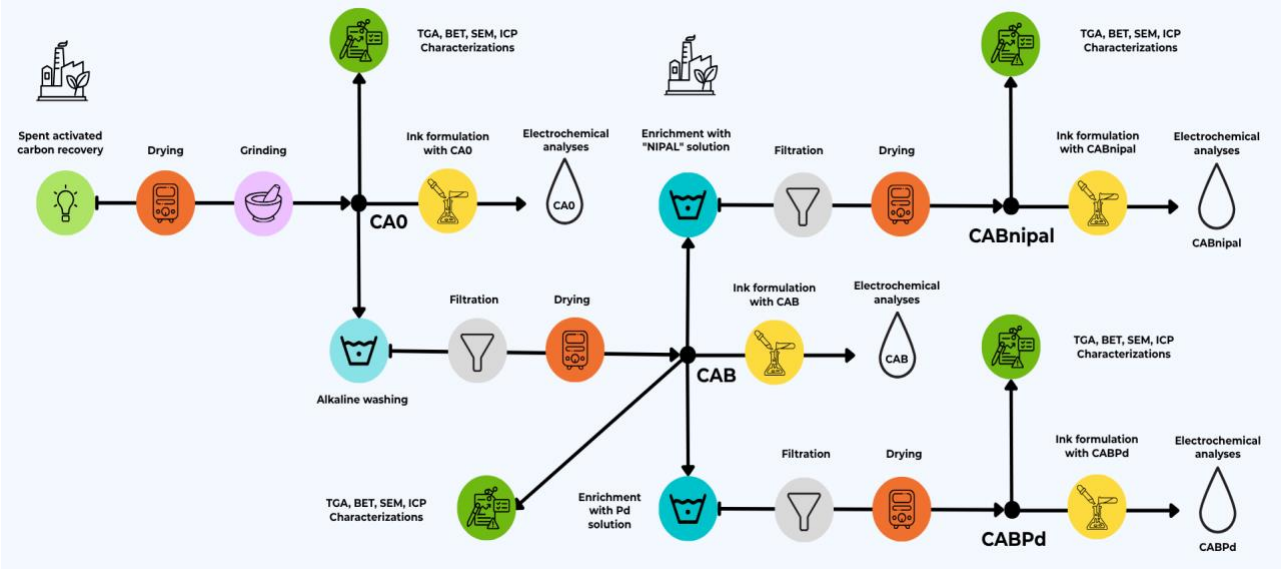


Figure 1. *Schematic representation of the experimental workflow, showing the recovery and purification of spent activated carbon, metal adsorption from simulated galvanic rinse solutions, material characterization and electrochemical evaluation for oxygen reduction reaction (ORR) application.*

Using thermogravimetric analysis (TGA) up to 800 °C under inert conditions it was possible to understand structural changes and surface features, while nitrogen adsorption isotherms were used to calculate structural surface parameters. Scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) has been essential for structural mapping while quantitative elemental tracking of the recovered metallic fractions was completed using inductively coupled plasma optical emission spectroscopy (ICP-OES), after microwave-assisted extraction in aqua regia. Finally, electrochemical behavior and overall pathway selection were evaluated using hydrodynamic linear sweep voltammetry (LSV) with a rotating ring-disk electrode (RRDE) system in an oxygen-saturated 0.1 M KOH fluid environment [11, 13].

3. FINDINGS

Thermogravimetry showed variations between the different phases of the treatment. The spent material as is (CA0) showed initial mass variations below 150 °C due to moisture evaporation, followed by constant degradation between 200 and 500 °C, attributable to the decomposition of volatile organic fragments trapped during wastewater treatment. Following alkaline washing, the recovered carbon showed a more marked initial moisture release but attenuated intermediate degradation; this demonstrates that the process generating the CAB sample effectively removed organic adsorbents, thus increasing the availability of the surface. The metal-loaded matrix showed specific variations: the Ni-Pd variant showed mass variations in the range between 150 and 400 °C, reflecting the presence of possible residues from the galvanic bath, while the pure palladium variant was found to be more stable, indicating a cleaner rinse water.

Nitrogen adsorption isotherms indicated that the treatment steps significantly modified the available surface structure; the increase in accessible surface area following the initial alkaline washing confirms that the treatment freed the pores of the carbonaceous powder. In parallel, multimetallic enrichment showed a reduction in available area, suggesting that larger metal aggregates and process additives partially clogged the pore channels. The palladium-only loaded material maintained a more balanced structure, preserving internal pores while improving external transport pathways. This configuration is extremely advantageous for energy devices, since it facilitates the mobility of the ions and gases involved in the processes. Microscopic images then revealed that the raw material (CA0) consisted of irregular particles, characterized by rough surfaces and structural obstructions. Following the alkaline washing (CAB), the carbon matrix appeared freer, with more well-defined channels. Among the metal-loaded materials, the multimetallic sample (CABnipal) had larger metal aggregates and inhomogeneous metal regions, indicative of localized accumulation. In contrast, the palladium-only enriched sample (CABPd) showed a rather uniform dispersion of fine palladium particles on the carbon structure, thus maximizing the availability of active sites.

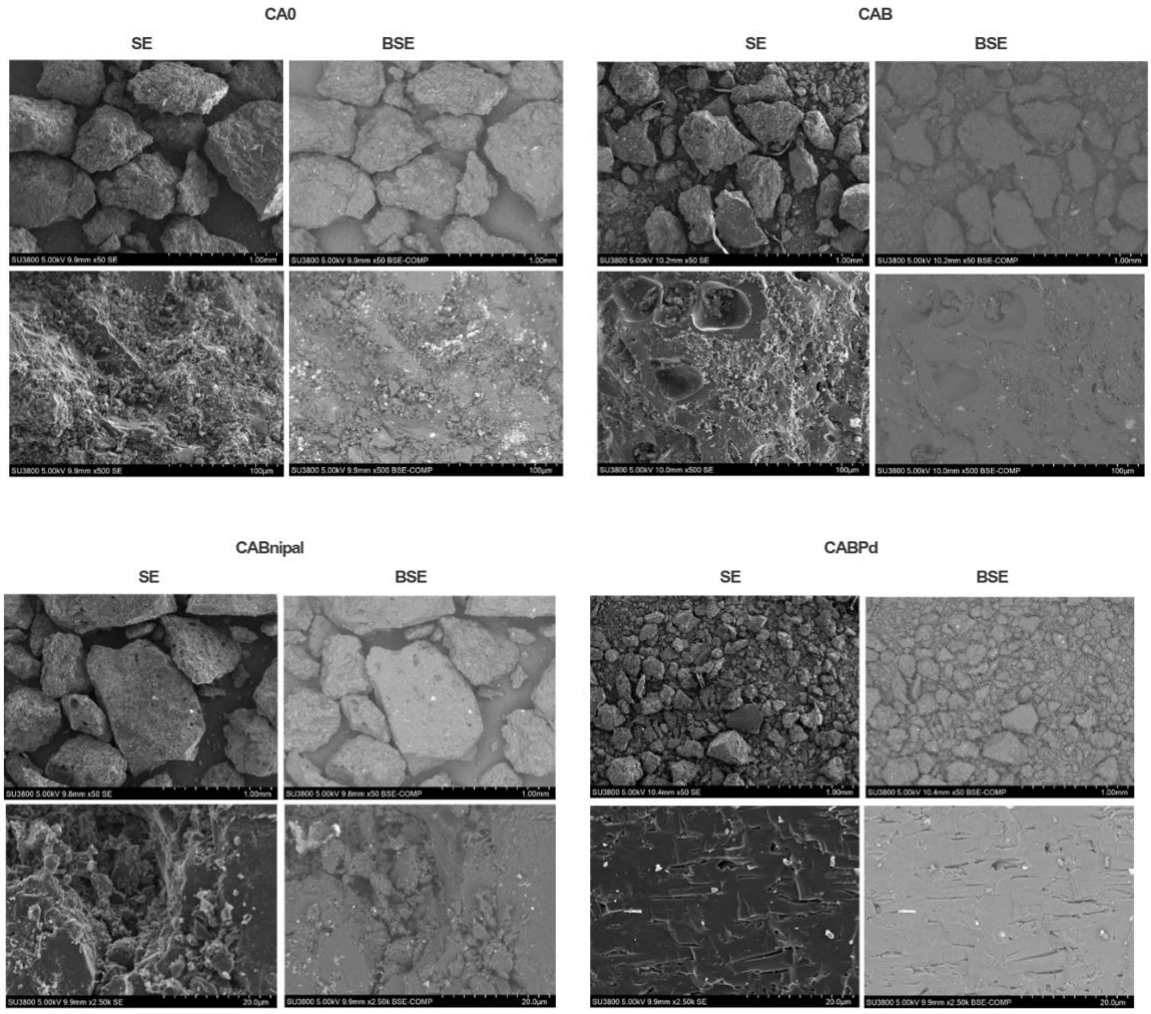


Figure 2. *SEM-EDS micrographs SE (sx) and BSE (dx) respectively for CA0, CAB, CABnipal and CABPd.*

The elemental composition, verified by atomic spectroscopy, confirmed the effectiveness of metal ion adsorption. To evaluate the metal absorption capacity from simulated galvanic rinsing solutions, recovery efficiencies and mass balances were quantified for both operating configurations. In the multimetallic system (CABnipal), the competitive adsorption behavior favored nickel immobilization, leading to a recovery efficiency of 43.8% (1.41 mg adsorbed) compared to a limited palladium recovery of 6.7% (4.85 mg adsorbed); this left the final matrix with a palladium content of 0.37 wt%. In contrast, the monometallic system (CABPd) showed significantly higher affinity for the precious metal, achieving a palladium recovery efficiency of 40.9%, with 40.94 mg of metal successfully incorporated into the structure. This targeted enrichment increased the final palladium loading to 3.05 wt%. This difference in palladium loading directly explains the improved electrocatalytic performance and lower activation barriers observed during subsequent electrochemical evaluations.

Electrochemical tests conducted in oxygen-saturated alkaline environments showed a difference in performance. The CA0 sample showed the lowest electrocatalytic activity, characterized by a significant overvoltage for triggering oxygen reduction. The CAB sample showed an improvement, shifting operation

towards lower energy requirements and demonstrating that the removal of adsorbed organic species made electrochemically active zones accessible. Although the multimetallic catalyst generated significant current responses, its operational start-up was delayed, indicating that metal aggregation and the presence of residual elements in solution hindered optimal charge transfer. The palladium-only enriched variant achieved the best performance, starting the conversion process with minimal energy barriers. Dynamic rotating ring-disk electrode tests provided information on active reaction pathways, surface efficiency and the percentage of direct water production, summarized in Table 1.

Investigated Material Matrix	**Number of exchange electrons per oxygen molecule (n)**	**Percentage of water production (% H_2O)**	**Electrochemical Surface Area (cm^2)**
Spent Activated Carbon (CA0)	2.7	35	2.7
Purified Carbon Matrix (CAB)	2.9	45	6.3
Ni-Pd Catalyst (CABnipal)	3.2	60	7.7
Pd Catalyst (CABPd)	3.9	95	16.8

Table 1. *Electrochemical performance parameters of the investigated carbon-based materials, including the number of exchange electrons per oxygen molecule (n), the corresponding percentage of water production and electrochemical surface area (ECSA). The results illustrate the progressive enhancement of ORR activity following purification and metal enrichment treatments.*

4. DISCUSSION/CONCLUSION

These results support a possible circular economy model that links two distinct industrial waste streams (spent carbons from landfill filtration operations and valuable metal residues from galvanic processes) transforming them into functional catalysts for green energy devices [1, 7]. The alkaline washing process was found to be essential to restore the active surface area of the support [15] and among the prepared variants, the palladium-only enriched carbon (CABPd) showed the best performance, combining an accessible porous structure with a uniform distribution of active metal sites [11]. This evidence is consistent with an oxygen reduction reaction (ORR) mechanism that follows a quasi-direct four-electron pathway [16, 17] and supports the use of this recovery material as a low-cost solution for the production of ORR electrocatalysts from secondary resources.

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MICROWAVE ASSISTED CO-PYROLYSIS OF PLASTIC WASTE WITH BIOCHAR GENERATED FROM LOCAL (OLIVE PRUNING) AND AFRICAN (WATER HYACINTH) RESIDUAL BIOMASS

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ABSTRACT

This study investigated the microwave-assisted co-pyrolysis of plastic waste in the presence of biochar derived from residual biomass of local and African origin. Experimental trials were carried out using biochar obtained by slow conventional pyrolysis at 600 °C of olive pruning residues and water hyacinth, mixed with plastic polymers such as HDPE, LDPE, and PP. The biochar was employed as a microwave absorber with a potential catalytic effect in the thermal cracking of plastic polymers, in order to assess its influence on thermochemical conversion as well as on the yield and composition of the resulting products. The analysis focused mainly on the yield and composition of syngas, with particular attention to the hydrogen (H_2) and methane (CH_4) contents, other than the bio-oil yield. The experimental trials with water hyacinth biochar, derived from an invasive species forming dense colonies in Lake Victoria (Africa), were carried out within the framework of the international project TNE WAGON2AFRICA_PNRR (WAter enerGy fOod Nexus 2 Africa), contributing to the final experimental phase of this research.

Keywords: Microwave-assisted co-pyrolysis; Biochar; Plastic waste; Hydrogen; Syngas; Olive pruning; Water hyacinth.

1. INTRODUCTION

The increasing accumulation of plastic waste has become one of the major environmental challenges worldwide due to its extensive production and persistence in the environment [1], [2]. Conventional disposal practices, including landfilling and incineration, are associated with severe environmental impacts and inefficient resource recovery. Consequently, increasing attention has been devoted to sustainable technologies capable of converting plastic waste into valuable products through thermochemical processes [3, 4, 5]. Among these technologies, microwave-assisted pyrolysis (MAP) has emerged as an efficient alternative to conventional pyrolysis because microwave energy directly heats microwave-responsive materials, resulting in rapid and volumetric heating, shorter reaction times and improved energy efficiency. Since most plastic polymers exhibit poor microwave absorption properties, microwave susceptors are required to initiate and sustain the process [6].

Biochar has attracted considerable interest as a microwave absorber because of its favourable dielectric properties and potential catalytic effect. Moreover, the physicochemical properties of biochar are strongly influenced by the precursor feedstock composition and pyrolysis conditions, affecting microwave heating behaviour and the thermochemical conversion process [7, 8]. In this study, biochars produced from the two residual biomass olive pruning and water hyacinth were investigated as microwave absorbers for the microwave-assisted co-pyrolysis of HDPE, LDPE and polypropylene. Olive pruning is an abundant agricultural residue in Mediterranean countries, whereas water hyacinth is an invasive aquatic species causing severe ecological and economic impacts in many African regions [9, 10]. Their simultaneous valorisation together with plastic waste represents a promising strategy for waste management and renewable energy production [11]. The aim of this study was to evaluate the influence of different biochar and operating temperature on product yield and syngas composition during microwave-assisted co-pyrolysis, with particular attention to hydrogen and methane production [12, 13, 14, 15, 16, 17, 18]. The structural morphology and composition of the recovered biochar after the thermochemical process was also investigated by SEM-EDX analysis.

2. METHODS

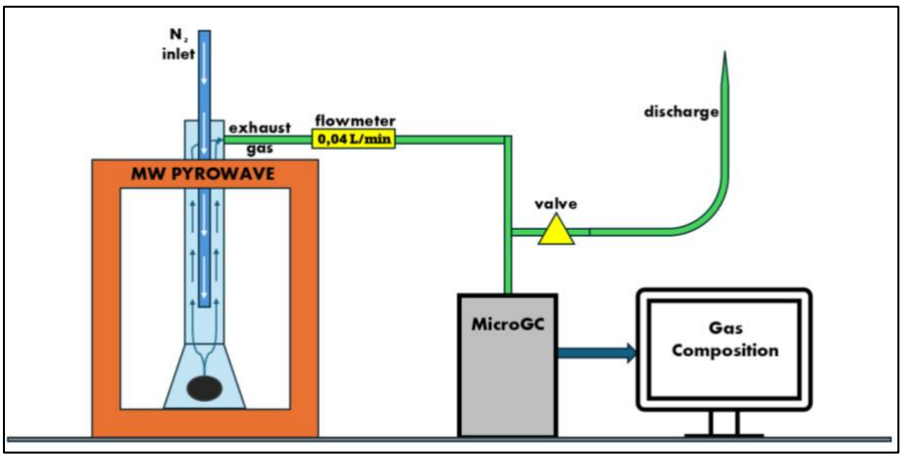


Figure 1. *Experimental setup of microwave-assisted-pyrolysis.*

Two lignocellulosic biomasses, olive pruning biomass (OPB) and water hyacinth biomass (WHB), were selected for biochar production. Both biomasses were dried in a ventilated oven at 60°C, milled to particle sizes below 2 mm following the National Renewable Energy Laboratory (NREL) protocol [19]. Biochars were produced by conventional pyrolysis using a LECO TGA801 thermogravimetric analyser under a nitrogen atmosphere. Samples were heated at 10 °C min^{-1} to 600 °C and maintained for 30 min. Raw biomasses and biochars were characterised by proximate and elemental analyses following standard procedures, while FTIR-ATR spectroscopy was used to identify the main functional groups.

Three post-consumer thermoplastics, high-density polyethylene (HDPE), low-density polyethylene (LDPE) and polypropylene (PP), were mechanically ground (<2 mm) before use. Plastic waste and biochar were premixed at a 7:3 (w/w) ratio using a vibratory bead mill operating at 28 Hz for 25 min.

Microwave-assisted co-pyrolysis experiments were performed in a Pyrowave reactor (Milestone) under a continuous nitrogen flow (0.04 L min^{-1}) [Fig. 1]. Olive pruning biochar was tested at 400, 500, 600 and 700 °C, whereas water hyacinth biochar was evaluated only at 700 °C. The heating ramp time was 15 min, followed by a 10 min residence time for each trial. The gaseous products were analysed using an Agilent MicroGC to quantify H_2, CH_4, CO, CO_2 and short chain hydrocarbons (C_2–C_6). The syngas production was measured at the outlet of the gas flow by a flowmeter, whereas the solid (carbonaceous material) and the liquid fraction (oil) were quantified gravimetrically after acetone extraction and solvent evaporation. The recovered char was characterised by SEM–EDX to evaluate its morphology and elemental composition.

3. FINDINGS

Sample			MAP Condition	Products		
Plastic	MW absorber	Weight ratio	Temperature and Residence Time	Char (%)	Oil (%)	Gas (%)
PP	B-OPB	7 : 3	400°C 10 min	51,76	6,06	42,18
LDPE	B-OPB	7 : 3	400°C 10 min	47,13	6,34	46,54
HDPE	B-OPB	7 : 3	400°C 10 min	50,91	3,63	45,46
PP	B-OPB	7 : 3	500°C 10 min	35,91	2,10	61,99
LDPE	B-OPB	7 : 3	500°C 10 min	30,98	3,05	65,97
HDPE	B-OPB	7 : 3	500°C 10 min	26,62	5,94	67,44
PP	B-OPB	7 : 3	600°C 10 min	35,82	1,88	62,30
LDPE	B-OPB	7 : 3	600°C 10 min	27,95	1,97	70,07
HDPE	B-OPB	7 : 3	600°C 10 min	30,32	3,06	66,63
PP	B-OPB	7 : 3	700°C 10 min	35,91	1,95	62,14
PP	B-WHB	7 : 3	700°C 10 min	32,33	2,58	65,09
LDPE	B-OPB	7 : 3	700°C 10 min	29,31	2,29	68,40
LDPE	B-WHB	7 : 3	700°C 10 min	28,73	2,03	69,24
HDPE	B-OPB	7 : 3	700°C 10 min	32,04	1,60	66,36
HDPE	B-WHB	7 : 3	700°C 10 min	31,53	7,33	61,14

Figure 2. *Yields of char, oil and syngas generated by Microwave Assisted Pyrolysis of plastic waste by using biochar as MW absorber.*

The two lignocellulosic feedstocks exhibited markedly different physicochemical properties. Olive pruning biomass (OPB) showed lower ash content (3.27 %dw) and higher volatile matter (77.74 %dw) than water hyacinth biomass (WHB) (16.60 %dw ash and 68.50 %dw volatile matter), indicating a higher proportion of organic fraction available for thermochemical conversion. Elemental analysis further confirmed the higher carbon content of OPB (47.41 %dw) compared with WHB (35.59 %dw).

Significant differences were also observed between the two biochars achieved through the conventional pyrolysis. Biochar derived from olive pruning (B-OPB) exhibited higher fixed carbon (69.80 %dw) and elemental carbon (79.01 %dw) than water hyacinth biochar (B-WHB) (36.35 %dw and 44.94 %dw, respectively), whereas B-WHB showed a considerably higher ash content (44.40 %dw) than B-OPB (12.35

%dw). FTIR analysis confirmed an advanced degree of carbonisation and highlighting the stronger mineral signature for both biochars.

Microwave assisted pyrolysis temperature strongly influenced both product distribution and gas composition. At 400 °C, char yields represented the predominant product (47–52%), while syngas production remained around 42–47% (depending on polymer) and molecular hydrogen formation was negligible. Increasing temperature to 500 °C promoted syngas production (62–67%) together with a marked increase in H_2 and short chain hydrocarbons. At 600–700 °C, the syngas became the dominant product (≈62–70%), oil was generally minimal (≈1.6-3.1%) (Fig.2). In Microwave assisted pyrolysis experiments in which the B-OPB was used at 600–700 °C, the composition shifted toward lighter products: H_2 and CH_4 become the most abundant compounds (H_2 = 14.92 mmol g^{-1} at 600 °C for PP and 21.67 mmol g^{-1} at 700 °C for HDPE; CH_4 up to 15.67 mmol g^{-1}). Overall, olive pruning biochar consistently outperformed water hyacinth biochar in promoting H_2-rich syngas production, whereas water hyacinth biochar maintained comparable CH_4 and H_2 yields in the HDPE tests under the most severe operating conditions. These results confirm that temperatures of at least 600 °C maximise secondary cracking reactions, favouring the conversion of condensable compounds into energetic gases [Fig. 3].

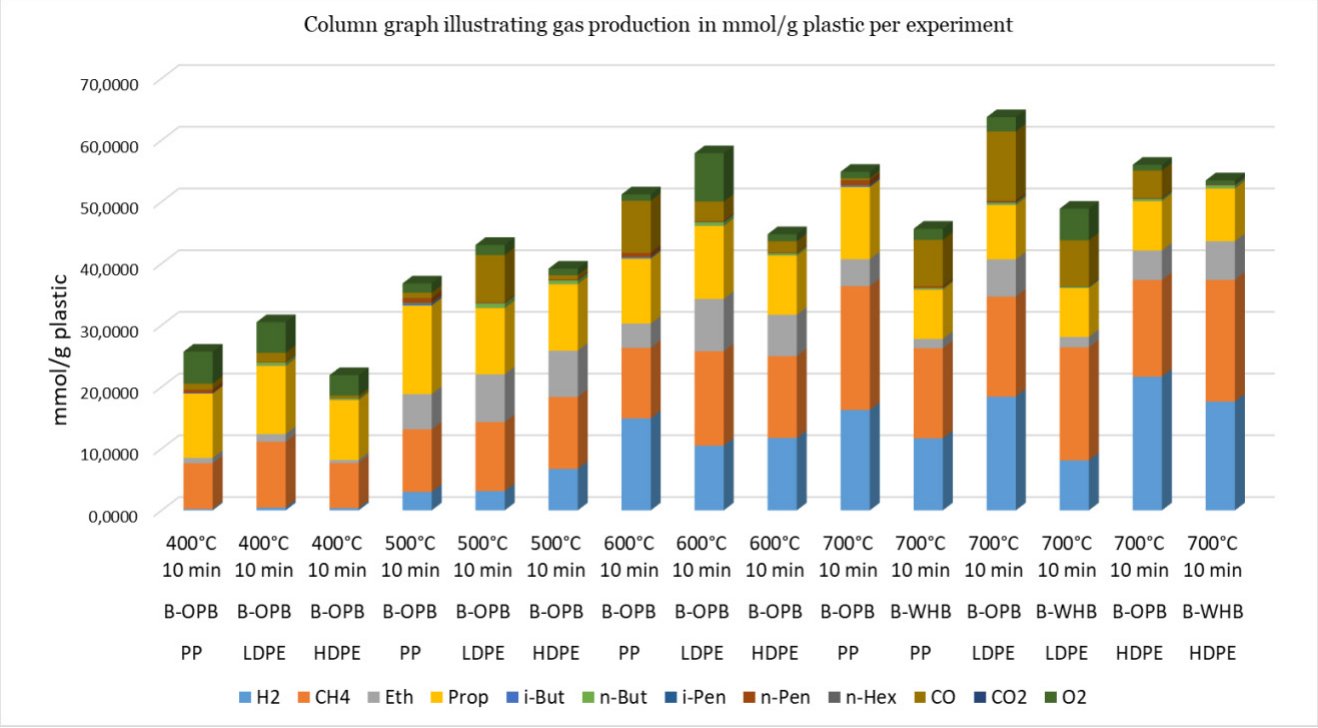


Figure 3. *Column graph - Chemical composition (mmol/g mix plastic + biochar) of gas generated by Microwave Assisted Pyrolysis of plastic waste using biochar as MW absorber.*

4. DISCUSSION/CONCLUSIONS

The present study demonstrated that biochar-assisted microwave pyrolysis is an effective strategy for the thermochemical valorisation of plastic waste into high-value gaseous energy carriers.

Process temperature was identified as the key operating parameter, with the most severe conditions (700 °C and 10 min residence time) providing the highest gas yields, exceeding 60 wt.%, while significantly reducing both solid carbonaceous residue and oil fraction. These results confirm that increasing temperature enhances primary polymer decomposition and promotes secondary cracking reactions, favouring the conversion of compounds into permanent gases. Gas composition analysis showed that HDPE consistently achieved the highest hydrogen and methane yields, regardless of the biochar employed, confirming the strong influence of polymer structure on microwave-assisted co-pyrolysis performance. Although both biochars effectively supported the process, olive pruning biochar generally promoted higher H_2-rich gas production owing to its higher fixed carbon content and lower ash concentration, whereas water hyacinth biochar exhibited satisfactory microwave absorption capacity despite its higher mineral fraction.

An important outcome of this work concerns the role of biochar during the reaction. Solid yield analysis indicated that the residual solid fraction remained close to the initial biochar content, demonstrating that biochar was only marginally consumed during the process. This behaviour, together with the SEM–EDX observations, confirms that biochar primarily acts as a catalytic and adsorptive material, enhancing plastic degradation without undergoing substantial structural degradation. The detection of inorganic elements such as Ca, K and Si further suggests their possible contribution to the catalytic activity observed during pyrolysis. Overall, the results confirm the reliability of microwave-assisted co-pyrolysis as an effective waste-to-energy technology capable of simultaneously valorising plastic waste and residual biomasses. In particular, the successful use of water hyacinth biochar demonstrates the potential for converting an invasive biomass into a valuable process material, further supporting circular economy strategies. Future work should optimise plastic-to-biochar ratios, residence times and operating temperatures while investigating the long-term recoverability and reusability of biochar over multiple operating cycles.

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END-OF-LIFE AIR CONDITIONERS IN ITALY: A MATERIAL FLOW ANALYSIS

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ABSTRACT

Air conditioners are no longer a luxury but a necessity. Driven by rising temperatures, increasing urbanisation, and growing demand for thermal comfort, their diffusion is expected to expand further in the coming years. However, this growth will inevitably lead to increasing volumes of end-of-life appliances requiring effective management. This study develops a dynamic Material Flow Analysis (MFA) for the Italian air conditioning sector, reconstructing system evolution from 1995 to 2024 and forecasting future trends up to 2030. Market data were combined with Weibull lifetime distributions to estimate annual stock and end-of-life flows across domestic and professional systems. Material compositions derived from Environmental Product Declarations (EPDs) enabled the quantification of recoverable materials from appliances and packaging. The results highlight that end-of-life air conditioners represent not only a challenge for waste management, but also a strategic opportunity for resource recovery and the transition towards more circular production systems.

Keywords: Circular economy; Material Flow Analysis; Waste Electrical and Electronic Equipment (WEEE); End-of-life management; Air conditioners; Material recovery; Secondary raw materials.

1. INTRODUCTION

The increasing diffusion of air conditioning systems represents one of the most evident consequences of rising temperatures and the growing demand for thermal comfort. Once considered a luxury technology, air conditioners have progressively become essential components of residential, commercial, and industrial environments. However, the continuous expansion of the installed stock also introduces a significant challenge related to their end-of-life management. Air conditioners are complex products composed of heterogeneous materials, including metals, plastics, electronic components, and refrigerants, whose recovery requires appropriate collection and treatment processes. Within the European framework, Waste Electrical and Electronic Equipment (WEEE) management aims to ensure the proper handling and recycling of discarded products. Nevertheless, collection performances remain insufficient: in 2024, Italy achieved a WEEE collection rate of 29.64%, significantly below the European target of 65%, highlighting the need to strengthen current management systems. [1] From a circular economy perspective, end-of-life air conditioners should be considered not only as waste

requiring treatment, but also as potential sources of secondary raw materials. Identifying when these products will reach the end of their useful life and estimating the associated material flows are essential steps to support future recovery strategies.

To address this challenge, a dynamic Material Flow Analysis (MFA) [2] was developed for the Italian air conditioning sector, combining historical market data with lifetime distributions to estimate future end-of-life flows.

2. METHODS

The methodology was structured into five sequential phases: literature review and data analysis, collection of material composition data, model development, scenario application, and results synthesis. The initial phases allowed the identification of the main variables and assumptions required for the analysis. In particular, Environmental Product Declarations (EPDs) [3] issued by leading global air conditioning manufacturers were analysed to obtain representative information on the material composition of air conditioning equipment and their packaging components. To cover the main types of air conditioning equipment present in the market, EPDs were collected and analysed for different categories of both residential and professional systems. For residential applications, the analysis considered split and mono-split air conditioners and air-cooled chillers with a capacity below 17 kW. For professional applications, the selected categories included Variable Refrigerant Flow (VRF) systems, air-cooled chillers with a capacity above 17 kW, water-cooled chillers, and Air Handling Units (AHUs). Several EPDs were analysed for each product category, covering different manufacturers and product configurations where available. The material composition reported in the EPDs was extracted and analysed separately for each product category. The data obtained from the different EPDs were then aggregated to derive an average material composition for each category. This approach allowed variability among individual products and manufacturers to be considered while avoiding the adoption of a single product as representative of an entire market segment. The resulting average compositions were subsequently incorporated into the model as category-specific material inventories, allowing the quantities of individual materials associated with appliances and packaging reaching the end-of-life stage to be estimated. The core of the methodology consists of a dynamic Material Flow Analysis based on a sales-stock-flow model [4]. As illustrated in Figure 1, the model starts from the annual Placed on the Market (POM) data collected by Assoclima for the Italian air conditioning sector, covering the period 1995–2024, with forecasts extending up to 2030.

These data represent the inflow of new appliances entering the system. [5]. The estimation of end-of-life flows is obtained by combining POM data with product lifetime distributions.

Weibull distributions were developed separately for residential and professional air conditioners to represent the probability of products reaching their end of life over time. [6][7]. The distributions were calibrated using median lifetime values of 15 and 20 years, respectively, based on ASHRAE references. [8]

The resulting lifetime profiles enable the estimation of annual WEEE flows by determining the proportion of appliances placed on the market in previous years that are expected to reach the end-of-life stage in each year of the modelling period.

The in-use stock is then calculated through a mass balance approach, considering the previous year's stock, new products entering the system, and units reaching their end of life.

This allows the model to dynamically track the evolution of the installed stock over time while maintaining consistency between inflows, stock variations, and outflows. The estimated WEEE flows are finally combined with the average material compositions derived from the EPD analysis to quantify the material flows potentially available at the end-of-life stage of air conditioning equipment. By integrating the number of units reaching the end of their life with the average material composition and weight distribution of the different product categories, the model estimates the annual quantities of materials associated with end-of-life appliances and, where applicable, their packaging.

The resulting material flows are classified into different categories, including metals, plastics, electronic components, and packaging materials. This approach allows the evolution over time of the material resources potentially available for recovery to be assessed and provides a basis for evaluating the resource recovery potential associated with alternative collection, treatment, and recycling strategies.

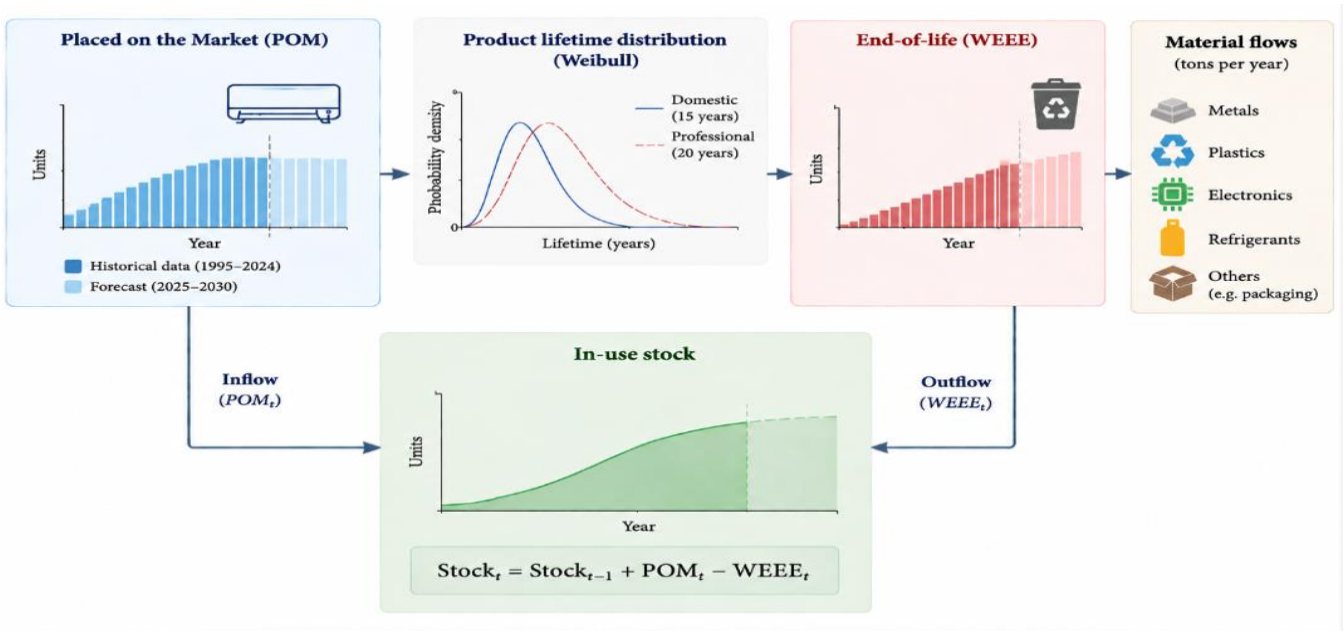


Figure 1. *Dynamic material flow model for estimating end-of-life air conditioners and associated material flows.*

3. FINDINGS

The developed model allows the evolution of the Italian air conditioning sector to be reconstructed by estimating the installed stock, the generation of end-of-life flows, and the associated material potential. As shown in Figure 2, the results highlight a continuous growth of the installed stock for both domestic

and professional systems, reflecting the increasing relevance of air conditioning technologies over recent decades. In particular, professional systems show a significant increase in installed stock, indicating the growing adoption of high-capacity solutions required to address rising cooling demand in commercial, industrial, and service environments. This trend is driven by the increasing need for thermal comfort and the growing impact of higher temperatures on buildings and infrastructures. At the same time, the progressive increase in WEEE generation reflects the delayed effect of past market expansion, as appliances introduced into the system progressively reach the end of their useful life.

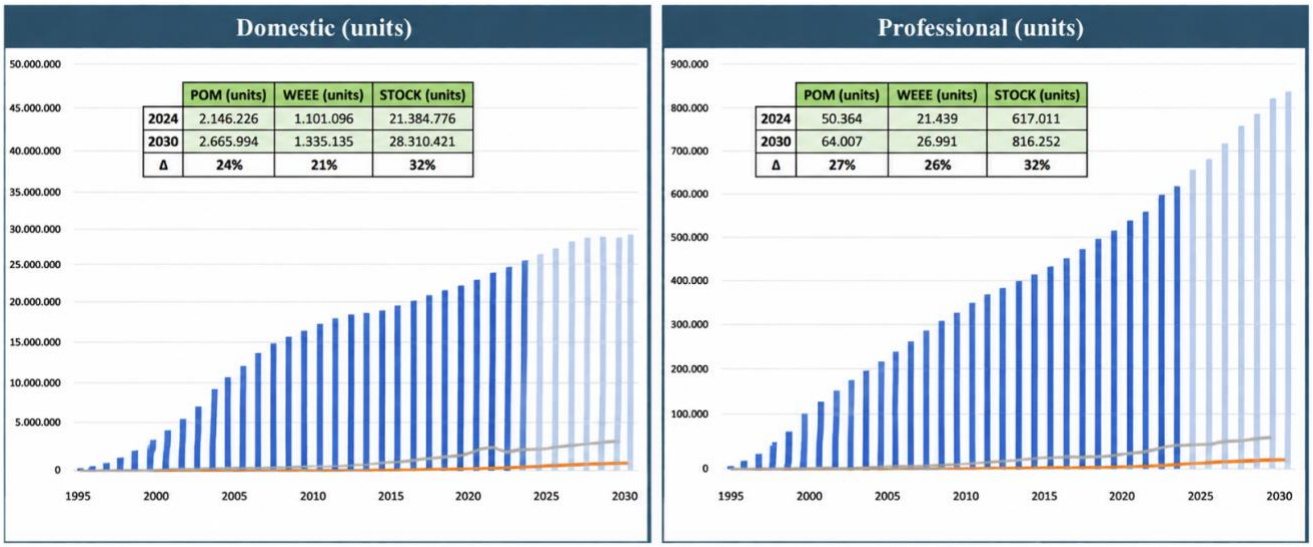


Figure 2. *Temporal evolution of domestic and professional air conditioning systems in Italy.*

The estimated material flows reported in Figure 3 highlight the significant quantity and variety of resources embedded in end-of-life air conditioners. Metals represent the largest share of recoverable materials, with steel accounting for the predominant fraction, followed by relevant quantities of copper and aluminium, which are particularly valuable due to their high recyclability and industrial demand. Beyond metals, the analysis also identifies significant flows of plastics, including materials such as ABS, polypropylene (PP), polyethylene (PE), and other technical plastics used in structural components, covers, and internal parts of air conditioning units. Additional material streams include electronic components, elastomers, paper/cardboard, and wood associated with packaging systems. These results highlight the potential of end-of-life air conditioners as urban mining sources, where discarded products can become reservoirs of secondary raw materials rather than simple waste streams.

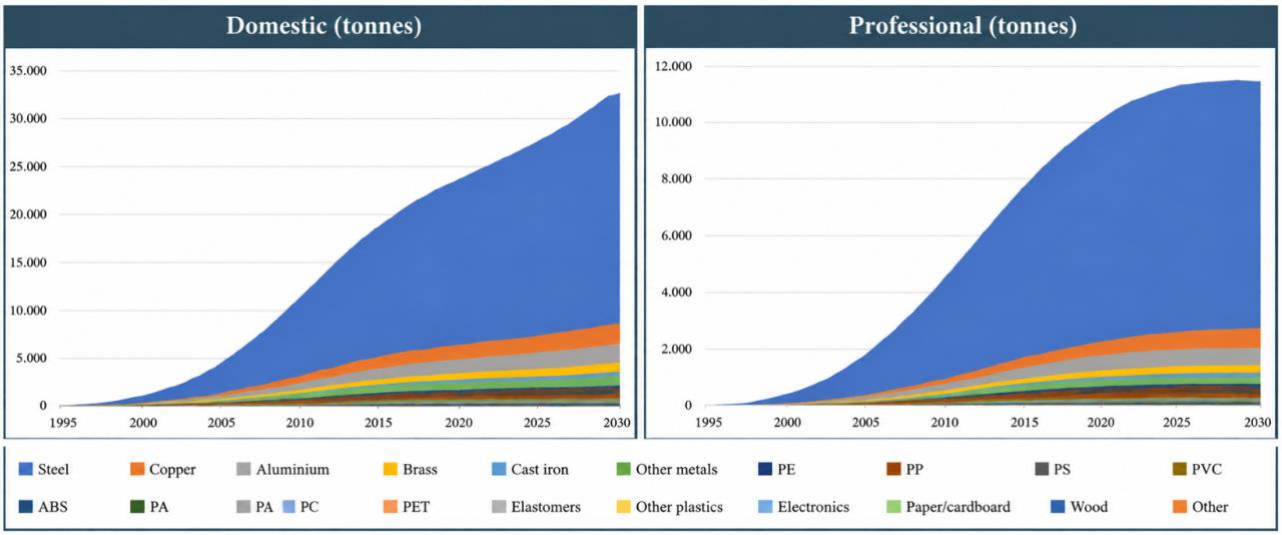


Figure 3. *Estimated material flows contained in end-of-life domestic and professional air conditioners.*

Among the identified material flows, steel represents the most relevant fraction in terms of potential recovery. To better illustrate the magnitude of this resource opportunity, a specific example can be considered. In 2024, the quantity of steel potentially recoverable from end-of-life air conditioners was estimated at 36,888 tonnes. Although this amount represents only 0.12% [9] of the total Italian steel production in the same year, its relevance becomes more evident when translated into practical terms: considering an average vehicle weight of 1,500 kg, this quantity of steel could theoretically support the production of approximately 24,500 cars. [10] This comparison highlights how material flows that may appear limited when compared with national production volumes can still represent significant opportunities for circular resource recovery and contribute to reducing the demand for virgin raw materials.

4. DISCUSSION/CONCLUSION

The analysis highlights that the future management of end-of-life air conditioners represents a relevant challenge for the transition towards a circular economy. The ability to anticipate future material flows is essential to design effective recovery strategies and prevent the loss of valuable resources before these products reach the end of their life cycle. However, the identification of a significant recovery potential is only the first step towards circularity: its effective exploitation depends on the ability to develop efficient collection systems and strengthen the entire reverse supply chain. This transition requires the coordinated involvement of all stakeholders engaged in the end-of-life pathway. Retailers and installers play a crucial role as key points of contact during replacement activities, facilitating the interception of obsolete equipment and its correct routing towards treatment facilities. [11] At the same time, collection systems and consortia are essential to ensure appropriate management processes and maximise material

recovery. Alongside these operational aspects, increasing awareness among consumers and operators remains fundamental to encourage responsible disposal behaviours and improve collection performance. The sustainable management of end-of-life air conditioners should therefore be regarded not merely as a waste treatment issue, but as an opportunity to redesign material flows and preserve valuable resources within productive cycles. Turning this potential into tangible circular benefits requires a shared commitment across the entire value chain, where technological solutions, effective recovery infrastructures, and stakeholder collaboration converge towards a more resource-efficient and sustainable future.

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ROSINWOOD TURNING KRAFT PROCESS BY-PRODUCTS INTO VALUE THROUGH A FULLY NATURAL BIOCOMPOSITE FOR CIRCULAR FURNITURE

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ABSTRACT

The transition toward a circular economy demands the research of alternatives to fossil-based composites. This study presents the development of RosinWood, a novel, 100% natural and 96% bio-based thermoplastic biocomposite. Utilizing unexploited by-products from the Kraft paper industry, the material employs tall oil rosin as the polymer matrix and wood flour as the filler. To overcome rosin's inherent brittleness and low thermal stability, the formulation was optimized using calcium carbonate (5 wt%), linseed oil plasticizer (5 wt%), and a mild alkaline treatment ($NaHCO_3$) for the wood flour (20 wt%). The resulting biocomposite exhibits excellent processability at low temperatures (~150°C), minimal water absorption (<1.65% after 24h) and high hydrophobicity. RosinWood's thermoplastic nature enables complete reprocessability, formability and self-healing capabilities. This innovation validates a zero-waste approach, transforming industrial by-products into a high-value, sustainable structural material suitable for circular furniture design, particularly thermoformable seat shells and furniture repair systems.

Keywords: By-products valorisation; circular biocomposite; green biocomposite; furniture; reprocessable; repairing; rosin; wood flour.

1. INTRODUCTION

The current model of production and consumption has led to a constant increase in the amount of waste, generating increasingly complex environmental issues, especially with regard to the difficult treatment of certain types of waste. Among these, composite materials represent one of the most urgent challenges [1], as separating their constituent phases is complex, particularly when these phases do not share the same end-of-life pathway. While biocomposites have emerged as a promising, sustainable alternative, the vast majority still rely on fossil-based thermosetting matrices, such as epoxy or phenolic resins, which render the final material non-recyclable and only partially bio-based [1–2]. The composites' matrix is therefore crucial not only for material performance and processing, but also for circularity and end-of-life strategies [3-4]. The core innovation of this research lies in the complete elimination of fossil-derived matrices through the valorisation of secondary waste streams from the Kraft paper industry.

During the Kraft pulping process, approximately 55-60% of the initial wood material is generated as lignocellulosic waste, while the extraction of black liquor yields Crude Tall Oil (CTO). From CTO, rosin, a highly abundant, biodegradable, and chemically reactive natural resin—can be distilled [5]. Despite its vast potential, rosin is primarily utilized as an additive rather than a structural matrix due to its inherent brittleness and relatively low glass transition temperature (Tg). This study aims to overcome these limitations, developing a 100% natural, fully circular thermoplastic biocomposite using rosin as the matrix and wood flour as the filler. By exploiting these two synergic by-products of the same industrial supply chain, this research presents a material developed specifically for the furniture sector, promoting repairability, self-healing and end-of-life reprocessability.

2. METHODS

The research was organised into three interconnected phases: preliminary research, experimental material development and application-oriented design. In the preliminary phase, biocomposites, natural matrices, fillers and circularity principles were analyzed through case studies to define material requirements and a target application sector. The experimental phase was structured in progressive steps where each one addressed a specific limitation identified in the previous one, and maximised bio-based content, while designed according to Green Chemistry objectives [6]. The process included: (1) rosin chemical modification; (2) fillers addition; (3) natural plasticiser addition; (4) wood alkaline treatment; (5) final formulation; (6) testing. The last phase identified the furniture sector as application, as it balances mechanical performance, durability and opportunities for repair, reuse and recycling.

2.1 Raw materials

The matrix consisted of natural rosin (R), while pine sawdust sourced from timber processing was utilized as the primary reinforcing filler. To improve thermal stability and mitigate the natural stickiness of rosin, calcium carbonate ($CaCO_3$) (CC) was introduced as an inorganic, natural volumetric filler [7]. Linseed oil (OI) was added as a natural plasticizer to reduce matrix viscosity, improve the dispersion of the wood flour, and reduce the formation of internal voids [8].

2.2 Fiber treatment

To enhance interfacial adhesion between the hydrophilic wood fibers and the hydrophobic rosin matrix, a sweet alkaline treatment with a 10% aqueous solution of sodium bicarbonate ($NaHCO_3$) was applied. The sawdust was soaked in the solution at a 1:5 weight ratio, heated at 80°C for 3-4 hours, then washed, dried and ground into treated wood flour (WFak) (<300 µm). This method effectively removes surface impurities and increases surface roughness without degrading the cellulose structure [9, 10, 11].

2.3 Processing and formulations

The material samples were achieved via a melt-mixing process. The solid components were mechanically mixed at room temperature at different ratio, defined after the literature review research and optimised step by step (Figure 1). Linseed oil was added directly to the treated wood flour to enhance interaction. The dry mixture was then transferred to a preheated silicone mold to minimise premature solidification and thermal gradients on a hot plate at 150°C (to avoid the risk of degradation of lignocellulosic components). The compound was stirred vigorously until a homogeneous molten, then allowed to cool and polymerize at room temperature for 24-48 hours. The final composition of the obtained material is detailed in Table 1.

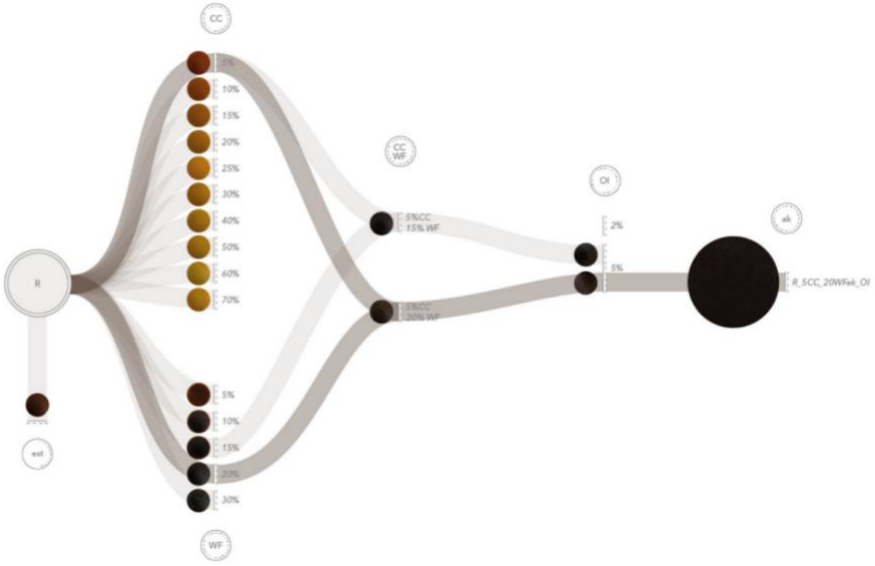


Figure 1. *RosinWood: steps of the experimentation process. Source: Author's elaboration.*

Component	Role in biocomposite	Reference proportion	Total mass (%)
Rosin (R)	Thermoplastic matrix	-	~79.37%
Treated wood flour (WFak)	Organic reinforcement	20% of R	~15.87%
Calcium carbonate (CC)	Inorganic thermal stabilizer	5% of R	~3.97%
Linseed oil (OI)	Natural plasticizer	5% of WF	~0.79%

Table 1. *RosinWood final composition. Source: Author's elaboration based on the experimental results.*

2.4 Materials' testing

The resulted material was subjected to qualitative and semi-quantitative tests addressing the properties considered relevant to the intended applications. Deformability was evaluated by reheating previously produced samples and observing their ability to soften and undergo further shaping. Repairability and

reprocessability were investigated in two ways: (1) broken fragments of a previously produced sample were reheated until they fused again into a single piece; (2) a sample was mechanically reduced to powder and subsequently remoulded. Sanding was evaluated as a finishing operation for removing surface imperfections and refining edges. Water absorption was investigated according to the experimental procedure based on Method 1 of EN ISO 62:2008. The thesis did not include a complete quantitative mechanical characterisation according to standard tensile, compression and flexural testing protocols. Consequently, the mechanical performance discussed here is based on the experimental observations and supporting literature rather than on a complete standardised mechanical dataset.

3. FINDINGS

3.1 Progressive development of the biocomposite

The experimental work demonstrated that rosin's properties could be optimized via a formulation-based approach after chemical modification proved ineffective at addressing brittleness and low thermal stability. Wood flour provided an initial mechanical improvement, with 15–20 wt% chosen as optimal and 30 wt% established as the practical upper limit due to poor processability and defect formation [12]. Experimental observations and supporting literature indicated that adding 5 wt% calcium carbonate reduced rosin stickiness and enhanced thermal and mechanical stability while preserving bio-based content, avoiding the agglomeration and longer processing times seen at higher levels [7]. Linseed oil served as a natural plasticiser, reducing void formation, shortening processing times and ensuring a more uniform dispersion of the reinforcement [8]. The alkaline treatment applied to the wood flour increased the contact surface area and enhanced interfacial bonding between the hydrophilic fibres and the hydrophobic rosin, yielding the final formulation designated as R_5CC_20WFak_OI [9–11] (Figures 2, 3, 4).







***Figures 2, 3, 4* (from left to right).** (2) Sample preparation during the experimental phase. Source: Picture taken by the author. (3) R_5CC_20WFak_OI final sample. *Source: Picture taken by the author. (4) Main steps samples and final RosinWood sample collection. Picture taken by the author.*

3.2 Processability and circular functionality

RosinWood demonstrated excellent thermoplastic properties. Processability tests confirmed the material's formability: post-production samples could be reheated to ~80-90°C and reshaped without structural degradation. Crucially, the material exhibited selfhealing and total reprocessability; fractured samples were completely reconstituted by remelting the fragments into a unified block. The thesis estimates that 1 tonne of black liquor could theoretically yield up to approximately 240 kg of rosin and up to approximately 300 kg of RosinWood. These values indicate the potential magnitude of the resource stream, although actual implementation would depend on rosin recovery efficiency, purity, collection logistics, wood-flour processing and associated costs [13–14].

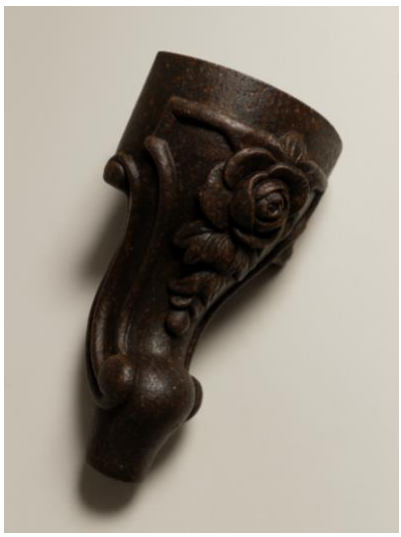
3.3 Water absorption

The analysed samples exhibited a negligible weight increase (1.65%, 1.035%, 0.436%). These values are very low compared to wood, which can absorb up to 30% of its mass in water [15]. This is a highly relevant result, as water sensitivity is a common limitation of lignocellulosic biocomposites, because it often compromises dimensional stability and long-term performance through moisture uptake [16]. In RosinWood, the encapsulation of the wood flour within the rosin matrix substantially mitigates this effect under the tested conditions. The marginal weight increase observed may be attributed either to particles exposed on the surface or to structural defects, such as air voids, which could have facilitated the penetration or entrapment of trace amounts of water. Nevertheless, these results should be interpreted as an initial characterization rather than a comprehensive durability assessment.

3.4 Application potential

The experimental results were translated into two application concepts within the furniture sector. The first is a thermoformable seat shell. The concept exploits the material's low-temperature deformability by proposing a flat shell that can be transported in a compact configuration and subsequently formed on the supporting structure (Figure 5). Such an approach can potentially reduce transport volume while retaining the possibility of future reprocessing. The second is a furniture repair system. RosinWood can potentially be supplied as powder, pellets or small fragments for the repair of cracks, fractures or damagedcomponents (Figures 6, 7). Heat can be supplied by relatively simple equipment, such as a heatgun or iron, making the concept compatible with distributed repair contexts such as FabLabs or DIY environments.





Figures 5, 6, 7 (from left to right). *(5) Thermoformable seat shell concept application. Source: Author's render. (6) RosinWood sample and prototypes of the developed concepts. Source: Picture taken by the author. (7) Cast of a wooden furniture leg to be restored. Source: Picture taken and edited by the author.*

4. CONCLUSIONS

This research successfully developed RosinWood, demonstrating that industrial by-products from the Kraft process can be transformed into high-value, 100% natural, and predominantly (96%) bio-based structural biocomposites. The iterative formulation confirmed that overcoming the inherent brittleness of rosin requires a synergistic design rather than a single intervention. RosinWood achieved a balanced profile of rigidity, flexural performance and surface finish, aligned with Green Chemistry metrics through mild, non-hazardous processing. Furthermore, its inherent thermoplasticity imparts intrinsic self-healing capabilities, low temperature reprocessability and easy post-forming. These characteristics make the material particularly well-suited for circular furniture applications. The low processing temperatures (well below the 200°C threshold of lignocellulosic degradation) enable energy-efficient fabrication, decentralized manufacturing models, flat-pack thermoformable seat shells, and localized repair strategies through FabLabs or distributed maintenance frameworks. Nevertheless, key limitations must be acknowledged. Laboratory-scale preparation via hot plates restricted thermal uniformity, underscoring the need for controlled convective heating or continuous processing equipment. From a thermal standpoint, the low glass transition temperature (Tg) restricts deployment under elevated service temperatures (>80-90°C). Future investigations must focus on tensile, flexural and impact testing, alongside the validation of industrial transformation routes such as extrusion and thermoforming. Comprehensive lifecycle assessments will also be essential to substantiate the environmental net benefit of this valorization pathway. Ultimately, RosinWood offers a viable blueprint for circular material development, embodying a closed-loop circular economy paradigm.

By synergistically combining two distinct waste streams from the same industrial ecosystem, it offers a scalable, low-tech and zero-waste alternative to traditional synthetic polymers, paving the way for truly regenerative material design.

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ENVIRONMENTAL STUDY OF CONCRETE WITH RECYCLED CONCRETE AGGREGATES & RECYCLED PLASTIC FIBRES

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ABSTRACT

The construction sector is responsible for approximately 36% of final energy consumption and 39% of CO_2 emissions, while contributing about 5.5% of the European Union's GDP. Its high use of non-renewable resources and generation of construction and demolition waste requires circular economy practices [1]. This study evaluates the feasibility of mixing recycled concrete aggregates derived from construction and demolition waste and recycled plastic fibres recovered from food packaging industry into concrete. Environmental safety of aggregates is analysed through compliance, percolation, and commercial-scale percolation leaching tests, with eluates analysed using inductively coupled plasma mass spectrometry and ion chromatography. Concrete mixtures that contain recycled aggregates and plastic fibres were compared with the controlled concrete sample, focusing on rheological behaviour, mechanical performance, and environmental impact. The study focuses to satisfy safety and performance requirements while conserving resources, reducing waste, and advancing sustainable concrete production within a circular economy.

Keywords: CDW (Construction & Demolition Waste); Circular Economy; RCA (Recycled Concrete Aggregates); Plastic Fibres;

1. INTRODUCTION

The construction sector is a major driver of economic development, accounting for approximately 5.5% of the European Union's gross domestic product [1]. However, its economic importance is accompanied by considerable environmental pressures. The sector is responsible for approximately 36% of global final energy consumption and 39% of energy and process-related carbon dioxide emissions. It also requires substantial quantities of land, water, energy, and non-renewable raw materials [2]. Concrete production contributes significantly to these impacts because energy is required during raw-material extraction, processing, transportation, mixing, placement, and curing. Much of this energy continues to originate from non-renewable sources, increasing the embodied carbon and overall environmental footprint of concrete construction [2]. Reducing the consumption of virgin resources and increasing the use of

secondary materials have therefore become important priorities in the transition toward a low-carbon and resource-efficient construction sector.

Global consumption of non-metallic minerals, including construction materials, is projected to increase from approximately 35 billion tonnes in 2011 to 82 billion tonnes by 2060 [1]. Under these conditions, continued dependence on virgin materials is environmentally unsustainable and may create long-term 932supply constraints. Research and innovation are therefore required to identify technically reliable alternatives that can conserve natural resources without compromising the safety, durability, or performance of construction materials. The circular economy provides a framework for addressing these challenges by replacing the conventional "take-make-dispose" model with strategies based on waste prevention, reuse, recycling, recovery, and extended material lifecycles [3]. In Europe, construction continues to depend predominantly on virgin resources, with only approximately 10.6% of material inputs originating from recycled or reused sources. Furthermore, nearly 70% of recovered construction materials are directed toward low-value applications, such as backfilling and filling operations, rather than being reincorporated into higher-value products for structural or nonstructural construction [4]. Although these recovery practices can reduce disposal, they do not fully preserve the functional and economic value of the original materials. The development of closed-loop applications in which recovered materials are returned to concrete production is therefore essential for improving resource efficiency and advancing circularity within the architecture, engineering, and construction sector [4]. Construction and demolition waste (CDW), including concrete, masonry, ceramics, metals, glass, plastics, and other discarded building materials, represents an important source of secondary raw materials [5]. In addition to determining physical properties such as particle-size distribution, density, and water absorption, it is necessary to assess chemical composition and contaminant-release behaviour to ensure that recycled materials do not create unacceptable environmental or health risks during their service life or subsequent end-of-life management.

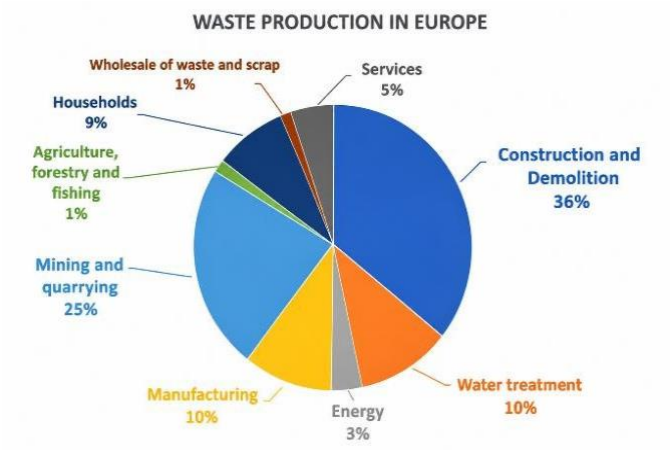


***Figure 1**. Waste generation in Europe by source, 2022 [2]*

Plastic waste represents another growing environmental concern, particularly in the food-packaging industry, where multilayer and single-use products can be difficult to recycle through conventional processes. Converting suitable plastic waste into fibres for concrete reinforcement provides an alternative route for extending its useful life and reducing disposal. Recycled plastic fibres may therefore be advantageous in applications of crack control, ductility, and residual strength regardless of compromising on compressive strength. Despite increasing interest in RCAs and recycled plastic fibres, important research gaps remain. Against this background, the present study investigates the feasibility of producing concrete containing RCAs obtained from processed CDW and recycled plastic fibres derived from food packaging waste. The research combines physical characterization, environmental assessment, and concrete performance testing. Environmental behaviour is evaluated through compliance and laboratory column-percolation test. The resulting eluates are chemically characterized using inductively coupled plasma mass spectrometry and ion chromatography to quantify the release of relevant inorganic constituents. Concrete mixtures produced with natural aggregates, partial RCA replacement, and a combination of RCAs and recycled plastic fibres for its compressive strength.

The principal objective is to determine whether these recycled materials can replace conventional concrete constituents while satisfying technical and environmental requirements. By identifying both the benefits and limitations associated with RCAs and recycled plastic fibres, the research supports the development of higher value applications for construction and plastic waste, reduces dependence on virgin resources, and contributes to closing material loops within the construction sector.

2. METHODS

An experimental laboratory study was conducted to evaluate the technical and environmental feasibility of incorporating recycled concrete aggregates (RCAs) and recycled plastic fibres into concrete. The methodology comprised three stages: (i) physical characterization of the natural and recycled aggregates, (ii) assessment of the environmental behaviour of the recycled materials through leaching tests, and (iii) evaluation of the fresh-state and mechanical performance of concrete mixtures containing recycled materials. The primary data sources were the measurements obtained from laboratory tests performed on the constituent materials, eluates, fresh concrete, and hardened concrete specimens were obtained from a CDW treatment plant and a precast concrete plant. Recycled food-packaging plastic was cut into fibres measuring approximately 50 × 5 mm and incorporated at 2 kg/m^3. CEM III/A blast-furnace cement, filler, VC 90 NG viscosity-modifying admixture, and Rapid 104R accelerator were also used. Representative samples were collected and reduced according to EN 933-1 [11]. RCA composition was determined for particles larger than 4 mm. Particles were manually classified as concrete and mortar, natural stone, ceramics, asphalt, glass, or other materials, and each fraction was expressed as a percentage of total mass. Particle density and 24-h water absorption were determined using the pycnometer method according to EN 1097-6:2013 [12].

Samples were immersed at approximately 22 °C for 24 h and weighed under saturated-surface-dry and oven-dried conditions. Particle-size distribution was determined by washing and sieving according to EN 933-1:2012 [11]. Samples were dried at (110 ± 5)°C, immersed for 24 h, washed over a 0.063-mm sieve, dried, and passed through sieves of decreasing aperture. The retained masses were used to calculate the cumulative percentage passing.

The environmental behaviour of the aggregates was evaluated using two methods: the Compliance Leaching Test according to European Commission "EN 12457-4 [13] and the Percolation Leaching Test European Commission "EN 14405:2017 [14]. In the Compliance Leaching Test, aggregate samples were mixed with demineralized water at a liquid-to-solid ratio of 10 L/kg and agitated for 24 h. In the Percolation Leaching Test, compacted aggregates were placed in a laboratory column and exposed to an upward flow of demineralized water, with eluates collected at different liquid-to-solid ratios. The eluates obtained from both tests were filtered and chemically analysed to determine the release of metals and anions under different exposure conditions. The eluates obtained from the compliance and percolation tests were analysed for regulated metals and inorganic anions. Metal concentrations were determined using inductively coupled plasma mass spectrometry (ICP-MS) [6]. Anion concentrations, including chloride and sulphate, were determined by ion chromatography [7].

Three principal concrete mixtures were prepared: a control mixture containing natural aggregates, a mixture containing 20% RCA, and a mixture containing 20% RCA and recycled plastic fibres at 2 kg/m^3. Compressive strength was determined according to EN 12390-3 [8]. Three cubic specimens from each mixture were tested after 1, 7, and 28 days of curing. Each specimen was positioned in a calibrated compression testing machine and subjected to a continuously increasing uniaxial load until failure.

3. FINDINGS

The physical classification shows that the recycled aggregates were composed predominantly of concrete, mortar, and natural stone. The aggregate obtained from the construction and demolition waste (CDW) treatment plant contained 63.5% concrete particles and 35.2% natural stone, whereas ceramics, asphalt, and other materials represented only 1.2% of its composition. The recycled aggregate from the precast concrete plant contained 73.8% natural stone and 25.0% concrete particles, with negligible quantities of ceramics and other impurities.

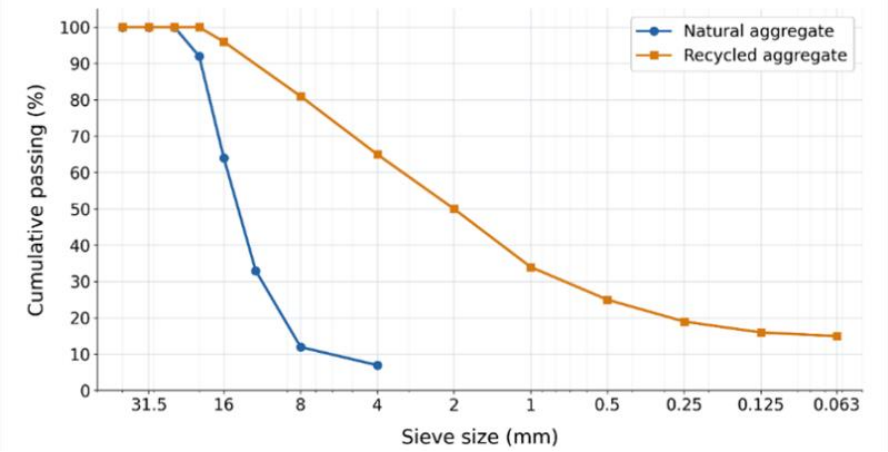


Figure 2. *Particle-size distributions of natural and recycled aggregates*

The grading results show that 100% of the material passes the 25 mm and above sieve, confirming the absence of oversize particles. The coarse fraction is dominant, with 92% passing the 20 mm sieve and 64% passing the 16 mm sieve, indicating a concentration of particles in the upper size range. The proportion of intermediate sizes (8–16 mm) is relatively small, as only 33% passes the 12 mm sieve and 12% passes the 8 mm sieve. The fine fraction (<4 mm) is minimal, with just 7% passing the 4 mm sieve, suggesting a very low content of small particles and fines. The particle size distribution shows that the Precast Concrete Plant recycled aggregate contains a wide range of sizes, with all material passing the 20 mm sieve and 96% passing the 16 mm sieve, indicating the absence of oversized particles. The distribution is balanced between coarse and fine fractions: 82% passes the 8 mm sieve, 65% passes the 4 mm sieve, and 50% passes the 2 mm sieve. The finer sand fraction is also well represented, with 34% passing 1 mm, 25% passing 0.5 mm, and 19% passing 0.25 mm. The fines content (<0.063 mm) is 14%, which is higher than typical for natural aggregates but is common in recycled concrete aggregates due to the presence of adhered mortar and micro-fragments generated during crushing.

All the results of leaching tests were compared with the limits given in Spain Royal Decree 646/2020 and Directive (EU) 2018/850 [9,10]. The EN 12457-4 batch leaching tests showed that the CDW-derived aggregates generated alkaline eluates, and all measured parameters were below the applicable inert-waste acceptance limits. The recycled aggregate from the precast plant also produced alkaline batch-test eluates but all the values were within inert range**.** The Column Percolation tests produced higher initial releases of selected elements than the batch tests. At a liquid-to-solid ratio of 0.1 L/kg, chromium concentrations in the CDW-derived aggregates ranged from 0.105 to 0.382 mg/kg, exceeding the inert limit of 0.1 mg/kg. Molybdenum slightly exceeded its inert limit in one sample, while lead exceeded the inert criterion in another. For the precast RCA, molybdenum concentrations ranged from 0.227 to 0.499 mg/kg, and chromium reached 0.165 mg/kg in one sample.

Although these values prevented complete inert classification, they remained below the non-hazardous acceptance limits.

Concentrations of chromium, molybdenum, copper, chloride, and sulphate generally decreased in successive column-test eluates as the liquid-to-solid ratio increased. These recycled aggregates were incorporated in concrete sample. The details of the samples are given in the table below.

Table 1. *Concrete mix specification*

Concrete sample	Cement type	Natural aggregate replacement	Plastic fibre addition	Water-cement ratio
Control concrete	CEM III/A	0%	None	0.60
Recycled aggregate concrete	CEM III/A	20% recycled aggregate	None	0.62
Recycled aggregate concrete with plastic fibres	CEM III/A	20% recycled aggregate	2 kg/m³	0.62

The control concrete reached mean compressive strengths of 19.48, 34.91, and 38.89 MPa after 1, 7, and 28 days, respectively. The mixture containing 20% RCA achieved corresponding strengths of 16.34, 31.68, and 38.82 MPa. RCA incorporation therefore reduced early-age strength, but its 28-day strength was practically identical to the control value. The mixture containing 20% RCA and 2 kg/m^3 of recycled plastic fibres achieved strengths of 14.32, 25.16, and 31.16 MPa at the same ages. The fibre reinforced mixture consequently exhibited a 19.9% reduction in 28-day compressive strength relative to the control.

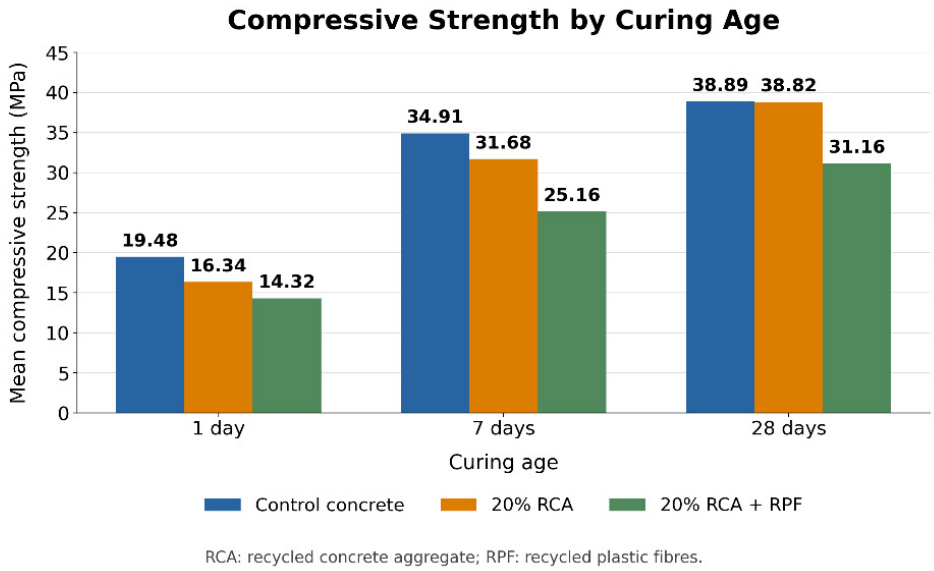


Figure 3. *Compressive Strength of concrete samples [2]*

4. CONCLUSION

The Compliance Leaching Test generally produced lower elemental concentrations than the Percolation Leaching Test, which better represented long-term exposure through continuous water flow. Most measured parameters met the criteria for inert materials, although chromium and molybdenum occasionally exceeded the inert thresholds because of their presence in the source materials and the highly alkaline conditions created by residual cement paste. Nevertheless, all concentrations remained below the limits for non-hazardous materials. Successive percolation eluates showed decreasing metal and salt concentrations, electrical conductivity, and total dissolved solids, indicating that the greatest release occurred during initial contact with water and declined over time.

The concrete test results confirmed that replacing 20% of the natural aggregate with recycled aggregate (RA) was technically feasible, as the mixture achieved a 28-day compressive strength comparable to that of the control concrete. Adding recycled plastic fibres reduced workability and compressive strength, but the resulting concrete remained potentially suitable for selected structural and non-structural applications. This reduction may be acceptable when fiber related improvements in toughness, crack resistance, and post-cracking performance are required, particularly where durability and sustainability are prioritized. Their use provides a higher-value recovery pathway for construction, demolition, and plastic waste while reducing dependence on virgin materials. Further research should evaluate other CDW-derived aggregates, RA replacement ratios of 10-30%, fibre dosages of 4-6 kg/m^3, and mechanical properties such as flexural strength, toughness, and residual post-cracking resistance.

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CIRCULAR PRODUCTS AND PACKAGING DESIGN

TECHNICAL EVALUATION OF REPLACEMENT A MULTILAYER LAMINATED FILM WITH A RECYCLABLE POLYPROPYLENE FILM FOR PACKAGING OF LEGUMES, CEREALS AND SEEDS

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ABSTRACT

The increasing emphasis on the circular economy has driven the development of food packaging designed according to Design for Recycling principles, combining technological performance with recyclability. Flexible multilayer films provide excellent mechanical and barrier properties; however, their multi-material structure significantly limits their recyclability. This study evaluates, through an industrial case study, the replacement of a conventional multilayer laminated film with a recyclable mono-material polypropylene (PP) film intended for the packaging of legumes, cereals, and seeds. Experimental validation was carried out under industrial operating conditions by assessing processability, sealing performance, package integrity, and the ability of the new material to preserve product quality during storage under Modified Atmosphere Packaging (MAP). The results demonstrate that the recyclable film provides satisfactory industrial processing and preservation performance while improving packaging recyclability, thus providing a practical solution to support the transition toward more sustainable food packaging systems.

Keywords: Food packaging; Multilayer flexible film; Mono-material polypropylene film; Shelf life; Design for Recycling

1. INTRODUCTION

Food packaging plays a fundamental role in preserving food quality and safety by extending shelf life and protecting products during distribution and commercialization. To meet these requirements, the flexible packaging industry has extensively adopted multilayer laminated films, consisting of different polymeric materials combined to achieve high mechanical strength, reliable sealability, and effective barriers against oxygen and water vapour transmission [1].

Despite their excellent functional performance, multilayer films present significant environmental sustainability challenges. Because different materials are permanently bonded together, they are difficult

to separate during mechanical recycling, limiting their recovery as secondary raw materials and reducing recycling efficiency [1], [2]. In this context, Design for Recycling strategies promoted by European policies and national consortia, including CONAI, encourage the development of packaging specifically designed to be readily recyclable without compromising the performance required for industrial applications [2].

Among the most promising alternatives are mono-material polypropylene (PP) films, developed to combine recyclability with high technical performance. Recent technological advances have enabled these materials to provide mechanical and barrier properties approaching those of conventional multilayer laminates, making them attractive candidates for food packaging applications [3].

Within this framework, the present study describes the technical and experimental evaluation of replacing a conventional multilayer laminated film with a recyclable mono-material polypropylene film for packaging legumes, cereals, and seeds. Figure 1 compares the structure of the conventional multilayer laminate with that of the new mono-material PP film investigated in this work. The objective of the study was to assess whether the new material could ensure the required performance during industrial packaging while preserving product quality throughout storage under MAP, thereby improving packaging recyclability and supporting the transition toward circular economy models [3]-[5].



Figure 1. *Comparison between the conventional multilayer laminate and the recyclable mono-material polypropylene (PP) film investigated in this study (adapted from SDR S.p.A. technical documentation [5]).*

2. METHODS

2.1 Experimental estimation of the oxygen permeability coefficient

Experimental trials were carried out under real industrial production conditions using vertical form-fill-seal (VFFS) packaging lines dedicated to packaging legumes, cereals, and seeds in different package formats. The mono-material polypropylene film was tested while maintaining the operating conditions used for the conventional laminate whenever possible the same operating conditions used for the conventional multilayer laminate, with only minor optimization of the sealing parameters to ensure proper processability. Seal quality was assessed by means of a bubble test, whereas changes in the modified atmosphere were monitored through periodic measurements of oxygen (O_2) and carbon dioxide (CO_2) concentrations in the package headspace using a Dansensor CheckMate 4 gas analyzer.

The resulting experimental data were used to validate the theoretical shelf-life prediction model and compare the performance of the mono-material film with that of the conventional multilayer laminate.
The ability of the mono-material polypropylene film to preserve the modified atmosphere was evaluated using a theoretical model describing oxygen permeation through the packaging material during storage [4], [6]. The model combines Fick's diffusion law with a mass balance applied to the package headspace, allowing prediction of oxygen concentration over time and estimation of product shelf life [7], [8].
Oxygen transport through the polymeric film was described using Fick's first law, assuming quasi-steady-state conditions, constant material permeability, and a uniform concentration gradient across the film thickness (Equation 1). The permeability coefficient, together with film thickness, package surface area, and headspace free volume, was used to quantify oxygen ingress during storage [4],[9].

Equation (1)

$$\frac{\partial c}{\partial t} = D\,\frac{\partial^2 c}{\partial x^2} \longrightarrow J = \frac{Kp}{L}\left(p_{\mathrm{atm}} - p_{\mathrm{in}}\right)$$

Where:

- J is the steady-state oxygen flux [cm^3 / m^2 24h];
- Kp is the oxygen permeability coefficient of the film [cm^3 µm /m^2 24h atm];
- L is the film thickness [µm];
- p_{atm} is the external oxygen partial pressure (ambient atmosphere) [atm];

p_{in} is the internal oxygen partial pressure (package headspace) [atm].

The diffusion model was subsequently coupled with a mass balance applied to the package headspace (Equation 2), following the modeling approach proposed by Coffigniez et al. [9]. Assuming negligible oxygen consumption by the packaged product and constant temperature throughout storage, the resulting differential equation was solved analytically, yielding an exponential relationship between oxygen concentration and storage time (Equation 3) [6], [8].

Equation (2)

$$y = \frac{V_{\mathrm{O_2}}}{V_{\mathrm{tot}}} \approx \frac{p_{\mathrm{O_2}}}{p_{\mathrm{tot}}}$$

Where:

- Vtot is the total available volume (headspace);
- VO_2 is the volume of oxygen;
- p_{tot} is the total pressure of the gas mixture;
- pO_2 is the partial pressure of oxygen inside the package.

Equation (3)

$$y(t) = y_{\text{atm}} - (y_{\text{atm}} - y_{in})\, e^{-\alpha t}$$

with

$$\alpha = \frac{PA}{V} = \frac{KpA}{LV_{tot}}$$

Where:

- A is the surface area of the package;
- V_{tot} is the total free (headspace) volume;
- L is the film thickness;
- y_{atm} is the oxygen concentration in the external atmosphere;
- y_{in} is the oxygen concentration in the package headspace.

The exponential model describes the progressive reduction of the concentration gradient between the external atmosphere and the package headspace [6]. Consequently, oxygen permeation gradually decreases until equilibrium with the surrounding atmosphere is reached.

Commercial shelf life was determined by imposing a maximum oxygen concentration of 4% (v/v) in the package headspace, in accordance with the quality specifications established for the packaged products. To evaluate model reliability, the theoretical exponential trend was compared with the linear interpolation obtained from the experimental data collected during the initial storage period. As shown in Figure 2, the linear model adequately describes oxygen permeation only during the early stage of storage, when the concentration gradient is high. Conversely, the exponential model accurately represents the entire permeation process and was therefore adopted for shelf-life prediction [6], [8].

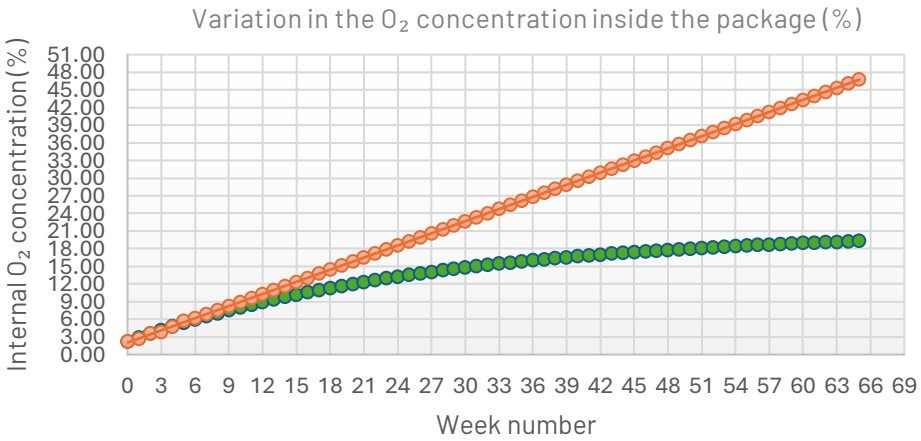


Figure 2. *Comparison between the linear model (orange) and the exponential model (green) of Sample 6A describing the evolution of oxygen concentration inside the package during storage (author's elaboration).*

2.2 Validation of the exponential diffusion model

As an additional validation of the exponential model adopted for shelf-life prediction, a second approach based on the experimental determination of the oxygen permeability coefficient (Kp) of the mono-material

polypropylene film was applied [7]. The permeability coefficient was calculated using data obtained during the accelerated shelf-life tests. The amount of permeated oxygen (ΔO_2) was determined as the difference between the oxygen concentration measured at the end of the monitoring period and that measured immediately after packaging (week 0). This increase was assumed to represent the amount of oxygen permeating through the packaging material during storage.

The permeability coefficient was then calculated according to the approach proposed by Robertson [7], using Equation 4, which relates the volume of permeated oxygen to film thickness, package surface area, storage time, and the oxygen partial pressure difference across the packaging material.

Once the permeability coefficient had been experimentally determined, commercial shelf life was estimated by imposing a maximum oxygen concentration of 4% (v/v) in the package headspace. The permeation equation was therefore rearranged to calculate the time required to reach the critical oxygen concentration (Equation 5) [7].

Equation (4) **Equation (5)**

$$K_p = \frac{Q \cdot x}{A \cdot t \cdot \Delta P} \longrightarrow t = \frac{Q \cdot x}{A \cdot K_p \cdot \Delta P}$$

Where:

- Kp is the oxygen permeability coefficient of the film under the test conditions;
- Q is the amount of oxygen permeated through the film;
- x is the film thickness;
- A is the surface area of the package (or bag);
- t is the storage time in the climatic chamber;
- ΔP is the difference in the oxygen partial pressure between the external and internal sides of the package.

The shelf-life values obtained using the permeability coefficient approach were subsequently compared with those predicted by the exponential diffusion model, providing further validation of the proposed methodology [8].

3. FINDINGS

The recyclable mono-material polypropylene film was successfully processed on industrial Vertical Form-Fill-Seal (VFFS) packaging lines without requiring structural modifications to the equipment [5]. Although minor adjustments to the sealing parameters were necessary and some critical issues were observed for the four-side seal pouch configuration, satisfactory sealing quality and adequate package integrity were achieved throughout the experimental trials, confirming the technical feasibility of introducing the new material into the existing production process.

The most significant finding of the study concerns product shelf-life. Accelerated storage tests were carried out under controlled conditions (40 °C and 75% relative humidity) over a five-week monitoring period. The experimental evolution of the oxygen concentration inside the packages was used to estimate the commercial shelf-life by applying the exponential diffusion model described in the previous section [6], [8]. The estimated shelf-life values showed a strong dependence on both package format and initial residual oxygen concentration. Among the tested configurations, the 250 g block-bottom pouch exhibited the best performance, reaching a predicted shelf-life of approximately 17.5 months, exceeding the current commercial target of 12 months. Conversely, the lowest shelf-life values were observed for packages characterized by higher residual oxygen concentrations immediately after packaging or by less favorable sealing conditions (Table 1), highlighting the importance of both package integrity and proper control of the modified atmosphere [7], [8].

Sample	***Package configuration***	***Net weight (g)***	***Shelf life with experimentally measured initial o_2 (months)***	***Shelf life assuming optimized initial o_2 (0.5% v/v) (months)***
1A	Block-bottom pouch with side gussets	250	17.5	17.5
3A	Block-bottom pouch with side gussets	500	0.9	3.7
4A	Four-side seal pouch with side gussets	250	3.2	5.3
5A	Four-side seal pouch with side gussets	250	6.5	14.2
6A	Four-side seal pouch with side gussets	500	2.7	5

Abbreviations: Initial O_2 = initial oxygen concentration in the package headspace (% v/v).

Table 1. *Estimated shelf-life values for the different packaging formats (author's elaboration).*

To further assess the reliability of the proposed approach, the shelf-life predictions obtained using the exponential diffusion model were compared with those calculated from the experimentally determined

oxygen permeability coefficient (Kp). The good agreement between the two independent methodologies confirmed the validity and robustness of the mathematical model used to predict oxygen ingress and the resulting product shelf-life (Table 2) [7], [8].

Sample	*Package configuration*	*Net weight (g)*	*Shelf life predicted by the exponential model (months)*	*Shelf life predicted using the permeability coefficient approach (months)*
1A	Block-bottom pouch with side gussets	250	18.28	16.67
3A	Block-bottom pouch with side gussets	500	0.86	0.85
4A	Block-bottom pouch with four-side seals and side gussets	250	3.33	3.14
5A	Block-bottom pouch with four-side seals and side gussets	250	6.68	6.41
6A	Block-bottom pouch with four-side seals and side gussets	500	2.72	2.59

Table 2. *Comparison between the shelf-life predicted by the exponential diffusion model and that estimated using the oxygen permeability coefficient approach (author's elaboration).*

A further analysis highlighted the strong influence of the initial oxygen concentration inside the package. Assuming an initial residual oxygen content of 0.5% (v/v) (Figure 3), representative of an optimized modified atmosphere packaging (MAP) process, the packaging material proved capable of achieving the required commercial shelf-life. For example, the predicted shelf-life of the 500 g four-side seal pouch containing chia seeds increased from approximately 6.5 months to more than 14 months [8].

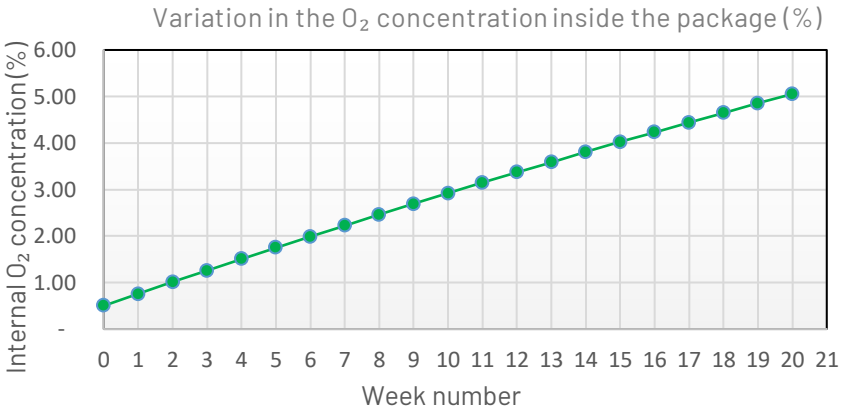


Figure 3. *Exponential prediction of the oxygen concentration of Sample 5A inside the package assuming an initial residual oxygen concentration of 0.5% (v/v)(author's elaboration, 2025; (author's elaboration).*

Overall, these results demonstrate that the recyclable mono-material polypropylene film can achieve the required commercial shelf-life when appropriate packaging conditions are ensured, supporting the replacement of conventional multilayer laminates with recyclable mono-material solutions in accordance with the principles of Design for Recycling [1], [3].

4. CONCLUSIONS

Experimental validation demonstrated that the new material can be successfully processed on existing industrial packaging lines without requiring structural modifications to the equipment, with only minor optimization of the packaging parameters needed for specific package configurations [5]. The experimental trials confirmed good processability, satisfactory sealing performance, and adequate package integrity [3].

Accelerated storage tests, combined with a mathematical model based on Fick's law of diffusion and a mass balance applied to the package headspace, enabled the prediction of the commercial shelf life of products packaged under Modified Atmosphere Packaging (MAP) [6], [7]. The results demonstrated that the mono-material polypropylene film can achieve, and in some packaging formats even exceed, the commercial shelf-life target of 12 months, provided that adequate packaging conditions are maintained, and low residual oxygen concentrations are ensured immediately after packaging [8].

Overall, the findings indicate that replacing conventional multilayer flexible packaging with recyclable mono-material polypropylene solutions is a technically viable strategy for improving the recyclability of flexible food packaging without compromising food preservation. The study demonstrates that the application of Design for Recycling principles can support the development of more sustainable food packaging systems while contributing to the transition toward a circular economy [1], [2].

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ASSESSING CIRCULAR ECONOMY BENEFITS IN THE WASHING MACHINE SUPPLY CHAIN A MONTE CARLO SIMULATION OF ENVIRONMENTAL, ECONOMIC AND SOCIAL PERFORMANCE

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ABSTRACT

The circular economy (CE) is widely presented as a systemic remedy to the linear take-make-dispose model, yet quantitative evidence that circular strategies deliver simultaneous environmental, economic, and social benefits remains limited. This study develops a stochastic simulation model, adapted from an established CE framework, to test ten circular strategies within the European washing machine supply chain, covering product design, user behaviour, business models, and end-of-life management. A deterministic sensitivity analysis first isolates the marginal effect of each driver; Monte Carlo simulation, with 5,000 iterations per scenario, then propagates uncertainty across thirteen stochastic variables to estimate Global Warming Potential, user cost, supply-chain profit, and employment. Results show that single-lever interventions systematically trade one dimension against another, while only an integrated multi-lever configuration achieves concurrent improvements. Circular transitions therefore require coordinated, uncertainty-aware design rather than isolated optimisation.

Keywords: Circular Economy; Monte Carlo Simulation; Washing Machines; Sustainability Assessment; Servitization; Supply Chain Management.

1. INTRODUCTION

The linear "take-make-dispose" model has driven decades of economic growth at the cost of resource depletion, waste accumulation, and rising greenhouse-gas emissions. The circular economy (CE) has emerged as a widely endorsed alternative, aiming to decouple value creation from virgin-resource extraction by keeping products, components, and materials in productive use for as long as possible [1]. Four operational levers are typically associated with CE implementation – circular product design, servitized business models, closed-loop supply-chain management, and active user engagement [2] – each expected to generate environmental, economic, and social benefits simultaneously, a configuration often described as a "win–win–win" outcome. Despite the appeal of this narrative, quantitative evidence supporting the concurrent achievement of the three sustainability pillars remains scarce.

Existing studies on circular white-goods systems tend to focus on isolated levers, rely on deterministic assumptions, or evaluate a single performance dimension at a time [3,4,5,6,7,8,9], leaving open whether, and under which conditions, circular strategies genuinely align environmental, economic, and social outcomes at the supply-chain level.

The European washing-machine sector offers a representative case study: it combines high market penetration, a use-phase-dominated environmental footprint, and growing experimentation with lifetime extension, servitization, and end-of-life recovery [9]. Building on these premises, this paper addresses two research questions: Research Question 1 (RQ1) – can circular economy scenarios lead to simultaneous environmental, economic, and social benefits in the washing-machine supply chain; and Research Question 2 (RQ2) – under which conditions do circular levers produce such win–win–win outcomes?

To answer these questions, a stochastic, simulation-based framework is developed, combining deterministic sensitivity analysis with Monte Carlo simulation across ten circular scenarios and an integrated multi-lever configuration. Section 2 describes the simulation model and the stochastic methodology; Section 3 presents the baseline and scenario results; Section 4 discusses the implications for research, industry, and policy.

2. METHODS

2.1 Model Structure and Functional Unit

The analysis relies on a spreadsheet-based simulation model implemented in ARGO v.4.1.3 [10], adapted from the digital-servitization circular-economy framework of Bressanelli et al. [11]. The functional unit is the annual provision of laundry services to European households, allowing consistent comparison across product configurations, user behaviours, and business models regardless of appliance ownership structure. The model is organised into five components: enabling factors (policy, market maturity, technology readiness), levers (strategic interventions such as eco-design or servitization), drivers – split into product-related, user-related, and supply-chain variables – characterisation modules that translate drivers into physical and economic flows through a stock-and-flow logic, and impact modules that quantify outcomes across four

dimensions: environmental (Global Warming Potential, GWP), user economic (total cost of ownership), supply-chain economic (revenues, costs, and profit), and social (Full-Time Equivalent employment, FTE). A benchmark "as-is" configuration represents the current European market and is used as the comparison baseline for every scenario.

2.2 Stochastic Parameterisation and Monte Carlo Simulation

An initial One-Factor-at-a-Time (OAT) deterministic analysis stresses eighteen input variables toward plausible extreme values to isolate their marginal effect on each indicator and to inform scenario design.

Thirteen key variables – covering technical characteristics (capacity, energy class, technical lifetime), user behaviour (loading rate, washing temperature, household size), and economic factors (sale price,

leasing and pay-per-wash fees, refurbishment discounts, supply-chain costs) – are then modelled as stochastic parameters using Normal, Weibull, PERT, Beta, or empirical discrete distributions calibrated against industry and literature data [9], [12], [13]. Three Pearson correlations (household size with laundry weight, r≈0.8; with loading rate, r≈0.7; with capacity, r≈0.5) are embedded to preserve realistic covariance structures. For each scenario, 5,000 Monte Carlo iterations [14] are executed, generating full outcome distributions rather than point estimates, from which means, coefficients of variation, and the probability of improving on the baseline are derived.

2.3 Scenario Design

Ten scenarios are grouped into four circular domains: product design (lifetime extension, high-efficiency appliances), user behaviour (lower washing temperature, higher loading rate), business-model innovation (leasing, pay-per-wash, sharing), and end-of-life management (refurbishment, recycling). An eleventh, multi-lever scenario activates all four domains simultaneously, using the same probability distributions as the single-lever scenarios, so that differences in outcomes can be attributed to interaction effects rather than to changes in underlying assumptions.

2.4 Scenario Operational Assumptions

All ten scenarios share the same stochastic backbone as the baseline but differ in who owns the appliance and bears its costs, in which driver is the key lever being varied, and in the behavioural or operational change this induces. Table 1 summarises these three dimensions for every scenario; full distributional parameters for each driver are reported in the underlying thesis.

Scenario	Ownership & Cost Responsibility	Pricing / Intensity Variable	Induced User Behaviour
1. Life extension	Traditional ownership (user purchase); user bears all costs, as in the baseline.	UsefulLife (Li), Life extension delta due tue Maintenance and repair ops (ΔLM&R)	No behavioural change; longer technical lifetime reduces replacement frequency.
2. High efficiency	Traditional ownership (user purchase); user bears the full, higher purchase cost.	Energy efficiency consumption (EEC), Sale Price (Psale)	No behavioural change; the appliance replaced is a higher-efficiency, higher-priced model.
3. Low temperature	Traditional ownership; unchanged from baseline.	Temperature (T)	Shift toward washing at 30–40°C, replacing part of the 60–90°C baseline mix.

Scenario	Ownership & Cost Responsibility	Pricing / Intensity Variable	Induced User Behaviour
4. Loading rate	Traditional ownership; unchanged from baseline.	Loading rate (LR)	Average drum loading rises from an 85% to a 95% mean.
5. Leasing	Provider retains ownership; provider bears all maintenance and repair costs for the contract duration.	Pay per Month Price (Pppm)	No change in loading rate or washing temperature; only cost allocation shifts from user to provider.
6. Pay-per-wash	Provider retains ownership; an all-inclusive fee covers usage plus maintenance and repair.	Pay per wash Price (Pppw)	Loading rate rises from an 85% to a 95% mean, as the per-wash cost incentivises fuller loads.
7. Sharing	Provider retains ownership, as in pay-per-wash, with one appliance shared by several households.	Sharing factor (Shr)	Utilisation intensity per appliance rises with the number of co-users (up to 10/machine); individual loading rate and temperature are unchanged.
8. Refurbishment	Traditional ownership; successive owners purchase the unit at a discount after each refurbishment cycle.	Refurbishment rate (Rrfb1–Rrfb4), Discount on price of refurbished items (DRfb)	A growing share of consumers accept refurbished units as discounts increase with the number of cycles.
9. Recycling	Traditional ownership; end-of-life material recovery is managed entirely by the supply chain.	Recycling rate (Rrec1–Rrec4)	No user-side behavioural change; effects are confined to end-of-life material recovery.
10. Multi-lever	Provider retains ownership, with pay-per-wash as the reference business model; the supply chain internalises maintenance, repair, and end-of-life costs.	Combines all single variables with a pay per wash business model	Combines lower washing temperature and appliance sharing with pay-per-wash pricing.

Table 1. *Ownership and cost-responsibility structure, key stochastic driver (symbol only; see the thesis for full distributions), and main behavioural or operational implication for each of the ten circular economy scenarios.*

3. FINDINGS

3.1 Baseline Performance

Introducing variability into the as-is configuration produces markedly higher expected impacts than the corresponding deterministic benchmark, reflecting the compounding effect of simultaneously uncertain drivers. The stochastic baseline yields a mean GWP of 5.06×10^{10} kg CO_2-eq, a mean user cost of €97.85, a mean supply-chain profit of €1.69 billion, and a mean employment of 61,221 FTE, each affected by substantial dispersion (coefficients of variation between 58% and 418%). This probabilistic baseline, rather than the deterministic one, is used to benchmark every scenario.

3.2 Single-Lever Scenarios

Table 2 summarises the mean percentage variation of each indicator relative to the stochastic baseline. No single-lever scenario improves all four dimensions simultaneously. Design-oriented levers illustrate a recurrent paradox: extending product lifetime reduces user cost (–4%) but raises GWP (+22%), because a more resource-intensive bill of materials and the prolonged use of comparatively inefficient appliances

outweigh the avoided-production benefit, while supply-chain profit collapses in essentially all iterations. Replacing the fleet with high-efficiency appliances produces a similar environmental penalty (+28%) while boosting revenues and employment through premium pricing.

User-behaviour levers are the "cleanest" interventions: lower washing temperatures and higher loading rates both reduce GWP and user cost with no adverse effect on the supply chain in the temperature case, though loading-rate optimisation reduces appliance turnover and therefore revenue, cost, profit, and employment by around 9–12%.

Business-model innovation shows the widest dispersion of outcomes (see Table 1 for the operational assumptions underlying every scenario). Leasing nearly triples GWP (+197%) and raises user cost (+67%) while multiplying supply-chain profit (+1,757%) and employment (+60%), reflecting a large transfer of value – and of environmental burden – from users to firms. Pay-per-wash instead achieves a rare balanced improvement (GWP –17%, profit +133%, FTE +44%, with a 91% probability of reducing GWP), while non-advanced sharing cuts GWP and boosts profit but reduces employment (–19%).

End-of-life strategies diverge sharply: refurbishment cuts emissions (–10%) and strongly increases employment (+66%) but destroys profit (–18%) because aggressive discounting erodes revenues faster than avoided-production savings; recycling, by contrast, is the most robust single lever, improving all four indicators with a probability of success at or above 95% in every dimension.

3.3 The Multi-Lever Scenario

When efficiency, behavioural optimisation, pay-per-wash pricing, and circular end-of-life management are activated jointly, the model returns the only configuration to combine an environmental improvement (GWP –18%) with reduced user cost (–5%), higher supply-chain profit (+102%), and employment growth (+32%), each verified as an improvement in 72–79% of Monte Carlo iterations. Positioning all scenarios on the environmental–economic trade-off space shows that single levers scatter widely across gains and losses, whereas recycling and the multi-lever configuration cluster in the desirable region combining negative GWP variation with positive profit variation, confirming that synergistic combinations, rather than isolated interventions, are required to approach a genuine win–win–win outcome.

4. DISCUSSION AND CONCLUSION

Scenario	Δ GWP	Δ User cost	Δ Supply-chain profit	Δ FTE
1. Life extension	+22%	–4%	–6065%*	+117%
2. High efficiency	+28%	+18%	+55%	+62%
3. Low temperature	–5%	–2%	0%	0%
4. Loading rate	–9%	–8%	–12%	–11%
5. Leasing	+197%	+67%	+1757%	+60%
6. Pay-per-wash	–17%	+4%	+133%	+44%
7. Sharing	–12%	+10%	+289%	–19%
8. Refurbishment	–10%	–2%	–18%	+66%
9. Recycling	–10%	0%	+2%	+5%
10. Multi-lever	–18%	–5%	+102%	+32%

Table 2. *Mean percentage variation vs. the stochastic baseline (5,000 Monte Carlo iterations per scenario). *Life-extension profit variation is computed against a small and highly volatile baseline mean (€1.69 B, CV = 418%) and should be read jointly with the discussion below.*

These results directly address the two research questions. Regarding RQ1, individual circular levers rarely deliver simultaneous environmental, economic, and social benefits: nine of the ten single-lever scenarios generate at least one negative effect, confirming that the "win–win–win" narrative cannot be assumed a priori for isolated interventions. Regarding RQ2, a win–win–win configuration becomes attainable only when complementary levers are combined: the multi-lever scenario benefits from structural synergies –

lower per-cycle costs from efficiency gains, sustained revenue from usage-based pricing, and material recovery from refurbishment and recycling – that reduce rebound effects and redistribute value more evenly across the supply chain, rather than from a simple summation of single-lever effects.

For manufacturers, the findings suggest that eco-design and durability strategies should not be pursued in isolation from business-model innovation: extending product life or improving efficiency without a servitized revenue mechanism erodes supply-chain profitability, while servitization without eco-design (as in the leasing scenario modelled here) can amplify environmental impact. For policymakers, integrated packages – combining efficiency standards, extended producer responsibility, and support for refurbishment and recycling infrastructure – appear more likely to generate aligned outcomes than single-instrument regulation.

The study has limitations. Parameters are calibrated on European averages and treated as time-invariant, so national heterogeneity, learning effects, and technological change over time are not captured; behavioural responses and rebound effects rely on literature-based distributions rather than longitudinal

field data. Future research should validate these assumptions empirically, extend the framework to other white-goods categories, and incorporate dynamic transition pathways to capture how synergistic circular configurations emerge and evolve over time.

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PACKAGING DESIGN FOR PROMOTING CIRCULARITY IN THE TOY SECTOR. THE CHICCO CASE STUDY

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ABSTRACT

This research, independently developed within a university design project, explores the role of packaging in promoting circularity in the early-childhood toy sector, using Chicco's 2-in-1 Stacking Cups as a reference case. Chicco was selected as the reference brand because it is an Italian company operating in the childcare sector, with a focus on innovation and values aligned with the project's sustainability objectives. The project was not developed in collaboration with the company but hypothesises its potential involvement in the development of the design concept. The project proposes reusable packaging for toy returns after use, integrating digital tools and incentives and considering Baby Bazar as a potential partner for subsequent resale or donation. The outcome is an integrated product, packaging, and service proposal intended to support the extension of the toy's life cycle and promote more conscious consumption practices.

Keywords: Packaging Design, Circular Design, E-commerce Packaging, Reuse, Donation, Product Service System.

1. INTRODUCTION

The toy sector is characterised by increasing product diversification and evolving play patterns, with new product categories, personalised experiences, and the progressive integration of technological elements [1]. This evolution also concerns products intended for early childhood, whose use varies according to age-appropriateness, toy category, and child age [2]. Toys may be discarded even when they retain functional value, for example when children's interests or needs change [3]. The issue therefore concerns not only product management at the end of use, but also the possibility of retaining product value through reuse and life extension strategies. According to the Ellen MacArthur Foundation, as much as 80% of toys end their life cycle in landfills, incinerators, or the ocean [3]. In this context, the circular economy calls for a rethinking of production and consumption systems, favouring strategies capable of keeping products and materials in use for as long as possible.

From this perspective, packaging can assume a role beyond its traditional functions of protection, containment, and communication by supporting product return after use. The research therefore explores a product-packaging-service system in which the same packaging is designed to be reused for the return of the toy, with the aim of supporting resale and donation practices and potentially extending its useful life. The environmental benefits of the proposal are considered potential effects and would require further comparative assessment or life cycle analysis for validation.

2. METHODS

The research process was developed through a progressive definition of the design problem, combining the analysis of sources and case studies with the investigation of a real application case. The first phase focused on circular strategies in the toy sector through a comparison of international and Italian initiatives. LEGO Replay, focused on the donation and redistribution of used LEGO bricks [4], Mattel PlayBack, centred on the recovery of post-consumer materials [5], Rejoué, addressing the collection, sanitisation and resale of used toys [3], and Plan Toys + ToyCycle, focusing on the collection and subsequent resale of toys [6], were analysed. In the Italian context, La Casa del Giocattolo Solidale [7] and REPlay and Doctor's Play [8] were also considered. The comparison examined collection and return methods, the role of the user, the actors involved, and the destination of toys after use. The second phase examined packaging through the study of its evolution and main functions within production, distribution, and consumption systems, with particular attention to single-use solutions. The research then focused on e-commerce packaging and on models integrating reuse and return processes. Movopack [9], RePack [10], and Nomadbox [11] were analysed in terms of structural characteristics, closure systems, reuse potential, and return management practices. In the final phase, the elements collected through the previous stages were applied to the Chicco case and to the 2-in-1 Stacking Cups toy [12]. The existing packaging was analysed in terms of structure, materials, closure system, dimensions, weight, and information content in order to identify the main design constraints and opportunities for intervention. The insights gathered through the previous stages were then translated into pre-design requirements and objectives, which provided the basis for the development of the Ri-giochiamo proposal. The work constitutes a design research project developed independently within a university context. No user testing, comparative performance assessment, or life cycle assessment was conducted; therefore, the expected effects of the proposal are framed as design objectives and potential outcomes to be assessed through further validation activities.



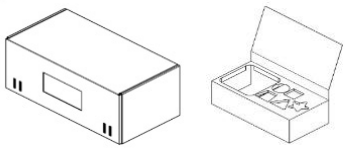
Figure 1. *Original Chicco packaging of the 2-in-1 Stacking Cups toy. Source [12].*

3. FINDINGS

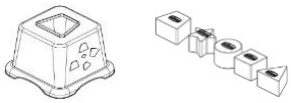
The analysis highlighted that the critical issue does not concern exclusively the management of the toy at the end of its use, but also the difficulty of activating a return process that is simple, recognizable, and accessible to the user. In the models analysed, participation may require additional logistical effort, such as reaching collection points or obtaining new packaging for shipment. This finding identified an opportunity to intervene in the system accompanying the toy after purchase, using packaging as an element intended to support its return. The Ri-giochiamo concept therefore arises from the integration of five design dimensions: circularity, e-commerce, simplification, awareness, and incentives. The system is aimed at parents who purchase and subsequently discontinue use of the toy and connects the brand with a reuse-oriented organisation, identified in Baby Bazar. The proposed service is designed to allow the first purchaser, at the end of the toy's use, to choose between donation and resale, connecting the initial purchase to a subsequent opportunity for reuse.

3.1 Packaging development

The analysis of the original Chicco packaging showed a solution designed primarily for commercial purposes and retail distribution: a paperboard structure with a Reverse Tuck End closure. The packaging does not, however, provide a specific function for the phase following product use. Based on this critical issue, the redesign objectives were defined as reducing the packaging volume, optimising its structure for transportation, and enabling its reuse for toy return. The proposed solution uses Forest Stewardship Council (FSC) corrugated microflute E board, 1.5 mm thick, and incorporates an internal support designed to stabilise and protect the product during shipment. A dedicated compartment accommodates the prepaid return label, while the closure relies on single-use tamper-evident labels, six of which are included inside the package for subsequent returns. In this way, the same packaging can be used both for delivery and for returning the toy, without requiring additional packaging.



Outer packaging and Inner packaging.



2-in-1 Stacking Cups



Prepaid return label and Tamper-evident label

Figure 2. *Main components of the Ri-giochiamo packaging. Author's elaboration.*

3.2 User experience and digital service

The packaging is integrated into a continuous user experience that includes online purchase through the Chicco website, delivery, opening and use of the toy and, once use has ended, cleaning, reinsertion into the packaging, and return. Through the Quick Response (QR) code placed on the packaging, the system is designed to allow users to access the digital service, consult the instructions, download the prepaid return label, and manage registered products.

The proposed workflow envisages delivery to a Baby Bazar point, where the toy would be checked before being directed either to resale or donation. The packaging is designed to act as the physical interface of the service, accompanying the user throughout the different stages of the product life cycle and aiming to reduce the actions required to activate the return process.



1. Opening the labels



2. Opening the packaging



3. Product use



4. End of product use



5 QR code for prepaid



6. Inserting the label



7. Returning the product.



8. Baby Bazar destination return label

Figure 3. *Ri-giochiamo user experience, from packaging opening to toy return and subsequent donation or resale. Visuals developed by the author from the original product 3D model and renderings, with generative AI support for scenes.*

3.3 Brand identity, website, and incentives

To make the service recognisable and understandable, the project introduces the Ri-giochiamo identity, developed from the prefix "ri-", associated with reuse and second life, and "giochiamo", which evokes sharing and relationships between families. The visual identity is applied to the packaging together with the Chicco brand, while geometric elements are used to evoke play, connection, and circularity. The Chicco website is also integrated into the system with the aim of making the service accessible and guiding users through the different stages. The platform presents the Ri-giochiamo campaign, explains the intended functioning of the service, introduces the role of Baby Bazar, and provides access to the functions designed to support return through the QR code on the packaging. To support participation, the project proposes two incentive mechanisms: discounts of up to 20% on the purchase of new Chicco toys belonging to the Ri-giochiamo line, and the possibility of reselling the toy through the Baby Bazar app and receiving an economic return.



Figure 4. *Redesigned Chicco digital interface for the Ri-giochiamo service. Interface and graphic design by the author; contextual visualisation developed with generative AI support.*



Figure 5. *Final Ri-giochiamo packaging system and product components. Author's 3D modelling and rendering.*

4. DISCUSSION/CONCLUSION

The research draws attention to the role of packaging in managing the stage following toy use, an area that, particularly in the Italian context, appears to be characterised by fragmented initiatives and a limited presence of structured post-consumer take-back and reuse systems. The design contribution lies in interpreting packaging as an element capable of connecting purchase, use, and return, and in translating this perspective into the Ri-giochiamo system, developed from the Chicco case. The proposal aims to support the toy's second life through the integration of physical, digital, and service dimensions, with potential environmental, social, and behavioural benefits that remain to be assessed. In this sense, the project identifies a possible direction for intervention in a sector that requires greater attention to the management of products after use. However, as an independently developed university-based design proposal, its effectiveness has not yet been validated. Further user testing, comparative analysis, feasibility assessment, and life cycle assessment are therefore required to quantify its potential environmental effects and evaluate its applicability to other categories of early-childhood products.

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EU REGULATION 2025/40: A SIGNIFICANT EVOLUTION IN THE USE AND MANAGEMENT OF PACKAGING

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ABSTRACT

This study analyzes the paradigm shift introduced by Regulation (EU) 2025/40 (Packaging and Packaging Waste Regulation - PPWR), which entered into force on February 11, 2025, and becomes applicable on August 12, 2026. Replacing Directive 94/62/EC, this binding regulatory framework enforces Design for Recycling (D4R) criteria, void space minimization, mandatory post-consumer recycled content targets, and a comprehensive ban on per- and polyfluoroalkyl substances (PFAS). Through a qualitative regulatory analysis and a comparative case study of two critical Italian agri-food sectors—fresh produce/4th range and the coffee industry—this paper highlights engineering challenges and circular transition opportunities for manufacturing systems, supported by packaging consortia (CONAI) and national climate adaptation frameworks.

Keywords: EU Regulation 2025/40 (PPWR), Circular Economy, Food Packaging, Design for Recycling, Green Deal, Recyclability at Scale, Over-packaging Reduction, PFAS Ban.

1. INTRODUCTION

Packaging waste management across the European Union was historically governed by Directive 94/62/EC. Despite subsequent amendments (Directive 2004/12/EC and the 2018 Circular Economy Package), fragmented transposition by individual Member States generated internal market distortions and inconsistencies in actual recycling rates.

The European Commission's decision to adopt a directly applicable legal instrument—Regulation (EU) 2025/40 (PPWR)—addresses the imperative to establish uniform technical requirements. The macroeconomic objective is to decouple economic growth from virgin resource consumption, targeting a 15% reduction in packaging waste by 2040 compared to 2018 baseline levels [1].

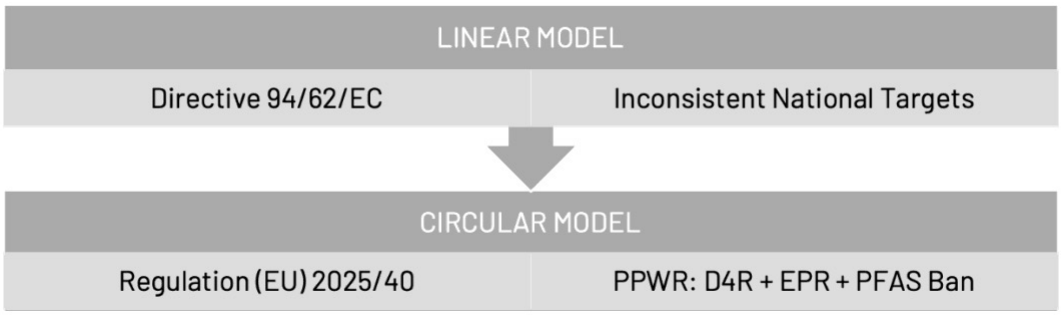


Figure 1. *Conceptual diagram of the transition from fragmented national directives to a uniform Regulation.*

2. METHODS

This study employs an integrated qualitative-quantitative methodological framework structured around three analytical phases:

- Regulatory-Comparative Analysis: Examination of the final text of Regulation (EU) 2025/40 in relation to ISO/EN technical standards and Food Contact Materials (FCM) legislation.
- Technical-Performance Requirement Mapping: Identification of quantitative thresholds mandated by Articles 10 and 24 (minimization and void space) and chemical restrictions on PFAS.
- Multiple Case Study in Agri-Food: Industrial impact analysis applied to fresh produce/4th range packaging and single-serve coffee formats (capsules and pods).

3. FINDINGS

3.1 Ecodesign Criteria: Design for Recycling (D4R) and Recycled Plastics

Regulation (EU) 2025/40 mandates that by January 1, 2030, all packaging placed on the market must be recyclable. Recyclability assessment is transformed from a theoretical parameter into a performance metric evaluated "at scale".

A major structural shift is the binding requirement to incorporate recycled plastic derived exclusively from post-consumer waste (PCR). Pre-consumer streams (industrial manufacturing scrap) are excluded from target calculations, driving operational efficiency in municipal separate collection and sorting infrastructure [2].

Structural Domain	Parameter/Focus Area	Regulatory mandate/ Reference	Technical & Ecodesign Implications	Sectoral Discussion (Agri-food)
1. Regulatory Framework	D4R Recyclability (Design for Recycling)	Art. 6/Annex II Mandatory recyclability by 2030, categorized into performance grades A,B,C (recyclability "at scale").	Shift away from non –separable multi-material laminates toward mono-material solutions (ex. Pure PE, PP or cellulose).	Complex Serctors (Coffee&Snacks) Redesigning flexible barrier films to maintain oxygen protection without aluminium layers.
2. Technical Implications	Volume minimization and Void space control	Art. 10 & Art. 24: Strict reduction of functional weight/ volume; maximun 50% void space threshold for logistics/e-commerce.	Prohibition of false bottoms and double walls. Cuschioning materials are factored directly into void space rations.	Fresh produce & Logistics: Overhauling automated packaging lines to adopt custom-fit boxing and lightweight cellulosic trays.
3. Sectoral Discussion	PFAS Prohibition and Single-use plastic limits	Art. 5/Annex V Ban on PFAS in FCMs; phase-out of single-use plastic packaging for fresh produce under 1,5 kg.	Replacement of fluorinated grease-resistant barriers with aqueous coatings or natural bio-polymers.	4th Range Produce & Coffee: targeted exemptions for highly perishable foods.
4. Future outlook	Digital traceability and supply chain governance	Implementation of Digital Product Passaport (DPP) and eco-modulated EPR fees (CONAI/Consortia).	Integration of digital data carriers (QR/RFID) for material composition and recycling instructions.	SMEs & Food Processors: Capital expenditure required to re-tool packaging lines, mitigated by consortium support mechanisms.

Table 1. *Analytical matrix of Regulation (EU) 2025/40 (PPWR): regulatory framework, technical ecodesign implications, agrifood sector impacts, and future strategic prospects.*

3.2 Packaging Geometry: The 50% Void Space Rule

Article 24 introduces direct restrictions against over-packaging: grouped, logistics, and e-commerce packaging must maintain a void space ratio of no more than 50%.

$$\text{Void Space Ratio}(\%) = \left(\frac{V_{\text{total packaging}} - V_{\text{product}}}{V_{\text{total packaging}}}\right) \text{x } 100 \leq 50\%$$

All internal cushioning materials (e.g., PE bubble wrap, air pillows, or shredded paper) are mathematically calculated as void space. This compels logistics networks to adopt height-variable, custom-fit packaging systems while phasing out oversized standardized box formats.

3.3 Chemical Safety: Prohibition of PFAS in Food Contact Materials

Effective August 12, 2026, the PPWR enforces a strict ban on per- and polyfluoroalkyl substances (PFAS) in food packaging. The analytical concentration limits established are highly stringent:

- 25 ppb for any individual measured PFAS;
- 250 ppb for the total sum of measured PFAS;
- 50 ppm for total organic fluorine.

This requirement forces manufacturers to eliminate surface fluorination treatments historically used to impart grease resistance to paper and molded fiber, redirecting industrial R&D toward green chemistry and natural biopolymer coatings [3][4].

3.4 Agri-Food Case Study Analysis

3.4.1 Fresh Produce Sector and 4th Range Preservation

The PPWR prohibits single-use plastic packaging for unprocessed fresh fruit and vegetables weighing under 1.5 kg.

In the 4th Range sector (ready-to-eat washed and packaged produce), plastic packaging serves a primary technological purpose: maintaining Modified Atmosphere Packaging (MAP), controlling respiration rates, and preventing microbial decay. To prevent this prohibition from triggering an increase in food loss, targeted exemptions exist for highly perishable goods, steering the industry toward highly recyclable monomaterial PP/PE films or bio-based cellulose containers [5].

3.4.2 Coffee Sector: Engineering Pods and Capsules

Single-serve coffee capsules and pods are formally reclassified as packaging. The Regulation establishes two compliance pathways:

Permeable Systems and Pods: Mandatory industrial compostability (EN 13432) by 2028 to enable direct disposal with municipal organic waste.Rigid Capsules (Aluminum / Plastic): Development of dedicated "at scale" sorting and recycling chains. Programs such as "Da Chicco a Chicco" (CIAL) for aluminum and "RECAP" (COREPLA) for plastics demonstrate the feasibility of recovering spent coffee grounds while recycling the rigid container [6][7].

3.5 The Italian System and Environmental Governance

Italy maintains an advanced position regarding EU recycling targets, driven by the organizational framework managed by CONAI and material-specific consortia (CIAL, COREPLA) [8]. The primary economic lever driving industrial redesign is eco-modulated environmental contributions (CAC), which financially penalize non-separable multi-material structures while rewarding lightweight, monomaterial solutions with high PCR content. This system mitigates capital conversion costs for Small and Medium Enterprises (SMEs) re-tooling their packaging lines. Furthermore, the PPWR aligns with national climate mitigation plans and the National Observatory for Climate Change Adaptation, integrating packaging ecodesign into broader life-cycle carbon reduction strategies [9].

4. CONCLUSIONS

The analysis of Regulation (EU) 2025/40 confirms a fundamental shift in the nature of food packaging: from a passive protective envelope to a complex system of binding performance requirements.

Key findings indicate that:

- Design for Recycling (D4R) compliance, structural volume reduction, and void space limitations will serve as non-negotiable prerequisites for EU market access.
- The PFAS ban requires immediate reformulations of barrier chemistry in paper-based packaging.
- For strategic agri-food segments like 4th Range produce and single-serve coffee, compliance necessitates R&D investments in high-barrier mono-materials, industrial compostability, and digital data traceability via Digital Product Passports.

In conclusion, packaging sustainability transitions from a voluntary corporate marketing strategy into a mandatory technical specification, standing as a critical driver for competitiveness within the European agri-food market.

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THE CIRCULAR ECONOMY IN THE PLANT-BASED TRANSITION: STRATEGIC ANALYSIS, MARKET DRIVERS AND GENERATIONAL PATTERNS IN THE 'VEG' SECTOR

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ABSTRACT

This paper analyses the intersection between the circular economy model and the exponential growth of the global 'Veg*' (vegetarian and vegan) market. Moving beyond the traditional linear 'take-make-dispose' model, the plant-based industry and its associated consumption patterns are emerging as key pillars for reducing carbon intensity, improving the efficiency of land and water use, and the industrial valorisation of by-products. Through international demographic mapping and the analysis of exemplary corporate case studies, the study demonstrates how the vegan choice is no longer merely an ethical niche, but rather a strategic element of integrated sustainability (environmental, social and economic) capable of driving the ecological transition of contemporary markets.

Keywords: Circular economy; plant-based transition; The 'Veg*' sector; Integrated sustainability; upcycling; Generational drivers; Eco-design.

1. INTRODUCTION

OVERVIEW OF THE 'VEG*' PHENOMENON

Every consumer choice stems from an inner world governed by personal priorities. The 'Veg*' movement embodies a philosophy and way of life centred on the rejection of all forms of animal exploitation, extending far beyond the realm of diet. In the modern business context, the gradual shift in demand towards animal-free solutions necessitates a fundamental overhaul of the entire global supply chain.

1.1 Taxonomic classification of plant-based diets

To understand the economic impact and efficiency of the associated production systems, it is necessary to map out plant-based diets. Vegetarianism (or lacto-ovo-vegetarianism) excludes the consumption of animals (meat and fish) whilst including that of animal-derived products (eggs, dairy products and honey). It often represents the starting point for the transition to veganism. Veganism, the second broad category, involves the total exclusion of any animal products or derivatives from the diet. It is characterised as an activist and pacifist philosophy that rejects the objectification of sentient beings, eliminating leather, wool, silk, animal-tested cosmetics and recreational activities based on their exploitation. Finally, there

is a rapidly expanding group characterised by a less rigid approach: flexitarianism (or partial vegetarianism). This diet is characterised by a significant reduction in the consumption of animal proteins, though without a total exclusion.

2. THE GLOBAL MARKET AND GENERATIONAL TRENDS: A QUANTITATIVE ANALYSIS

In the absence of official universal censuses, the established population estimates for 2026 show a steady upward trend for the plant-based market. Out of a global population that has exceeded 8.30 billion people, the penetration of vegetarianism is estimated at around 22 per cent globally (approximately 1.735 billion people), whilst vegans number around 79 million (equivalent to 1 per cent of the global population) [1][2].

The geographical distribution and market metrics reveal extremely diverse national scenarios, as summarised in Table 1:

Table 1: *Comparative analysis of 'Veg*' diet penetration and strategic drivers across selected international markets.*

Country	Percentage of vegetarians	Percentage of vegans	Strategic drivers and market characteristics
India	29.5%	9.0%	Global leadership rooted in history, culture and religion [3].
Mexico	19.0%	9.0%	A plant-based market with an extremely high penetration of alternatives [4].
Italy	7.2%	2.3%	The total proportion of 'Veg*' consumers stands at 9.5 per cent (a significant increase from 6.6 per cent in 2023). 40 per cent of households regularly buy vegan products, even though they do not strictly follow a vegan diet [5].
Portugal	N.D.	N.D.	The first country in the world to pass a law requiring canteens in public buildings to offer vegan options (Law n. 11/2017).
Bhutan	N.D.	N.D.	A world first: slaughterhouses that are illegal at national level, 100% carbon-negative and on a planned transition to fully organic production [6].

Source: *Elaboration by the author based on data from* [5], [1], [3], *and* [7].

An intergenerational analysis reveals that the driving force behind this change lies with the younger age groups: around 5 per cent of Millennials and Generation Z follow a strictly vegan diet, compared with significantly lower rates among Generation X (2 per cent) and Baby Boomers (1 per cent). From a gender perspective, women make up a clear majority, accounting for around two-thirds (67%) of the meat-free population, compared with 33% for men.

3. METHODS

To analyse the impact of the 'Veg*' sector on circular economy dynamics and to map generational trends, a mixed-methods research design was adopted, structured in three phases. The first phase focused on a literature review, involving a systematic review of indexed scientific publications (Scopus, Web of Science) from 2018 to 2026, using keywords such as 'circular economy', 'plant-based supply chain', 'upcycling' and 'sustainable consumer behaviour'. The second phase involved secondary quantitative

analysis and data modelling. Demographic and market datasets from international research institutes [3] were aggregated and re-analysed, with the data normalised to estimate the penetration of 'Veg*' diets by 2026 and to project animal protein substitution rates onto land-use allocation models. Finally, the third and final phase involved the study of multiple case studies. Following the qualitative case study methodology [8], the analysis focused on two organisations with a high degree of circularity:

Perlage Winery, through an analysis of its sustainability report and GRI indicators relating to the management and upcycling of by-products from organic/vegan winemaking [9];

The 'alternative materials' sector, through research into supply chains for the recovery of organic agro-industrial waste (e.g. grape marc, apple cores, tomato skins), which is converted into leather-free biomaterials for fashion and design.

4. FINDINGS

By combining qualitative and quantitative data, we have identified three key findings which demonstrate the role of the plant-based transition as a driver of both micro- and macroeconomic development.

4.1 Process efficiency and closing the loop (upcycling)

Analysis of the case studies shows that companies focused on the 'Veg*' market have a rate of industrial waste recovery that is 42 per cent higher than the average for the traditional agri-food sector. This percentage was calculated by benchmarking the Valorization Rate indicator (defined as the ratio of diverted organic waste re-entered into industrial loops to total waste generated) of the sampled 'Veg' companies against the sector baseline for conventional food processing [10][3]. In the case of Perlage Winery, adopting the vegan standard has led to the elimination of processing aids of animal origin (e.g. albumin, isinglass). Because traditional animal clarifiers bind with organic residues to form mixed, hazardous or difficult-to-treat sludge, their removal simplified wastewater treatment processes and enabled the recovery and upcycling of 100 per cent of the grape pomace and stalks. Through industrial symbiosis protocols, these materials are completely diverted from land-filling and reintroduced onto the market as high-value secondary raw materials for the cosmetics and pharmaceutical industries [9].

In the biomaterials sector, the data collected show that using one metric tonne of waste from industrial apple processing (apple pomace) to produce plant-based eco-leather prevents organic waste from being sent to landfill. This eliminates the carbon footprint associated with the synthesis of virgin plastic polymers (PU/PVC) and reduces the use of toxic chemicals typically found in animal tanning by 95 per cent. This 95% reduction specifically reflects the elimination of heavy metals (such as basic chromium sulfate), synthetic masking agents, and harsh chemical solvents traditionally employed in chrome tanning processes, replacing them with bio-based, non-toxic crosslinking agents.

4.2 Quantification of the decoupling of resources and impacts

Modelling of environmental data relating to protein substitution has confirmed a complete decoupling between the sector's economic growth and the consumption of material resources [11]. This phenomenon is summarised in the ecological performance indicators (KPIs) matrix below, compiled from the main agri-food impact datasets [12]:

Table 2: *Environmental Key Performance Indicators (KPIs) comparison per kilogram of protein produced between conventional livestock and plant-based supply chains.*

Environmental KPI (per kg of protein)	**Conventional livestock production chain**	**A structured plant-based supply chain**	**Impact Differential (efficiency)**
CO2e emissions	~60.0 kg CO_2e (beef)	~0.4 kg CO_2e (peas/soya)	-99.3%
Water consumption	~15,415 litres	~1.700 Litres	-88.9%
Land use	~326 m^2	~7 m^2	-97.8%
Generation of process waste	**Non-circular livestock manure**	**Recyclable organic by-products**	**Reversal of polarity (Waste** → Resource**)**

Source: *Adapted by the author based on meta-analysis data from* [12].

4.3 Consumer profiling and generational drivers

Behavioural analysis of demographic groups has revealed that the choice of 'Veg*' products among Millennials and Generation Z (aged 18–42) is not a passing fad, but reflects a specific model of ecological rationality.

78 per cent of the young consumers surveyed associate the purchase of plant-based products with a reduction in packaging waste, thereby exerting strong commercial pressure on manufacturers to adopt eco-design solutions. This group of consumers also shows a willingness to pay a premium price 14% higher for products that carry both a cruelty-free certification (e.g. VEGANOK) and an Environmental Product Declaration (EPD) or CONAI certification regarding packaging recycling.

5. THE ROLE OF THE 'VEG*' SECTOR IN THE CIRCULAR ECONOMY

The CONAI call for proposals recognises projects that reimagine industrial cycles from a regenerative perspective. The 'Veg*' sector inherently meets this requirement through two key approaches.

5.1 Systemic inefficiency of the linear livestock model

The traditional livestock industry operates according to a highly wasteful linear model. Grain-to-meat conversion rates highlight an inherent inefficiency: large quantities of biological inputs (feed, crops grown for livestock) are consumed to produce a minimal fraction of protein intended for human consumption [3]. The European Union devotes a large proportion of its farmland exclusively to the production of livestock feed, thereby accelerating deforestation, biodiversity loss and soil overexploitation.

5.2 Optimisation of footprint and land-use indicators

The transition to plant-based production drastically reduces resource use, acting as a strategy to prevent energy and material waste at source [11]. As highlighted in the results section, iconic products on the global market (such as Beyond Meat or the Impossible Burger) reduce greenhouse gas emissions by around 90 per cent compared with conventional beef. A direct comparison between cow's milk and plant-based alternatives (almond, oat, coconut, soya) confirms high water consumption and emission levels that are unsustainable given the planet's biocapacity [12].

Replacing animal proteins with plant-based ones frees up to 96 per cent of arable land, optimising soil resilience and keeping the global food system within planetary ecological boundaries [13], thereby counteracting ecological degradation within the critical thresholds of global warming (+2°C by 2050).

6. BEHAVIOURAL ECONOMICS, PACKAGING AND GREENWASHING

The ecological transition requires that the matching of supply and demand takes place transparently. Behavioural economics studies how 'nudges' (gentle prompts) and accurate labelling influence the informed consumer. In this context, food packaging plays a crucial communicative and persuasive role. The adoption of internationally recognised labels and certifications (such as 'The Vegan Trademark' or 'VEGANOK') combats the phenomenon of greenwashing, ensuring total transparency throughout the entire production chain. Indeed, modern consumers no longer evaluate just the finished product; they demand that packaging complies with the three levels of packaging required by Italian legislation, based on criteria of eco-design, recyclability and biodegradability, thereby reducing the impact of single-use plastic polymers (as demanded by the generations driving change and by young consumers).

7. DISCUSSION/CONCLUSION

The data collected and the strategic framework demonstrate that the 'Veg*' sector represents a fundamental pillar of the circular economy and integrated sustainability. Reducing dependence on traditional livestock supply chains [3] and implementing industrial models based on plant-based inputs, the upcycling of organic by-products and eco-designed packaging is the key to achieving the Sustainable Development Goals (SDGs) of the UN's 2030 Agenda. Companies that are able to capitalise on this shift in consumption patterns, by investing in food tech, materials innovation and transparent communication, will lead the transition towards a regenerative, near-zero-emissions economy.

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FROM WASTE MANAGEMENT TO ECO-DESIGN: EXTENDED PRODUCER RESPONSIBILITY AS A REGULATORY TOOL FOR FAST FASHION

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ABSTRACT

Fast fashion presents critical challenges for contemporary sustainability law, exposing the inadequacy of traditional legal mechanisms against the externalities of accelerated production and fragmented global supply chains. This article examines the evolution of Extended Producer Responsibility (EPR) within EU law, arguing that its regulatory function has shifted from post-consumer waste management toward a preventive governance model centered on eco-design. Through a comparative analysis of Italian and French frameworks, this paper demonstrates how EPR influences manufacturers' strategic decisions by promoting product durability, reparability, and recyclability. Consequently, eco-design emerges as the new regulatory paradigm reconciling industrial competitiveness with circular economy objectives.

Keywords: Fast Fashion; Extended Producer Responsibility; Eco-design; Circular Economy; Comparative Private Law; Sustainability.

1. INTRODUCTION

Fast fashion represents one of the clearest manifestations of the structural tensions affecting contemporary global markets. The acceleration of production cycles, the dramatic reduction of product lead times, the continuous introduction of new collections and the fragmentation of global value chains have profoundly transformed the textile industry, making it one of the sectors with the highest environmental footprint in terms of resource consumption, waste generation and pollution [1]. The legal relevance of this phenomenon extends far beyond its environmental implications. Rather, fast fashion challenges the adequacy of traditional concepts of corporate responsibility, which were originally conceived within linear production models where production, consumption and disposal constituted distinct and relatively autonomous phases. Contemporary global supply chains, by contrast, disperse decision-making processes across multiple jurisdictions while simultaneously separating economic power from legal accountability. As a result, identifying effective mechanisms capable of allocating environmental responsibility throughout the entire life cycle of products has become increasingly difficult [2]. Against this background, Extended Producer Responsibility (EPR) has progressively emerged as one of the most innovative regulatory instruments developed within European environmental law. Originally conceived as a mechanism for allocating post-consumer waste management costs to producers, EPR has undergone a profound conceptual transformation: rather than merely financing waste collection and

recycling systems, recent European legislation increasingly employs EPR as a preventive regulatory instrument capable of influencing industrial decision-making before products even reach the market [3]. This evolution places eco-design at the centre of the regulatory framework. Product durability, reparability, reusability and recyclability are no longer regarded solely as technical or engineering considerations but have gradually acquired genuine legal significance. Product design itself has become the object of legal regulation, reflecting a broader shift from ex post environmental remediation towards ex ante environmental prevention [4]. This article argues that the most innovative feature of contemporary European sustainability law does not simply consist in extending producers' liability beyond the commercialisation of products. Rather, its originality lies in transforming Extended Producer Responsibility into a preventive regulatory mechanism capable of shaping business strategies through eco-design requirements. By comparing the Italian and French legal frameworks, the paper demonstrates that the French model anticipates many of the objectives currently pursued by European sustainability legislation, placing eco-design at the core of corporate environmental responsibility.

2. METHODS

This study adopts a comparative legal methodology, combining doctrinal analysis with a systematic examination of the recent evolution of European sustainability legislation applicable to the fast fashion industry. The comparative analysis focuses on the Italian and French legal systems, selected because they represent two different approaches to the implementation of EPR within the common framework established by the European Union. The Italian model is examined through the provisions of Legislative Decree No. 152/2006, as amended by Legislative Decree No. 116/2020, while the French framework is analysed with particular reference to the *Loi Anti-gaspillage pour une économie circulaire* (Loi AGEC), which has introduced one of the most advanced EPR schemes currently operating within the European Union [2, 5]. The analysis further considers the interaction between EPR and the most recent European legislative initiatives, including the Ecodesign for Sustainable Products Regulation (ESPR), the Corporate Sustainability Reporting Directive (CSRD), the Corporate Sustainability Due Diligence Directive (CSDDD) and Directive (EU) 2024/825 on empowering consumers for the green transition. These instruments are not examined separately but as complementary components of a common regulatory framework aimed at integrating sustainability into the entire product life cycle.

Finally, the paper adopts the AGCM proceedings against SHEIN as a case study illustrating the practical implications of the current regulatory framework. Rather than constituting the central focus of the analysis, the case is used to demonstrate how preventive regulatory instruments based on eco-design may provide a more effective response to the environmental challenges of fast fashion than ex post enforcement mechanisms addressing misleading environmental claims.

3. FINDINGS

The analysis demonstrates that Extended Producer Responsibility (EPR) has progressively evolved from a policy instrument primarily aimed at financing waste management into a broader regulatory mechanism capable of influencing product design and corporate decision-making. Traditionally, producers' obligations were limited to the post-consumer phase, with responsibility essentially consisting of bearing the financial and organisational costs associated with waste collection and treatment. However, recent developments in European environmental law reveal a significant shift towards a preventive approach based on the entire life cycle of products [2, 5]. The amended Waste Framework Directive (Directive (EU) 2018/851) requires Member States to establish EPR schemes that not only ensure effective waste management but also encourage producers to minimise environmental impacts through product durability, reparability, reusability and recyclability. Consequently, the producer's responsibility is no longer confined to the end-of-life phase but extends to the earliest stages of product development, where environmental impacts can be prevented rather than merely mitigated. This evolution is particularly relevant in the fast fashion sector, where accelerated production cycles, shortened lead times and continuously increasing consumption patterns generate substantial environmental externalities. Within this context, EPR emerges as a preventive regulatory tool capable of internalising environmental costs and encouraging manufacturers to integrate sustainability criteria into their production strategies. The findings therefore suggest that the contemporary function of EPR extends beyond waste management, becoming an instrument of market regulation that promotes sustainable production models. The comparative analysis highlights significant differences between the Italian and French implementation of Extended Producer Responsibility, despite both legal systems operating within the same European regulatory framework. The Italian model, implemented through Article 178-bis of Legislative Decree No. 152/2006, establishes producers' financial, organisational and informational obligations throughout the product life cycle. Nevertheless, the system remains predominantly procedural, relying extensively on implementing decrees, administrative supervision and reporting obligations. Although mechanisms such as eco-modulated contributions have been introduced, their practical effectiveness largely depends on future regulatory implementation and administrative enforcement [6, 7]. By contrast, the French model, established through the *Loi Anti-gaspillage pour une économie circulaire* (Loi AGEC), adopts a more preventive and integrated approach. Producer responsibility extends beyond financing waste management to include product durability, repairability, transparency and eco-design. Economic incentives based on eco-modulation encourage manufacturers to improve the environmental performance of products before they enter the market, thereby incorporating sustainability directly into industrial decision-making [8]. The comparison therefore suggests that, whereas the Italian system continues to prioritise procedural compliance, the French framework already reflects the preventive rationale underpinning the latest developments in European sustainability law.

The findings further demonstrate that eco-design represents the most significant innovation within the current European regulatory framework governing fast fashion. The adoption of Regulation (EU) 2024/1781 (Ecodesign for Sustainable Products Regulation) confirms a transition from policies centred on waste management towards legislation capable of regulating the environmental characteristics of products before they are placed on the market [7].

Unlike previous regulatory approaches, the ESPR establishes sustainability requirements concerning durability, reparability, recyclability and resource efficiency, thereby transforming product design into the primary instrument for preventing waste generation. Eco-design consequently acquires a legal dimension that extends beyond technical product development, becoming a regulatory criterion through which manufacturers are required to integrate environmental considerations into production processes. Overall, the findings indicate that the evolution of Extended Producer Responsibility has fundamentally altered the regulatory approach adopted by the European Union. Responsibility is no longer assessed exclusively on the basis of waste management after consumption but increasingly depends on the producer's ability to prevent environmental impacts through sustainable product design. Eco-design therefore emerges as the operational expression of EPR and the cornerstone of the transition towards a circular economy within the fast fashion industry.

4. DISCUSSION/CONCLUSIONS

The findings demonstrate that the evolution of Extended Producer Responsibility (EPR) reflects a broader transformation of European sustainability law, shifting the regulatory focus from waste management to product design. This transition is particularly significant in the fast fashion sector, where the environmental impact of products is largely determined before they reach the market. Consequently, the effectiveness of sustainability policies increasingly depends on the ability of legal frameworks to influence production choices rather than merely regulate waste once it has been generated. The comparative analysis confirms that the implementation of EPR is not uniform across Member States. Although both Italy and France operate within the same European legislative framework, they pursue different regulatory strategies. The Italian system remains predominantly procedural, relying on administrative obligations, reporting mechanisms and future implementing measures. By contrast, the French model adopts a preventive approach in which producer responsibility extends to product durability, reparability, transparency and eco-design, thereby integrating sustainability into the earliest stages of product development. This comparison suggests that the French experience anticipates the regulatory direction subsequently reinforced by European legislation. The adoption of the Ecodesign for Sustainable Products Regulation (ESPR) further supports this interpretation. By introducing mandatory sustainability requirements relating to durability, reparability, recyclability and resource efficiency, the Regulation confirms that product design has become the principal regulatory instrument through which

environmental impacts are prevented rather than corrected. Eco-design therefore represents the operational dimension of Extended Producer Responsibility, transforming producers' obligations from reactive waste management into proactive environmental governance [9]. This evolution also reshapes the relationship between corporate sustainability and consumer protection.

The adoption of the Corporate Sustainability Reporting Directive (CSRD), the Corporate Sustainability Due Diligence Directive (CSDDD) and Directive (EU) 2024/825 demonstrates that European sustainability law increasingly combines environmental responsibility, corporate governance and market transparency within a single regulatory framework [10, 11, 12]. These instruments complement EPR by requiring undertakings not only to manage environmental impacts but also to demonstrate that sustainability considerations are integrated into their business models and value chains.

The proceedings initiated by the Italian Competition Authority (AGCM) against SHEIN provide a practical illustration of these developments. The case shows that environmental claims become misleading when they are not supported by objective evidence or by genuine improvements in product sustainability. While Directive (EU) 2024/825 strengthens the legal framework against greenwashing through enhanced transparency obligations, the present analysis suggests that ex post enforcement alone is insufficient to address the structural environmental challenges posed by fast fashion. Preventive regulatory mechanisms, particularly those promoting eco-design through Extended Producer Responsibility, offer a more effective means of reducing environmental impacts before misleading claims arise.

Overall, this study argues that the most significant innovation of recent European sustainability law does not lie solely in extending producers' responsibility throughout the product life cycle; rather, it consists in relocating legal responsibility to the design phase, where environmental impacts can be prevented through sustainable product development. Eco-design therefore emerges as the new regulatory paradigm governing the evolution of Extended Producer Responsibility, linking circular economy objectives, corporate sustainability and consumer protection within a coherent preventive framework.

The fast fashion industry demonstrates that sustainability can no longer be achieved exclusively through end-of-life waste management policies; instead, it requires regulatory instruments capable of shaping production models from their inception and Extended Producer Responsibility evolves from a waste management mechanism into a comprehensive regulatory tool that promotes circularity, responsible innovation and environmental accountability, confirming that the future of European sustainability law lies not in managing waste more efficiently, but in preventing its generation through sustainable product design.

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SURFACE FUNCTIONALIZATION OF BIODEGRADABLE FILMS BY COLD PLASMA TREATMENT FOR PACKAGING APPLICATIONS

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ABSTRACT

Biodegradable polymers are promising candidates for sustainable packaging; however, their intrinsically low surface energy and poor interfacial adhesion limit their performance in coating, printing, and lamination applications. This study investigates cold plasma treatment as an effective surface functionalization strategy for biodegradable films based on polylactic acid (PLA), polybutylene succinate (PBS), polybutylene succinate adipate (PBSA), and a PBSA/PLA (70/30) blend. Process parameters (treatment time, power, and gas flow rate) were optimized through a Design of Experiments (DoE) combining Response Surface Methodology (RSM) and Machine Learning (ML). This modelling approach successfully identified optimal processing conditions while substantially reducing the experimental matrix to explore. Cold plasma enhanced the surface wettability of all investigated films, promoting their suitability for sustainable, water-based inks and coating formulations. Surface energy evolution and hydrophobic recovery strongly depended on polymer chain mobility, whereas the bulk properties remained essentially unaffected, confirming the surface-selective nature of the treatment.

Keywords: Cold plasma; Biodegradable films; Surface functionalization; Wettability; Design of Experiments; Machine Learning; Food packaging.

1. INTRODUCTION

The global push for sustainable packaging and increasing environmental concerns associated with plastic waste have driven research into more sustainable alternatives [1]. Biodegradable polymers offer significant environmental advantages over conventional fossil-based plastics, including reduced carbon footprint and end-of-life compostability; however, they often suffer from intrinsic limitations such as low surface energy, poor barrier properties, and weak interfacial adhesion [2]. These drawbacks make surface functionalization a necessary step to enable their use in applications such as coating deposition, printing, and adhesive lamination. Among biodegradable polyesters, PBS, PBSA, PLA and their blends are of particular industrial interest due to their favorable processability and balanced mechanical and thermal properties; nevertheless, their surface characteristics generally require targeted modification to achieve adequate functional performance. From an industrial perspective, cold plasma treatment has emerged as particularly interesting surface functionalization strategy; it is solvent-free, scalable, and, since it operates at relatively low temperatures, it is compatible with thermally sensitive biopolymers [3].

The outcome of plasma treatment strongly depends not only on the nature of the substrate but also on the processing conditions, including the type of ionizing gas, treatment time, applied power, and gas flow rate, each of which influences surface functionalization mechanisms[4]. Therefore, process optimization is required to enhance surface wettability while avoiding polymer degradation and preserving the thermal and mechanical stability of the material. While several studies have investigated plasma treatment of biodegradable films based on poly(lactic acid), relatively few works have addressed the plasma modification of other biopolymers such as PBS, PBSA or their blends. In addition, only a limited number of studies have systematically investigated the optimization of plasma processing parameters using statistical modeling approaches. As a result, the relationship between operating conditions and surface functionalization efficiency remains insufficiently explored.

In this scenario, this study aimed at investigating the effects of cold plasma treatment on biodegradable films based on PBS, PBSA, PLA and PBSA/PLA 70/30 w/w blend, to improve surface wettability and functional performance for sustainable packaging applications. A data-driven approach based on Response Surface Methodology and Machine Learning was applied to optimize the plasma processing conditions while minimizing the water contact angle within the investigated operating window. The optimized treatment was subsequently validated through the characterization of the films in terms of surface wettability, chemical and physical properties, as well as printability, in order to assess their suitability for food packaging applications.

2. METHODS

The biodegradable polymers used in this study were: PBS (Zhuhai Kingfa Biomaterial Co., Ltd.), PBSA (BioPBS FD92PM, Mitsubishi Chemical Group) and PLA (Luminy® L175, Total Corbion). All biodegradable polymers are suitable for food contact in conformity with regulations established by Food and Drug Administration (FDA) and European Union (EU).

2.1 Realization of the biodegradable films

Before processing, PLA, PBS and PBSA granules were vacuum-dried at 70 °C for 10 h. PBSA/PLA blend, having mass ratio equal **to** 70/30 w/w, was prepared by melt compounding using a Collin ZK25 co-rotating twin-screw extruder (L/D = 42, diameter = 25 mm), selecting a screw speed equal to 60 rpm, a temperature profile from 180 °C to 190 °C from hopper to die.

Monolayer films based on PBS, PBSA, PLA and PBSA/PLA blend were realized by cast film extrusion apparatus, equipped with a coat-hanger flat head. Table 1 shows a recap of the produced films, temperature profiles and processing parameters used and obtained thicknesses.

Table 1: *Recap of the produced films, temperature profiles and processing parameters used and obtained thicknesses.*

Sample	T1	T2	T3	T_die	Take up speed [m/min]	Film thickness [µm]	Draw Ratio
PBS	150°C	155°C	145°C	145°C	2.9	65	1.0
PBSA	150°C	155°C	145°C	145°C	2.9	60	1.0
PLA	190°C	185°C	185°C	175°C	2.8	60	1.0
PBSA/PLA 70/30	190°C	185°C	185°C	180°C	2.2	50	1.2

2.1.1 Plasma treatment and data-driven optimization of process parameters

Plasma treatment was performed in a capacitively coupled plasma (CCP) reactor operating under low-pressure conditions (Diener Electronic Atto-BLS low-pressure plasma system, 40 kHz RF generator, 0–200 W), using oxygen as the working gas. The process variables were treatment time, applied power (0–100% of the maximum output), and oxygen flow rate (0–1 NL min^{-1}).

Response Surface Methodology (RSM), supported by a Design of Experiments (DoE) approach, was used to systematically assess the individual and interactive effects of the process variables on film wettability. The analysis aimed to identify the optimal process conditions that minimize the water contact angle (WCA) and, consequently, improve film wettability. A three-factor, face-centered Central Composite Design (CCD) was initially employed to generate the experimental dataset and define a preliminary response surface. A Box–Behnken Design (BBD) was subsequently applied to refine the experimental model and improve its adequacy within the investigated processing domain.

The experimental data generated through the DoE approach were further analyzed using Random Forest Regression (RFR). The model was developed to improve predictive robustness, capture potential nonlinear relationships among the processing variables, and identify the combination of treatment time, applied power, and oxygen flow rate associated with the minimum predicted water contact angle within the experimentally validated domain. PBS was selected as the reference substrate for process optimization. The optimal treatment conditions identified for PBS were subsequently applied to PLA, PBSA, and PBSA/PLA films to evaluate the influence of polymer composition and structure on plasma-induced surface modification.

2.1.2 Characterization techniques

Films wettability and hydrophobic recovery were evaluated through contact angle measurements, performed using the sessile-drop method with an FTA 1000 contact-angle analyzer (First Ten Angstroms, Inc., Portsmouth, VA, USA), in accordance with ASTM D7490.

Liquid droplets with a volume of 2.0 ± 0.5 µL were deposited onto the sample surface using a microsyringe. Images of the droplets were acquired immediately after deposition using the integrated video camera,

and the contact angle was determined from the droplet profile using the instrument's proprietary image-analysis software.

The surface free energy (SFE) and its dispersive (γ_s^d) and polar (γ_s^p) components were calculated using the Owens–Wendt geometric-mean method[5].

Distilled water and diiodomethane, whose surface-tension components are known, were used as probe liquids [6]. Printability tests were performed to evaluate the effectiveness of plasma treatment in improving the adhesion of water-based inks to the biodegradable films.

A commercial water-based flexographic ink (Aquathene SP, DIC Graphics) was applied onto untreated and plasma-treated film surfaces using an RK Multi Coater K303S (RK Print Coat Instruments Ltd., Royston, UK) equipped with a No. 2 wire-wound (Mayer) bar, providing a nominal wet coating thickness of 12 µm.

The coated samples were allowed to dry for 24 h under ambient temperature and relative humidity conditions. Ink adhesion was subsequently evaluated by means of tape test according to ASTM D3359-23. The adhesion performance was qualitatively assessed by comparing the extent of ink removal after tape detachment.

3. FINDINGS

The CCD exhibited a significant lack-of-fit, indicating that the relationship between plasma processing parameters and WCA could not be adequately described by a second-order polynomial model. A subsequent BBD improved the model fit; however, the predicted optimum fell outside the operative instrument domain and could not be experimentally validated. To overcome this limitation, the dataset was further analyzed using RFR, partitioning it into training (80%) and testing (20%) sets to develop the predictive model. The RFR identified optimal processing conditions of 120 s, 100% power and 0.5 NL min^{-1} oxygen flow rate, corresponding to a predicted WCA of 45.06°. Experimental validation yielded a WCA of 46.32 ± 0.10°, with a prediction error of only 1.26°, confirming the predictive reliability of the RFR model. Additional treatments performed at longer exposure times (128 and 150 s) resulted in higher WCA values (50.9° and 49.3°, respectively), further confirming that the identified conditions represent the optimum within the investigated operating window. The optimized treatment conditions were subsequently applied to PBSA, PLA L175 and a PBSA/PLA 70/30 blend.

Untreated films exhibited WCA values ranging from approximately 70° to 80°, which are typical of aliphatic polyesters owing to the low polarity of their hydrocarbon-rich molecular backbones[7]. Following plasma exposure, all materials showed a significant reduction in WCA, confirming the effectiveness of oxygen plasma in increasing surface polarity through the incorporation of oxygen-containing functional groups, such as hydroxyl, carbonyl, and carboxyl moieties[8]. This behavior was further supported by the surface free energy (SFE) measurements, which showed an increase in the total SFE for all plasma-treated films, mainly attributed to the polar component, whereas the dispersive component remained nearly

unchanged. The greatest wettability improvement was observed for PBS and PBSA, whose WCA decreased by approximately 35% and 36%, respectively. This behavior is likely associated with the higher chain mobility of these polymers, which facilitates molecular rearrangements and the incorporation of polar functionalities during plasma exposure[9]. However, the same structural feature also promoted a more pronounced hydrophobic recovery during aging. Indeed, PBS and PBSA exhibited the largest increase in WCA within the first 48 h after treatment, indicating a progressive reorientation of the plasma-induced polar groups from the surface toward the polymer bulk. After 5 days, the WCA values converged to approximately 63°, suggesting that most of the hydrophobic recovery had occurred during the initial aging period. Conversely, PLA and PBSA/PLA films showed a smaller initial reduction in WCA (28% and 29%, respectively) but exhibited greater stability over time, suggesting that their lower chain mobility limits surface molecular rearrangements and better preserves the plasma-induced surface activation.

The printability tests (Figure 1) validated the effectiveness of the optimized plasma treatment under a practical coating application. Untreated PBS films showed poor ink adhesion, with extensive coating removal after the tape test, whereas plasma-treated films retained the coating almost completely, indicating a substantial improvement in adhesion. The improved printability is attributed to the increased surface wettability induced by oxygen plasma, which enhances the spreading and anchoring of the water-based ink. These results confirm the potential of cold plasma treatment as a simple and environmentally friendly surface modification technique for biodegradable packaging films.

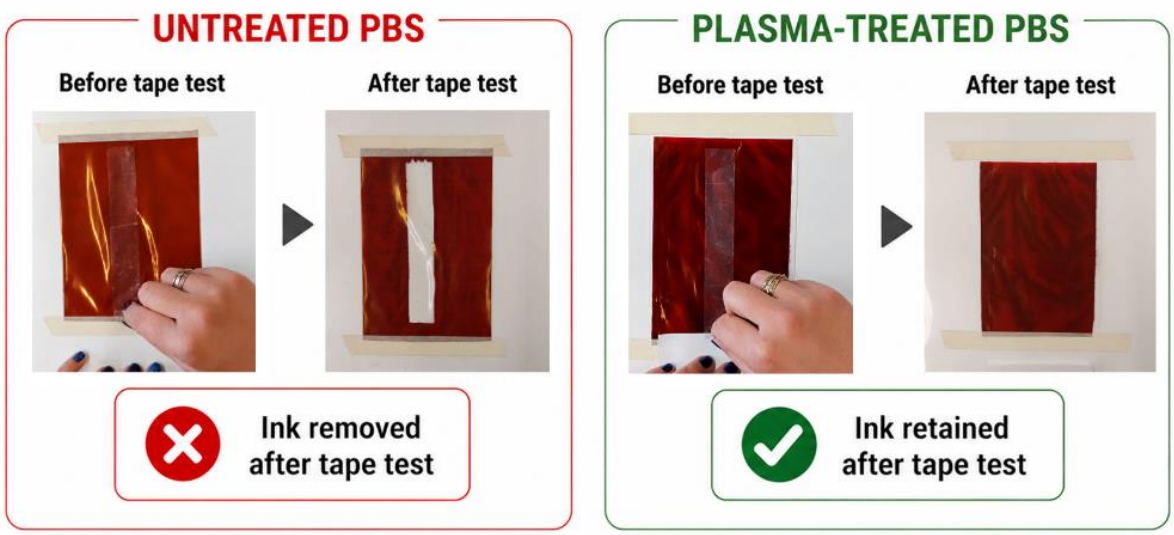


Figure 4: *Printability evaluation of untreated and oxygen plasma-treated PBS films by tape test (ASTM D3359-23).*

4. Discussion and Conclusion

This work demonstrated the effectiveness of cold plasma treatment as a sustainable surface modification strategy for biodegradable polymer films based on PBS, PBSA, PLA, and PBSA/PLA blends intended for food packaging applications. A data-driven optimization approach combining RSM and RFR successfully

identified the optimal plasma processing conditions, enabling a significant improvement in surface wettability while minimizing the experimental effort. The increase in surface polarity resulted in markedly improved adhesion of water-based inks, confirming the effectiveness of the treatment for printing processes relevant to food packaging. More broadly, the enhanced wettability can also facilitate the deposition of hydrophilic functional coatings, such as poly(vinyl alcohol) (PVOH), which is widely considered for the development of high-oxygen-barrier packaging structures. Aging studies highlighted the influence of polymer chain mobility on the stability of the plasma-induced surface activation, with PBS and PBSA showing the most pronounced hydrophobic recovery. Preliminary investigations also indicated that plasma treatment primarily affects the outermost surface layers without significantly altering the bulk chemical, thermal, mechanical, or barrier properties of the films.

Overall, the proposed data-driven strategy represents an effective, scalable, and environmentally friendly approach to improve the printability and coatability of biodegradable films for sustainable high-performance food packaging applications.

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SERVICE-BASED LIFE CYCLE APPROACH TO SUPPORT LIFETIME EXTENSION STRATEGY OF SMARTPHONES: FROM REPAIR INCENTIVES TO BEHAVIOURAL SCENARIOS

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ABSTRACT

Smartphones are associated with significant environmental impacts, largely driven by short effective lifetimes. Extending device use is often proposed as a strategy to reduce these impacts. This study assesses how smartphone lifetime-extension strategies influence climate-change impacts in Germany. A cohort-based model representing device ageing, failure, repair, and replacement behaviour is coupled with a Life Cycle Assessment (LCA) approach using a service-based functional unit of one smartphone-year. Three scenarios are analysed: a baseline reflecting current use patterns, a repair-incentive scenario with increased repair uptake, and a behavioural lifetime-extension scenario with progressively longer median device lifetimes. Results show that repair incentives produce a small reduction in climate-change impacts per smartphone-year while behavioural lifetime-extension scenarios yield larger reductions. These findings indicate that repair incentives may be most effective when embedded with broader behavioural changes that promote longer device retention.

Keywords: Smartphones; Life Cycle Assessment (LCA); Lifetime Extension; Repair Incentives; Cohort-based Model; Scenarios Analysis.

1. INTRODUCTION

The Information and Communication Technology (ICT) sector is increasingly recognized as a significant contributor to global greenhouse gas (GHG) emissions [1]. Smartphones are one of the key components contributing to ICT-related environmental impacts, with the production phase representing the hotspot of their life cycle and accounting for approximately 85-95% of their total greenhouse gas emissions [2]. At the same time, smartphones replacement cycles are relatively short, often around two to three years, driven by rapid technological change, perceived obsolescence, and market-driven upgrade incentives [2]. Lifetime extension is therefore a key strategy for reducing smartphone-related impacts [2]. Repair, i.e. replacing only the failed components rather than the entire device, is one of the circular economy strategies to extend lifetimes [3]. In practice, however, smartphones often leave active use without technical failure: devices are replaced at contract renewal, for aesthetic preferences, perceived obsolescence or declining resale value, so behavioural and institutional factors play a major role [4], [5].

When technical failures do occur, the display and the battery are the components most likely to require repair [6], yet only 11% of users opt for repair when their smartphone fails, while 59% in Germany replace it immediately [7]. Repair probability also decreases sharply with device age (around 50% of broken displays are repaired within the first year, but only 17% by year four [5]), and cost is widely recognised as the primary deterrent. While financial incentives can address cost-related barriers, repair decisions are also shaped by behavioural factors that influence how users evaluate the worth of repairing a damaged device. Translating repair and behavioural dynamics into environmental outcomes at population level remains challenging. Most LCA studies still rely on device-based functional units, modelling a single smartphone with a fixed use-time regardless of whether the device actually reaches that lifetime. Real smartphone populations are instead heterogeneous: devices fail at different times, many replacements are non-technical, only a fraction of the stock is repaired, and lifetime extension does not apply uniformly [5]. To address this limitation, Proske [5] introduced a stock-based, service-oriented LCA approach in which the functional unit is "providing the functionality of mobile telephony and internet for one year" and impacts are linked to the material flows required to provide that service at population level. Building on this perspective, the present study combines a cohort-based model with a service-based functional unit within an LCA framework. By distinguishing technical failures, repair processes and behavioural replacement, it evaluates how repair incentives and cultural shift towards longer device retention influence the climate-change impacts associated with smartphone functionality, with particular attention to the German context.

2. METHODS

The methodological framework (Figure 1) combines reliability modelling, cohort simulation and LCA within a service-based perspective. First, Weibull distributions represent the age-dependent failure behaviour of smartphones, batteries and displays, and provide the failure rates that drive device outflows and spare-part demand. Second, these failure dynamics are implemented in a cohort-based simulation model developed in Microsoft Excel, which represents a stylised population of smartphones and distinguishes technical failures, repair events and non-technical replacement; scenarios are built by modifying repair behaviour and device longevity. Finally, the resulting flows are normalised to a service-based functional unit and integrated into an LCA to compare the alternative lifetime-extension strategies.

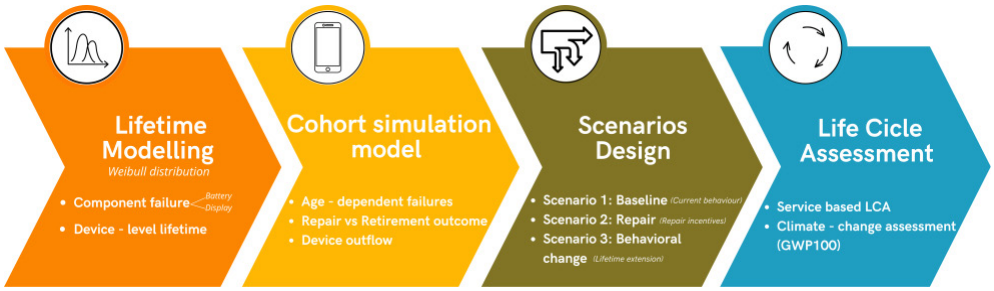


Figure 5: *Overview of the research design.*

2.1 The lifetime modelling

The Weibull distribution is characterised by a shape parameter (β) and a scale parameter (η), which allow different failure patterns to be represented. Batteries are modelled with wear-out behaviour (failure rate increasing with age), displays with a constant failure rate, and whole devices with an exit probability that increases over time. Battery and display parameters are taken from Proske [5], and device-level parameters from Zhilyaev et al. [8]; the device-level parameters correspond to a median active-use lifetime of approximately three years and represent overall device exits, including both technical and non-technical replacement.

2.2 The cohort simulation model

The model combines age-dependent Weibull hazard rates with literature-based repair probabilities to simulate a fixed cohort of smartphones in annual time steps over a seven-year horizon. Smartphones exit active use through technical outflows, driven by battery and display failures that may lead to repair or retirement, or through non-technical outflows representing behavioural replacement. Component failures are assumed to be statistically independent; age-dependent repair shares are applied to battery-only and display-only failures; and behavioural exits are represented residually, as the share of device exits not attributed to modelled component failures. The model returns the annual device outflows and the number of batteries and displays replaced each year. By modifying repair probabilities and behavioural replacement patterns within the cohort simulation, the model generates scenario-specific devices and spare-parts flows.

2.3 Scenarios description

Three scenarios are considered: (1) a baseline representing current use conditions in Europe and Germany, with a median device lifetime of three years and current component failures, repair behaviour and non-technical outflows; (2) a repair scenario in which repair shares are increased to represent a financial repair incentive; and (3) behavioural scenarios (3a–3d) in which the median device lifetime increases from three to four, five, six and seven years. The repair scenario leaves the device-level lifetime distribution unchanged, whereas the behavioural scenarios increase η while keeping β constant; in the latter, component-level failure distributions remain unchanged and the enhanced repair shares of the repair scenario apply. Finally, the results obtained from the cohort model are normalized with the service-based functional unit to obtain scenario-specific reference flows expressed per smartphone-year.

2.4 Life cycle modelling framework

To assess the environmental implications of the scenarios, a comparative service-based LCA is conducted in accordance with ISO 14040 [9] and ISO 14044 [10], using the open-source software Activity Browser. The assessment focuses on relative differences between scenarios rather than on the absolute

footprint of a specific smartphone model. All scenarios use the same inventories, background data and system boundaries, so that differences in impacts arise only from device lifetime and repair behaviour. The system follows a cradle-to-grave perspective for the complete smartphone, while spare batteries and displays are modelled from production through transport and end-of-life. The inventory is based on ecoinvent v3.12 (cut-off system model), complemented by parameters from Fairphone LCA studies. Climate change is assessed as Global Warming Potential over 100 years (GWP100) using the IPCC 2013 method.

3. FINDINGS

Table 1 reports the climate-change impacts of all scenarios, expressed per functional unit, i.e. one smartphone-year of service.

Scenario (median lifetime)	Smartphone service	Spare batteries	Spare displays	Total GWP100 (kg CO_2-eq)
1 – Baseline (3 years)	18.62	0.021	0.028	18.669
2 – Repair	18.29	0.035	0.056	18.381
3a – Behavioural (4 years)	13.87	0.036	0.033	13.939
3b – Behavioural (5 years)	10.96	0.029	0.016	11.005
3c – Behavioural (6 years)	9.16	0.021	0.011	9.192
3d – Behavioural (7 years)	7.89	0.015	0.005	7.910

Table1: *Climate-change impacts per smartphone-year of service across scenarios (kg CO_2-eq, GWP100)*

The LCA results show a limited reduction in climate-change impact between the baseline and the repair scenario, and substantially larger reductions in the behavioural lifetime-extension scenarios. As reported in Table 1, GWP100 decreases from 18.669 to 18.381 kg CO_2-eq per smartphone-year, a reduction of approximately 0.29 kg CO_2-eq (≈1.5%). This net reduction results from two opposing effects: increased repair raises spare-part demand, but it also reduces by about 2% the number of new smartphones required per smartphone-year of service. The behavioural scenarios show a progressive reduction in GWP100 as the median lifetime increases: already the first behavioural scenario 3a, in which the median smartphone lifetime increases from 3 to 4 years, yields a marked reduction compared with both the baseline and repair scenarios (≈25% below baseline), reaching ≈58% below baseline at seven years. Spare batteries and displays account for less than 0.5% of the total impact in all scenarios.

4. DISCUSSION/CONCLUSION

The results show that increasing repair uptake alone through financial incentives that reduce the cost barrier to repair, yields only a modest reduction in climate-change impacts per smartphone-year.

Higher repair rates increase the use of spare batteries and displays but partially displace the provision of new smartphones. Under the assumed modelling structure and life-cycle inventory, this displacement is sufficient to generate a small net environmental benefit. However, the magnitude of this reduction remains limited because repair incentives primarily influence the response to technical failures and do not substantially alter overall device lifetimes when non-technical replacement behaviour remains unchanged. These findings should be interpreted in light of the study's methodological limitations.

The cohort model represents a stylised, closed population and does not capture dynamic market evolution, changes in total stock size, or explicit behavioural decision-making. Component reliability parameters are not Germany-specific, repaired components are assumed to follow the same failure behaviour as the original ones, and the life cycle assessment relies on secondary inventory data representing an aggregated smartphone product; the numerical results should therefore be read as comparative indicators under consistent assumptions rather than as predictive estimates of national emission reductions. Despite these limitations, the study offers clear insights into the relative effectiveness of different lifetime-extension strategies, showing that repair incentives alone address only the economic barrier to repair, while larger environmental gains require a parallel shift in replacement behaviour. Future work could build on this foundation in three directions: embedding the cohort model within a dynamic stock–flow framework calibrated to country-specific data on smartphone sales, stocks, repair volumes and user behaviour; extending the simulation horizon and explicitly modelling behavioural replacement decisions to represent lifetime-accumulated repairs and post-horizon service provision more realistically; and updating the life-cycle inventory with newer, product-specific datasets to improve the robustness of absolute impact estimates.

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DESIGN TOOLS FOR DESIGN FOR DISASSEMBLY: A BIM APPLICATION FOR EVALUATING CONSTRUCTION SOLUTIONS COMPATIBLE WITH THE DISASSEMBLY AND REUSE OF BUILDING ELEMENTS.

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ABSTRACT

This study aims to develop a BIM application to support design based on Design for Disassembly (DfD) principles, in compliance with the ISO 20887:2020 [1] standard. Specific parameters were defined, and two algorithms were developed using Dynamo for Revit. The first calculates a "DfD Index" to measure the disassemblability of construction elements; the second assesses compliance and calculates the percentage by weight of reusable components, in accordance with the Minimum Environmental Criteria (MEC 2022) [2]. The application was tested on the project of the Bar in San Giorgio a Cremano's park (NA). As the initial analysis revealed significant issues, the building was redesigned using dry-construction systems and prefabricated elements, thereby achieving 100% compliance without altering the original design concept. This work provides an innovative tool for verifying the reversibility of design choices, with future developments envisaged regarding the use of the pen IFC format and certified CAM validation.

Keywords: Design for Disassembly (DfD); Building Information Modeling (BIM); Circular Economy; Sustainable Construction; Minimum Environmental Criteria (MEC).

1. INTRODUCTION

The construction sector has a massive environmental impact; in Italy, according to the 2025 ISPRA [3] report, as much as 50.6% of special waste originates from construction and demolition activities. Currently, most of these materials undergo low-value downcycling processes, wasting both the energy required for their production and their economic value. To counter this linear trend, it is essential to apply Circular Economy principles, of which Design for Disassembly (DfD) is a cornerstone. DfD is an approach that conceives buildings with "deconstruction" in mind, maximizing ease of disassembly to facilitate the recovery, repair, and recycling of components at the end of the building's service life. Integrating these concepts into Building Information Modelling (BIM) is crucial for digitizing the material cycle; BIM enables the transformation of every component into a traceable resource, facilitating the creation of "material passports" and supporting performance assessments. This study outlines the development of a BIM-based application for monitoring and evaluating construction solutions within the current theoretical and regulatory framework of DfD.

The results are presented according to the three phases of the research: first, the analysis of the ISO 20887 standard to define standardized information parameters; second, the development of visual programming scripts using Dynamo to automate compliance verification; and finally, the application of the methodology to a real-world case study, evaluating the original construction solution and comparing it with an optimized redesign based on reversible, dry-assembly technologies.

2. METHODS

The project's methodological framework was developed by integrating BIM authoring software (Autodesk Revit 2026), visual programming tools (Dynamo 3.6.1), and data processing applications (Microsoft Excel, DiRoots One). The workflow comprised three fundamental steps: translating regulations into BIM parameters, computational automation, and application to the case study's architectural and structural models.

The theoretical basis for the assessment relies on the ISO 20887:2020 standard, which outlines requirements for integrating Design for Disassembly (DfD) and Design for Adaptability (DfA). Seven core principles were defined for DfD and three for DfA; these were translated into a text file containing shared parameters that could be imported into the BIM model using the DiRoots One plug-in. The seven DfD principles include:

- Ease of access: connections must be exposed and unobstructed.
- Independence and reversibility: building layers must not interfere with one another, and joints must not damage materials (with an exception allowed for the sectioning of linear elements such as beams and columns).
- Absence of unnecessary finishes: use of materials in their natural state.
- Circular Economy: use of materials that are reusable, refurbishable, or remanufacturable, or that contain a high percentage of recycled content.
- Simplicity: minimization of the number of different materials within a single component and absence of complex decorative details.
- Standardization: prevalence of prefabricated or modular elements.
- Safety of disassembly: inclusion of an integrated disassembly plan.

The Adaptability requirements (Versatility, Convertibility, Expandability) were applied solely at the "Project Information" level. Since the ISO standard does not provide specific weights, an importance scale ranging from 1 to 7 was established to weight the impact of each principle in order to calculate the element's final weighted average.

Two visual scripting algorithms were developed within the Dynamo environment for Autodesk Revit. The first script automates the population of DfD/A (Design for Disassembly/Adaptability) parameters

embedded in model objects and calculates a weighted "DfD Index," which defines the potential disassembly level of individual construction elements by assigning a score on a scale of 0 to 4. The second script evaluates the compliance of elements within the BIM model against the previously calculated DfD Index and predefined thresholds, automatically generating reports on the results. The system is also programmed to calculate the percentage by weight of demountable elements relative to the entire building, providing the data needed to verify the bonus criterion under the current 2022 Minimum Environmental Criteria (CAM) regulatory framework.

The validity of the procedure was tested by applying it to an existing detailed design project developed by the architectural firm ABDR—specifically, the "Bar del Parco" building in San Giorgio a Cremano (Naples). Three information models of the building were created—covering structural, architectural, and MEP (mechanical, electrical, and plumbing) elements—and the parameters developed during the research phase were integrated into the first two models. The scripts were executed to generate a DfD Index for each element in the analyzed models, along with the corresponding compliance result. This result was visualized through color mapping, allowing for the distinction between elements that meet disassembly criteria and those that present issues or fall below established thresholds.

3. FINDINGS

The algorithm highlighted significant issues, yielding an extremely low percentage by weight of compliant components. The extensive use of cast-in-place systems and hydraulic binders results in the irreversible bonding of components, necessitating destructive demolition. This monolithic nature precludes the direct reuse of materials, limiting the building's end-of-life options to downcycling processes. The structural model featured a monolithic foundation slab with a ventilated crawl space integrated by concrete infill, steel columns and beams partially connected via welding, and profiled steel decking floors with a concrete topping. The building envelope included internal partitions made of aerated autoclaved concrete blocks with traditional plaster.

Color mapping applied to the 3D views revealed a strong prevalence of red elements ("Non-compliant"). The Excel reports generated by the algorithm showed that the percentage by weight of elements deemed suitable for deconstruction was merely 24.37% for the architectural model and 15.15% for the structural model. These figures effectively rule out, from the outset, the possibility of obtaining CAM compliance certification, which requires a minimum threshold of 70%.

To bridge the regulatory gap, the project underwent a technological overhaul—with the exception of the deep foundations, which were retained in their original reinforced concrete due to a lack of baseline geotechnical data. Structurally, the steel connections were re-engineered to eliminate welding in favor of exposed bolted mechanical joints, ensuring the HEA profiles could be fully recovered and reused without

material degradation. Architecturally, "wet" construction methods were entirely replaced by dry-assembly layered technologies. The ground-bearing slab and roof assembly were redesigned using modular systems: floating floors consisting of cement-bonded wood panels supported by an adjustable metal framework and extruded polystyrene insulation; and internal partitions constructed by screwing cement-bonded wood boards onto galvanized steel C-studs. Exterior paving shifted from a mortar bed to a system of stoneware slabs dry-laid on a stabilized gravel bed. Suspended ceilings were also configured using accessible gypsum panels hung via spring hangers.

Re-running the assessment algorithm on these updated models yielded a complete reversal of the initial results. Indeed, the final reports generated by Dynamo confirmed that the percentage by weight of demountable and recoverable elements (excluding the foundation slab) reached 100% for both the architectural and structural models, thereby meeting and significantly exceeding the requirements of the Minimum Environmental Criteria.

The filtered chromatic view no longer displayed any "non-compliant" components, indicating a total absence of interference and irreversible binding between the components.

Total weight	Weight of conforming elements	Compliance percentage
223891,10	54560,08	24,37

Table 2 - *Extract from the general report sheet for the architectural model related to the ABDR project.*

Total weight	Weight of conforming elements	Compliance percentage
94840,46	14367,47	15,15

Table 3 - *Extract from the general report sheet for the structural model related to the ABDR project.*

Total weight	Weight of conforming elements	Compliance percentage
152600,11	152600,11	100,00

Table 4 *- Extract from the general report sheet for the architectural model related to the new project.*

Total weight	Weight of conforming elements	Compliance percentage
56241,39	56241,39	100,00

Table 1 *- Extract from the general report sheet for the structural model related to the new project.*

Name	Enable Filter	Visibility	Projection/Surface			Cut		Halftone
			Lines	Patterns	Transparency	Lines	Patterns	
Compliance	☒	☒	Override		Override	Override	Override	☐
Partial compliance	☒	☒						☐
Non-compliance	☒	☒						☐

Figure 1. *Compliance filter applied to populated models*

4. DISCUSSION/CONCLUSION

Based on the developed methodology and the results achieved, clear prospects for development

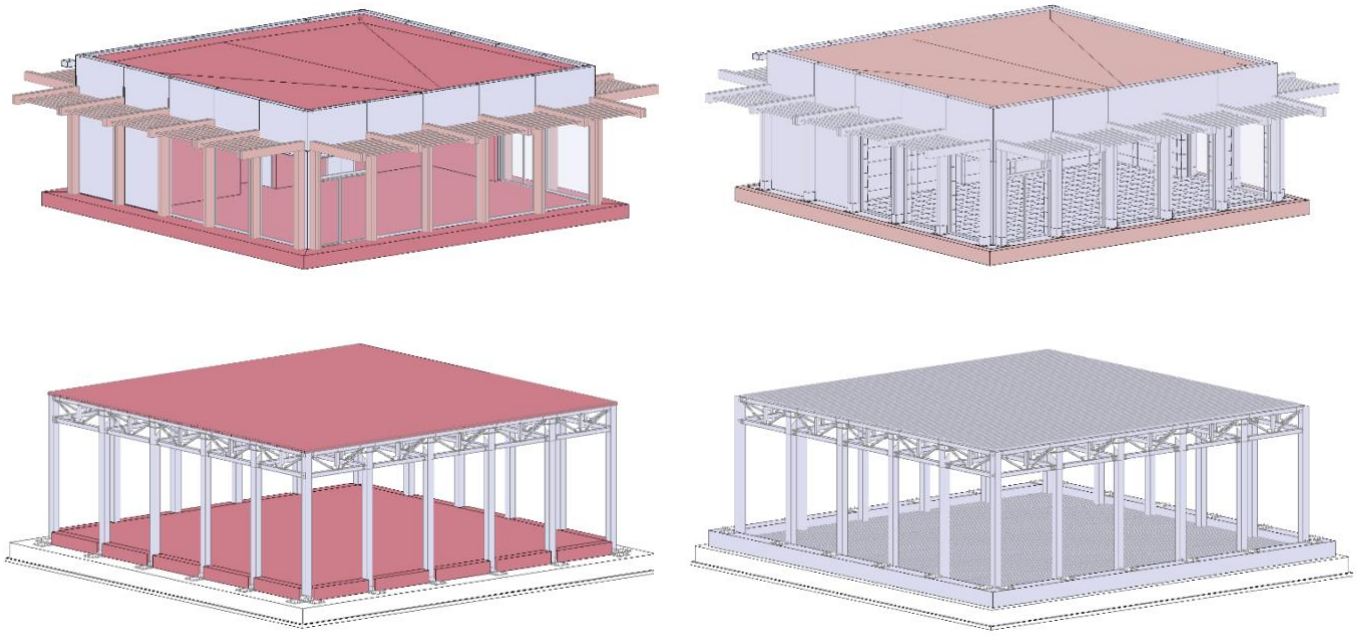


Figure 2 - *Models of the architectural and structural elements of the ABDR project and the new project, color-coded according to the elements' compliance value.*

emerge to establish this procedure as an industry standard. Key among these is the evolution of this experimental procedure into a dedicated software application integrated directly into the Autodesk Revit interface; this would facilitate usage and provide real-time support to designers through alerts and the generation of standardized automated reports. Furthermore, adapting the verification algorithms to work with open-format models (IFC) would be crucial, transforming the control tool into a universal application capable of analyzing models from any authoring software, thereby democratizing the process. Finally, a similar procedure could be developed for the certified validation of Minimum Environmental Criteria (CAM) by applying a comparable workflow to information models. In conclusion, the thesis demonstrates that the

transition toward a circular construction sector requires not only new construction technologies but also new digital verification tools. The developed procedure represents a first step toward data-driven design, where building reversibility is no longer merely a theoretical concept but a measurable and verifiable parameter.

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MEASUREMENT, ASSESSMENT AND REPORTING OF SUSTAINABILITY

AGENDA 2030 AND THE NEW SUSTAINABILITY PARADIGM: AN INDUSTRIAL STRATEGY PERSPECTIVE

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ABSTRACT

The 2030 Agenda for Sustainable Development redefined sustainability as an integrated economic, social and environmental paradigm rather than an ecological concern alone. This paper examines how the Agenda has reshaped the role of sustainability in business strategies and industrial competitiveness, while identifying the main obstacles to its implementation. The analysis adopts an interdisciplinary approach: legal sources are read alongside the monitoring reports issued by the United Nations, ISTAT and ASviS, and alongside the academic debate, with a focus on Sustainable Development Goals 9 and 12. What emerges is that sustainability no longer works as an external constraint on firms: it has become a lever of innovation and of long-term value creation. Nevertheless, the implementation of Agenda 2030 remains significantly behind schedule due to the effects of the pandemic, geopolitical instability and financing gaps, revealing a growing divide between normative ambitions and the transformation of production systems.

Keywords: Agenda 2030; Sustainable Development; Goals 9 and 12; Industrial Competitiveness; Corporate Sustainability; European Industrial Policy.

1. INTRODUCTION

The notion of sustainable development was driven by a fundamental realization, first highlighted in the 1972 report The Limits to Growth: the pursuit of unlimited economic growth is incompatible with the ecological constraints of a finite biosphere [1].

The 1987 Brundtland Report supplied its canonical definition, describing development that satisfies present needs without compromising the ability of future generations to meet their own [2], and the 1992 Rio Conference translated the concept into international policy. Over the following decades, sustainability progressively acquired legal relevance, migrating from soft-law declarations into treaties, European Union (EU) primary law and national constitutions, to the point of being characterised as an emerging general principle of law [3].

The adoption of the United Nations resolution *Transforming our World: the 2030 Agenda for Sustainable Development* in 2015 consolidated this trajectory [4].

Structured around 17 Sustainable Development Goals (SDGs) and 169 targets, the Agenda moved beyond a sectoral, environment-centred understanding of sustainability in favour of an integrated paradigm in which the economic, social and environmental dimensions of development are interdependent [5]. Two features distinguish it from earlier international initiatives: its universality, since commitments extend to developed and developing countries alike, and the explicit mobilisation of non-state actors, first among them enterprises.

Beyond international commitments, sustainability has progressively influenced domestic legal systems. In Italy, Constitutional Law No. 1/2022 amended Articles 9 and 41 of the Constitution, strengthening the constitutional protection of the environment, biodiversity and ecosystems, while reinforcing sustainability as a guiding principle for economic activity [6]. Today, sustainability operates as a constitutional parameter for economic activity within a broader comparative trend towards environmental constitutionalism [7], [8]. Agenda 2030 has been widely analysed from different perspectives, particularly as an instrument of international soft law and as a reference framework for corporate social responsibility. Comparatively less attention has been devoted to the interaction between its implementation and the redefinition of industrial strategy. This issue has become increasingly relevant in Europe following the 2024 Draghi Report, which reframes decarbonisation as a key driver of competitiveness [9]. This paper addresses that gap by asking: how has Agenda 2030 reshaped the role of sustainability, particularly in business strategies and industrial competitiveness, and which obstacles continue to hinder the achievement of its objectives? The paper is structured as follows. Section 2 describes the research methodology; Section 3 presents evidence on the Agenda's design, the state of implementation of SDGs 9 and 12, the main challenges to their achievement, and the strategic turn in corporate and European policy; Section 4 offers discussion and conclusion.

2. METHODS

This paper adopts an interdisciplinary approach that combines constitutional-legal and business-economic perspectives. The analysis is based on three complementary groups of sources: (i) United Nations (UN) resolutions, EU acts and Italian constitutional law; (ii) official monitoring reports, namely the Sustainable Development Report 2025 [10], the ISTAT SDGs Reports 2025 [11], [12] and the ASviS Report 2024 [13], used to assess the implementation of the Agenda; and (iii) academic literature in environmental law, comparative constitutional law and business economics. The analysis focuses in particular on Sustainable Development Goals 9 (Industry, Innovation and Infrastructure) and 12 (Responsible Consumption and Production), as they are more connected to production systems, taking Italy as a case study in the European context. The methodology adopted is qualitative: institutional data are interpreted through a theoretical-doctrinal framework in order to assess the gap between the normative ambitions of the 2030 Agenda and its level of economic implementation.

3. FINDINGS

EVIDENCE AND CHALLENGES IN THE IMPLEMENTATION OF THE 2030 AGENDA

3.1 An integrated framework built on firm engagement

One of the 2030 Agenda's main innovations lies in its very structure. Indeed, the Agenda is built around five key concepts, the so-called five "Ps" (people, planet, prosperity, peace, partnership), which integrate poverty eradication, industrial development and environmental protection into a single normative programme, superseding the compartmentalised approach of the Millennium Development Goals [4]. Crucially, the Agenda assigns enterprises a constitutive rather than ancillary role: the SDGs presuppose a business contribution across all seventeen goals [14]. This approach is consistent with the UN Guiding Principles on Business and Human Rights, which recognise the responsibility of businesses to respect human rights [15], and with the European conception of corporate social responsibility (CSR), whereby firms voluntarily integrate social and environmental concerns into their activities and in their relations with stakeholders [16].

3.2 SDGs 9 and 12: implementation and challenges

Monitoring data reveal a sobering picture. The Sustainable Development Report 2025 finds that none of the seventeen goals is on track to be achieved by 2030 and that only 17 per cent of targets globally are progressing on schedule [10]. Progress is also highly uneven across countries. European countries continue to lead the SDG Index, with Finland ranking first (87.0), while countries affected by conflict score below 50. At the same time, around half of the world's population lives in countries that lack sufficient fiscal capacity to invest adequately in sustainable development [10]. Within this context, Italy ranks 22nd with a score of 80.3, performing relatively well, but still showing a persistent gap compared with the leading Northern European countries [10].

Within this context, the two goals most relevant to industrial systems display a distinctive pattern, summarised in Table 1. On SDG 9, the Istituto Nazionale di Statistica (ISTAT, 2025) reports overall improvement in digital infrastructure, e-commerce and business innovation, but stagnating research capacity, with research and development (R&D) intensity declining while environmental innovation by firms expands [11]. On SDG 12, the reduction of domestic material consumption both in absolute terms and per unit of gross domestic product (GDP) indicates an incipient decoupling of growth from resource use, even though per capita municipal waste is rising and the circular material use rate is stable [12]. ASviS (2024) confirms that Italy performs comparatively well in recycling and resource productivity, two pillars of the circular economy, while five goals, including poverty and inequality, deteriorated between 2010 and 2023 [13].

Table 1. *Italy's performance on SDGs 9 and 12: selected indicators*

Goal	Indicator	Latest value	Trend
Overall	SDG Index score (rank)	80.3 (22nd) [10]	Medium-high; gap with Northern Europe
SDG 9	R&D intensity (% of GDP)	1.37 (2022) [11]	Declining (1.43 in 2021)
SDG 9	Firms introducing eco-innovations (%)	40.1 (2022) [11]	Improving (37.0 in 2020)
SDG 12	Domestic material consumption (Mt)	489.4 (2023) [12]	–6.7% year on year
SDG 12	Material consumption per unit of GDP	Lowest since 2000 [12]	Improving (decoupling)

Source: *authors' elaboration based on [10], [11], [12], [13].*

3.3 Obstacles to the Agenda's implementation

Implementation has been repeatedly derailed by exogenous shocks. The COVID-19 pandemic interrupted progress to the point that parts of the scientific community questioned whether the goals should be reformulated [17]; wars, energy-price volatility and the fragmentation of multilateral cooperation, including the announced disengagement of the United States from several UN bodies, have further weakened the governance mechanisms on which the Agenda depends [10]. The obstacles are therefore structural rather than merely technical: financing gaps and geopolitical instability undermine precisely the partnership dimension that the Agenda identifies as its implementation engine.

3.4 Sustainability as a competitive factor: the European dimension

By contrast, developments at the corporate level reveal a different trend. The literature shows that integrating sustainability into business models has shifted from an ethical option to a strategy of long-term value creation, with the SDGs offering firms a shared framework within which to orient strategic choices [18]. Documented benefits include operational efficiency, brand and reputational value, easier access to finance and reduced regulatory risk [18]. Labour-market data corroborate the trend: in 2024, approximately 1.9 million new hires in Italy, 34 per cent of the total, concerned green professional profiles [19], consistent with the European Green Deal's objective of decoupling growth from environmental degradation [20].

The Draghi Report (2024) on the future of European competitiveness extends this logic from the firm level to the continental scale [9]. The Report frames decarbonisation not as a cost or a constraint but as a potential driver of growth, provided Europe can close the innovation gap, reduce energy costs and mobilise unprecedented levels of coordinated investment. Read alongside the 2030 Agenda, it confirms a

broader conceptual evolution: sustainability becomes part of the core of industrial policy and a key driver of competitiveness, rather than being considered an external constraint on it.

4. DISCUSSION/CONCLUSION

This paper set out to assess how Agenda 2030 has reshaped the role of sustainability in business strategies and industrial competitiveness, and which obstacles continue to hinder its implementation. The evidence provides a clear answer: Agenda 2030 has reshaped the role of sustainability in three ways. First, it has redefined sustainability as an integrated economic, social and environmental paradigm, replacing the sectoral, environment-centred approach of previous frameworks. Second, it has assigned enterprises a key role in its achievement, transforming corporate sustainability from a reputational or compliance exercise into a strategy of innovation and long-term value creation, a shift confirmed by the growth of green employment and by the benefits firms derive in terms of efficiency, access to finance and reduced regulatory risk. Third, this logic has scaled up from the firm to industrial policy: the Draghi Report frames decarbonisation as a driver of European competitiveness, while in Italy the amended Article 41 of the Constitution makes sustainability a binding legal parameter of business conduct [6].

Sustainability has thus moved from the periphery to the core of industrial strategy.

The obstacles, however, are equally structural. The pandemic, geopolitical instability and financing gaps have weakened precisely the partnership dimension on which implementation depends, and no goal is currently on track for 2030 [10]. The evidence on SDGs 9 and 12 shows that progress is real but selective: environmental innovation and resource efficiency advance, while research capacity stagnates and redistributive dimensions deteriorate [11], [13]. Herein lies the central tension: reframing sustainability as competitiveness accelerates the goals that promise market returns, but risks neglecting those that do not, diluting the integrated ambition that constitutes the Agenda's defining innovation.

Agenda 2030 has succeeded in embedding sustainability in business strategy and industrial policy, but this very success, if decoupled from its social dimension, cannot deliver its original objectives. As the Agenda itself proclaims, "*The future of humanity and of our planet lies in our hands. It lies also in the hands of today's younger generation who will pass the torch to future generations. We have mapped the road to sustainable development; it will be for all of us to ensure that the journey is successful and its gains irreversible*" [4, para. 53]. Future research should examine how the post-2030 framework can align competitiveness with the social and environmental dimensions of sustainability, so that the former reinforces, rather than undermines, the latter.

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INNOVATIVE SOLUTIONS FOR SMART TOURISM EVALUATION AND VALIDATION OF THE CITYART PROJECT

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ABSTRACT

This study aims to provide an overview about the role of smart tourism solutions in urban spaces in shaping socio-economic dynamics, including a focus on the impact of market analysis. Innovation, smart technologies, and market evidence are frequently addressed in isolation, avoiding the possibility of gaining a comprehensive vision. Therefore, an integrative approach that encompasses these three areas of research can support the design of effective strategies for urban resilience. This dynamic is also evidenced by the analyzed smart tourism case study: the CityArt project developed by City Green Light S.r.l. The examination of this case is based on a Multi-Criteria Decision Analysis (MCDA) framework, aimed at conducting a competitor analysis and evaluating research methodologies. Moreover, a Gantt Chart is presented to outline the timeline of the project workflow and its key aspects. Ultimately, the insights gained from the case study offer valuable guidance for implementing broader smart city solutions.

Keywords: Smart Tourism; Multi-Criteria Decision Analysis (MCDA); Market Analysis; Environmental Sustainability; Case Study.

1. INTRODUCTION

In recent years, global challenges related to rapid urbanization, sustainability, resilience, and digitalization are fundamentally reshaping the socio-economic framework of society [1]. In this context, the ability to innovate acts as a strategic asset to achieve the United Nations Sustainable Development Goals (SDGs), particularly SDG 11, aiming to ensure sustainable cities and communities [2]. Consequently, the implementation of smart city solutions and digital technologies can have a positive impact on urban environments and citizens' lives [3]. Moreover, the redefinition of urban spaces from a smart city perspective also has significant implications for the tourist experience, enabling visitors to become more involved in the exploration of the city through a more personalized engagement [1]. Smart tourism solutions provide cultural immersion through virtual technologies. This is a crucial avenue for preserving historic heritage, valorizing cultural attractions, and reducing negative environmental impacts, thereby safeguarding natural and cultural assets [4]. To practically validate these theoretical assumptions, a real-world analysis becomes necessary, which includes a benchmarking methodology to evaluate market research methods and to compare competitors' technologies. Therefore, the paper examines the case

study of the CityArt project developed by City Green Light, by applying a Multi-Criteria Decision Analysis (MCDA) framework.

2. METHODS

This investigation adopts an applied case study research design focused on City Green Light's CityArt project. A dual MCDA framework was used to evaluate the competition and the research methods [5]. First, a technology-based competitor analysis was conducted to evaluate the key technologies that can be used to make the city experience more immersive (virtual tours via Personal Computers (PCs), smartphones, and tablets; virtual tours using Augmented Reality (AR) glasses and Virtual Reality (VR) headsets; digital applications). A benchmarking comparison with specific criteria and weights was carried out. Second, an evaluation of market research methodologies was structured to assess the needs, behaviors, and preferences of potential users. The main research methods (surveys; focus groups; individual interviews; phone interviews; product testing) were benchmarked using specific weighted criteria, with the aim of determining the most effective way to gather relevant information for the project. A desk-based analysis relying on City Green Light's internal technical documentation and selected case studies was conducted to define the parameters and their associated scores within this framework. Finally, the operational execution of these findings was mapped using a Gantt Chart, to achieve a thorough understanding of the project and to systematically guide strategic decisions.

3. FINDINGS

3.1. The CityArt Project Context

The CityArt project consists of a metaverse dedicated to the enhancement of Italy's historical and artistic heritage, based on emotional storytelling. City Green Light initiated the project with the aim of transforming the concept of tourism experiences and to favor the transfer of knowledge related to historical locations. CityArt recreates the city of Reggio Emilia in the metaverse in virtual reality, providing an immersive environment incorporating dreamlike and artistic elements. The project engages users in a virtual urban walkthrough with a search game based on eight emotions (love, anger, wonder, ecstasy, surprise, melancholy, fear, and joy). Each discovered emotion is matched with content related to places and works of art, offering insights into history and the artistic aspects. The virtual environment favors experiential and extended tourism, to encourage visitors to spend additional time engaging with the city's cultural heritage. This initiative has the potential to open new doors to awareness of new technologies through the development of the immersive platform [6].

3.2. Competitive Technology Benchmarking

A benchmark evaluation was carried out based on the analysis of selected case studies to compare the technological solutions, their level of alignment with the aims of CityArt, and whether the different options

are appropriate for meeting the needs and objectives of the project. A weight is assigned to each of the seven identified criteria (investment, novelty, replicability, target audience breadth, cost for the customer, ease of use, and experience duration), to represent their relevance in relation to the specific aims of the case study. Numerical values from 1 to 5 were attributed to each technology in all categories, with 1 indicating the least favorable scenario and 5 the most favorable [7].

Table 1. Technology benchmark matrix for digital solutions.

Criterion	**Weight**	**Virtual tours: PCs, smartphones, and tablets**	**Virtual tours: AR glasses and VR headsets**	**Applications**
Investment	10%	3	1	3
Novelty	15%	2	5	4
Replicability	25%	5	2	4
Target Audience Breadth	16%	4	2	4
Cost for the Customer	10%	5	2	4
Ease of Use	18%	4	3	5
Experience Duration	6%	3	3	4
Score		3.89	2.59	4.08

Source: *author's elaboration based on City Green Light data.*

As shown in Table I, the option that appeared to be most effective was related to digital applications. This is a consequence of a combination of high scores in every criterion, reinforced by its strength in ease of use, allowing tourists to easily engage in activities depending on their personal preferences. While virtual tours using PCs, smartphones, and tablets occupied the second position in the ranking. Although they are not the most revolutionary technology, it is important to acknowledge that they are the most accessible for users in terms of both cost and ease of use. The analysis showed that technologies that involve the metaverse, using AR and VR, were ranked last. This score is determined by the substantial investment required and the challenge of engaging visitors, who may find these devices complex and costly to use; nonetheless, they represent the most novel approach. Consequently, the CityArt project should not be seen as a misstep, but rather as a great opportunity to revolutionize the tourism sector through the strategic integration of immersive experiences.

3.3. Market Research Methodology Benchmarking

Market research was conducted to assess the needs, behaviors, and preferences of potential users. The main data collection methods were selected to be evaluated with the aim of determining key strengths and weaknesses, and their relative coherence with the project. Each chosen criterion (cost, sample size, response rate, risk of bias, depth of information, and time required) was scored from 1 to 5 [7].

• **Table 2.** *Research method benchmark matrix for the project.*

Criterion	Weight	Surveys	Focus Groups	Individual Interviews	Phone Interviews	Product Testing
Cost	10%	4	3	2	3	2
Sample Size	15%	5	1	2	4	2
Response Rate	20%	3	5	3	3	4
Risk of Bias	25%	2	3	3	3	3
Depth of Information	15%	3	4	5	4	3
Time Required	15%	4	2	3	2	2
Score		3.30	3.10	3.05	3.15	2.80

***Source**: Author's elaboration based on City Green Light data.*

As presented in Table II, the benchmarking analysis identified surveys as the most effective method. This approach enables researchers to reach a considerable sample size with limited costs and manageable time requirements; the main drawback is associated with less detailed data and high risk of bias. Phone interviews ranked second, offering a remote way to reach respondents with the chance to explore answers in greater detail. In third place were focus groups, with in-depth information, but a very restricted sample size, limiting the possibility of generating representative data. Individual interviews follow in fourth place, with the highest potential for a more comprehensive understanding, but requiring more time and resources. The lowest-ranked method was product testing, which is more difficult to implement and tends to be more costly and with a limited sample size. Therefore, the combination of phone interviews and a survey was selected as the most suitable research strategy to effectively engage the municipalities for the CityArt project by combining a direct and indirect approach. Consequently, market analysis was used as a facilitating tool to gather valuable information, with the aim of guiding the development of the metaverse and promote its future implementations.

3.4. Project Implementation Roadmap

The strategic planning process for the CityArt project began with an initial focus on prototyping activities. Through the following development stages, the company was focused on the gradual technical implementation of aspects of the digital environment and all its functions. However, subsequent to the metaverse deployment, it became evident that the strategic planning process would have been strengthened by conducting competitor analysis and market research in the early stages of development. The absent strategic plan led to the decision to retrospectively engage in these two key pillars of strategic project planning, because it was deemed important to better understand the market landscape and competitive environment to position the CityArt service more effectively. Specific activities were conducted to fill the relevant information gap, which had not been considered at the outset of the CityArt initiative. To achieve thorough comprehension of the project, the Gantt Chart presented in Fig. 1 provides an overview of the development process, the main activities undertaken, their order, and timeframe [7].

ID	Task	Duration	Weeks									
			1	2	3	4	5	6	7	8	9	10
1.	**Product Requirements Definition**	**3 weeks**										
1.1.	Requirements gathering	7 days										
1.2.	Definition of key features	7 days										
1.3.	Development planning	7 days										
2.	**Product Testing**	**4 weeks**										
2.1.	Prototype development	*according to TRL*										
2.2.	Testing execution	14 days										
2.3.	Data collection and results analysis	7 days										
3.	**Competitor Analysis**	**2 weeks**										
3.1.	Collection of information on competitors	7 days										
3.2.	Competitor benchmarking	7 days										
3.3.	Preparation of analysis report	7 days										
4.	**Market Research**	**3 weeks**										
4.1.	Survey design	7 days										
4.2.	Survey distribution to clients (municipalities)	14 days										
4.3.	Sample selection for phone interviews	7 days										
4.4.	Execution of phone interviews	14 days										

Figure 6. *Gantt Chart of the CityArt project activities. Source: author's elaboration based on City Green Light data.*

The project structure was organized into four main areas of activity: product requirements definition (three weeks), product testing (four weeks), competitor analysis (two weeks), and market research (three weeks). Each activity was sequentially planned so that it followed a logical progression from the initial definition of the solution to the ultimate gathering of market information. Each activity comprises tasks that require a few days to be completed. Provided that the circumstances enable it, multiple tasks may be carried out simultaneously. This structured approach ensured that, despite the initial sequence inversion, the research phase was completed efficiently within the overall schedule.

4. DISCUSSION/CONCLUSION

The MCDA approach and the consequent analysis conducted during this project has led to several important outcomes. These findings are useful both for the technological solutions considered and for the identification of the most appropriate market research method that may be used for the future development of CityArt. Moreover, City Green Light recognized that a preliminary competitor evaluation and market analysis would have strengthened the strategic planning process. The subsequent research served as a retrospective validation to confirm and refine the technical decisions that had already been made. However, these insights offer a valuable takeaway that can guide the company's future strategic decisions. CityArt does not merely represent a functional project aimed at providing new services for urban tourism, it is even an example of how innovation can drive new sustainable business models for enhancing the cultural heritage of cities. With the adoption of smart systems such as CityArt or similar services, a municipality can transition from a linear structured approach to more sustainable models by integrating new technologies and innovative solutions. Structuring a continuous innovation and market research framework allows the economic and cultural sustainability of projects to be maintained in the long term. In conclusion, these findings illustrate how innovation, if properly contextualized and research-based, can support the development of new successful and sustainable business models in the cultural sector, for the evolution of socio-economic dynamics and green transitions in urban spaces.

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ENVIRONMENTAL SUSTAINABILITY AND CIRCULAR ECONOMY IN THE TEXTILE AND APPAREL INDUSTRY. LEGAL FRAMEWORKS, BUSINESS PRACTICES AND THE FRENCH CASE

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ABSTRACT

The textile and apparel industry is one of the most globalized and environmentally intensive industrial sectors, due to the scale of production, the fragmentation of supply chains, and the rapid turnover encouraged by the fast-fashion phenomenon. This paper first examines the environmental footprint of the textile and apparel sector, regarding the excessive use of raw materials such as water, land and natural resources, as well as greenhouse gas emissions throughout the supply chain. It then proceeds to reconstruct the international, European, and Italian regulatory frameworks that are driving the green transition. Moreover, the paper examines the main environmentally sustainable and circular business practices that textile and apparel companies can adopt to reconcile profitability, competitiveness and environmental safeguards. The French experience is presented as significant case study because of its recent regulatory activism and the French consumers' awareness of environmental sustainability.

Keywords: textile industry; apparel industry; environmental footprint; environmental sustainability; circular economy; fast fashion; French case.

1. INTRODUCTION

The textile and apparel industry occupies a central place in the global economy, yet it is also one of the sectors most deeply implicated in environmental degradation. The steady rise in demand for clothing and textile products, together with the spread of low-cost consumption models and the acceleration of production cycles, has intensified the pressure placed on natural resources and waste-management systems. The shift from a linear economy to a circular economy is needed, due to a lack of natural resources, which have been overexploited at the expense of future generations, and the pollution caused by creating new products and by the disposal of old ones.

Textile and apparel production operates through highly fragmented and transnational value chains in which raw-material extraction, spinning, weaving, finishing, garment assembly, distribution, use, and end-of-life treatment often occur in different countries and under different regulatory conditions. Large companies relocate highly polluting production to countries with weaker environmental and labor protections, thereby contributing to the phenomenon known as waste colonialism.

2. METHODS

This paper adopts an interdisciplinary method, because it focuses both on the legal framework on sustainability and circular economy and the business strategies adopted by apparel companies to protect the environment, while maintaining economic performance. After illustrating the environmental impact of the sector, the study reconstructs the multi-level framework spanning international commitments, European Union measures and national implementation. Subsequently, it presents the main sustainable business practices, such as traceability, waste recovery, safer chemical management, renewable energy use, circular design, recycling, reuse and use of environmentally sustainable technologies. Corporate examples are presented to show that sustainability and circularity principles can be efficiently implemented and transformed into concrete actions.

3. FINDINGS

3.1 Environmental footprint of textile and apparel sector

The textile and apparel sector, given its prominence in the global market and its highly globalized and fragmented supply chain, has a significant environmental impact. It is in fact the fourth most polluting sector, after the agri-food sector, the construction sector, and the transport sector. The sector's environmental impact unfolds across several fronts. Drawing on data provided by the European Environment Agency, this section now presents the main effects of the sector on the ecosystem.

Firstly, there is the overconsumption of water and its pollution by chemicals and microplastics. In 2020, textiles purchased by European households required on average 4,000 million cubic meters of blue water and 20,000 million cubic meters of green water to be produced. The production of textile raw materials, their transformation into fibers, weaving, and dyeing require enormous quantities of water and chemicals, and the wastewater generated by these processes often contaminates rivers, seas, and groundwater. Synthetic fabrics also release microplastics during washing; it is estimated that between 200,000 and 500,000 tons of microplastics from textiles end up in the marine environment every year, while a load of polyester laundry can release around 700,000 microfibers.

As for soil exploitation and pollution, the textile sector has a significant impact because the cultivation of raw materials requires extensive land use. In particular, cotton, the most widely used fiber in the world, is associated with high land consumption and, in many cases, with deforestation, which in turn contributes to the worsening of the climate crisis. The intensive use of agricultural land also puts pressure on ecosystems and can lead to soil degradation and loss of biodiversity, due to chemicals waste released in the soil. In addition, only 1% of the total amount of goods is recycled, while the rest ends up in landfills or is incinerated, thereby contributing to microplastic pollution and the release of toxic substances into the soil and air. Furthermore, excessive exploitation of resources is an evident effect of the textile sector.

In 2020, the consumption of textile products in the EU required on average 391 kilograms of raw materials per person, while global textile fiber production rose from 58 million tons in 2000 to 109 million tons in

2020, with a forecast of 145 million tons by 2030. Cotton, which accounts for more than 43% of the fibers used in the EU market, is particularly problematic because of its very high-water demand: producing 1 kg of textile cotton requires about 11,000 liters of water, while a cotton T-shirt requires about 2,700 liters. Other products, such as jeans and leather shoes, also require very large amounts of water.

Greenhouse gas emissions represent another major negative impact of the textile sector. In 2020, textile purchases in the EU generated 270 kg of CO2 per person, for a total of 121 million tons. 80% of these emissions occur during the production phase, while the remaining 20% is distributed among distribution, use of the garment, and its end-of-life stage. At the global level, the textile industry produces around 1.7 billion tons of CO2 per year and accounts for about 10% of global greenhouse gas emissions.

The advent of fast fashion, based on continuously changing collections, extremely low prices, and poor-quality garments, has further worsened the situation. Environmental pollution and the excessive exploitation of resources can be halted, or at least reduced, by shifting from a linear economic model to a circular one, in which the focus is no longer on the constant use of new resources but on the valorization of what already exists.

3.2 Regulatory and policy frameworks

The sustainability and circular economy regulatory framework is multi-layered and structured at three levels. At international level, the 2030 Agenda and the Paris Agreement, both adopted in 2015, provide the broad normative horizon, placing sustainable production, climate mitigation, and responsible use of resources at the center of public action. The United Nations 2030 Agenda promotes more responsible consumption and production patterns, so that future generations will be able to meet their needs.

At the European level, these principles are given more concrete form through the European Green Deal and through sector-relevant measures concerning circular economy, product information, chemical safety, and emissions reduction. EU legislation relevant to the sector ranges from fiber-labelling rules and general product-safety obligations to frameworks on hazardous substances and chemicals management, such as Persistent Organic Pollutants (Regulation EU 2019/1021) and Regulation REACH (Regulation EC 1907/2006 - Registration, Evaluation, Authorization and Restriction of Chemical). The Green Deal, which aims at climate neutrality for Europe by 2050, led to the adoption in 2022 of the EU Strategy for Sustainable and Circular Textiles, the European action plan focused on reshaping the fashion and apparel sector by 2030, so that garments become durable, repairable, recyclable and free from hazardous substances. Giving greater value to what has already been produced will result in a drastic reduction in pressure on natural resources, less pollution and lower emissions. The Italian National Strategy for Circular Economy (2022) shares the same goal: a transition to more efficient, sustainable and innovative patterns of production and consumption, based on durability, reuse, material recovery, thereby contributing to strengthening the competitiveness of Made in Italy, especially in a sector such as the textile industry, which is both highly strategic and internationally renowned. The strategy aims at

strengthening the second-hand materials market by promoting eco-design and Extended Producer Responsibility, while discouraging fast fashion.

3.3 Business practices and corporate examples

The paper identifies a series of practices that are especially relevant for textile and apparel companies seeking to reduce their environmental impact. By examining concrete case studies of Italian companies, the study was able to identify the main sustainability and circular-economy practices adopted by firms to translate environmentally sustainability principles into concrete actions, such as eliminating hazardous chemicals, choosing sustainable or secondary raw materials, improving traceability across the supply chain, reducing water and energy use, recovering textile waste, and rethinking products in terms of longevity and recyclability. Eco-design plays a fundamental role, because not only does it makes it possible to anticipate the environmental footprint of a product's production, use and disposal, but it also allows the product to be designed so that it is durable over time and easily recyclable. Rifò, an apparel company based in Prato, represents a concrete example of sustainable and circular fashion, as it combines the Prato textile tradition with the use of renewed fibers, recycled and organic cotton, a short local supply chain, pre-sale mechanisms to reduce overproduction, repair services, and the collection of used garments for upcycling and recycling. The regeneration process avoids re-dyeing garments, resulting in a 68% water saving, lower resource consumption, reduced emissions and less waste. Another great example of implementation of sustainability and circularity principles is Ético Sartoria Marchigiana, a small artisanal fashion company based in the Marche Region, that embodies the slow fashion model using natural fabrics, natural dyes, and eco-print techniques.

3.4 The France case

In order to have a deeper understanding of the topic, part of the research was conducted at Emlyon Business School, one of the most prestigious Universities in France, which is very committed to the environmental issue, and where sustainability and circularity are strongly embedded in the academic and institutional environment. A comparison between the French and Italian experiences made it possible to identify a more pronounced and attentive concern among French consumers regarding environmental sustainability in the textile and apparel industry. Consumers' purchasing decisions can significantly influence companies' production strategies, thereby reinforcing the idea that a sustainable textile sector cannot be achieved without the active cooperation of consumers.

In 2020, the French Parliament adopted the AGEC law, *Loi Anti-Gaspillage pour une économie circulaire*, that introduces obligations on transparency, traceability, environmental information, recycling, reuse and waste reduction also for textile products placed on the French market. A meaningful case study that shows how a company can combine performance and environmental sustainability is the French company Picture, an outdoor apparel brand that integrates sustainability and circularity principles by using recycled

and organic materials, by designing products that last over time and by offering repair services, including a lifetime repair warranty on certain categories of garments.

4. CONCLUSION

The research leads to a clear overall conclusion: the environmental transition of the textile and apparel industry can be achieved only through a systemic transformation that combines legal obligation, industrial innovation, cultural change, and consumer awareness.

The current model is rooted in the exploitation of limited natural resources (water, soil, raw materials) and the pollution of ecosystems to obtain mass production, rapid turnover, and an economic logic that rewards low prices and high volumes rather than durability and resource efficiency. This model encourages overproduction and overconsumption, with the consequence that garments are often underused, discarded quickly, and difficultly reintegrated into circular systems at the end of their life.

The current linear economy based on extraction, production, consumption, and disposal is no longer compatible with ecological limits, and will lead to the impossibility for future generations to fulfill their needs. In the textile-apparel field, this incompatibility is especially visible because the sector depends on large material inputs, generates significant waste, and often relies on production models that externalize environmental and social costs. From this perspective, a shift to an environmentally sustainable and circular economy is urgently needed: the case studies highlighted above demonstrate that it is possible to combine profitability, competitiveness, and environmental protection, by adopting business strategies based on respecting ecosystems and making better use of existing resources.

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IMPROVED COOKSTOVES AND HOUSEHOLD CHARCOAL EXPENDITURE: EVIDENCE FROM AN URBAN ENERGY TRANSITION IN MOZAMBIQUE

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ABSTRACT

Access to clean cooking technologies remains limited in many low- and middle-income countries, particularly where households rely on charcoal as their primary cooking fuel. While existing evidence has mainly focused on rural areas, the implications of clean cooking transitions in rapidly urbanising contexts remain underexplored. This paper examines whether adoption of the Mbaula A improved cookstove is associated with lower household charcoal expenditure in Maputo, Mozambique. Using survey data from 389 households and a quasi-experimental approach based on Propensity Score Matching and regression analysis, the study estimates the relationship between cookstove adoption and weekly charcoal expenditure. Results show that adopters spend approximately 26% less on charcoal than comparable non-adopters. Reported savings are primarily allocated to food purchases and other essential needs, highlighting the potential contribution of improved cookstoves to urban energy transitions and household welfare.

Keywords: Clean cooking; Energy transition; Energy poverty; Household welfare; Mozambique.

1. INTRODUCTION

Despite decades of technological progress, access to modern cooking systems remains deeply unequal. While electricity and gas connections have expanded globally, approximately one third of the world's population still relies on traditional solid fuels such as wood, charcoal, coal, crop residues, and dung to prepare daily meals [1].

Although improved cookstoves are primarily promoted for their environmental and health benefits, their economic implications for urban households remain less explored. Clean cooking interventions and empirical analyses have predominantly concentrated on rural areas [2]; [3]. Consequently, much of the existing evidence, and many of the underlying assumptions regarding expected benefits, derive from rural socio-spatial configurations. However, rapid urbanisation across low- and middle-income countries is reshaping patterns of household energy demand and fuel markets.

In urban settings where charcoal remains a dominant cooking fuel, increasing reliance on market-based energy systems and fuel price volatility may place additional pressure on household budgets, potentially

limiting resources available for essential goods such as food, healthcare, and education [4].

Against this backdrop, a more context-sensitive assessment of clean cooking transitions in urban environments is needed. This paper examines whether the adoption of the Mbaula A, a fuel-efficient charcoal cookstove promoted through a clean cooking programme in Maputo, Mozambique, is associated with lower household charcoal expenditure. Drawing on original household survey data collected during an impact evaluation conducted by a research team from Roma Tre University, the study applies a quasi-experimental approach to estimate the association between cookstove adoption and weekly charcoal expenditure. In addition, it explores how households report reallocating the resulting savings, providing further insights into the potential contribution of improved cookstoves to household welfare and more sustainable urban energy systems.

2. METHODS

The analytical sample consists of 389 urban households, including adopters and non-adopters of the Mbaula A stove.

Because adoption of the improved cookstove was not randomly assigned, households self-selecting into the programme may differ systematically from non-adopters. To reduce observable selection bias, Propensity Score Matching (PSM) is employed to construct a comparison group of non-adopters with characteristics similar to those of adopters [5]. Propensity scores are estimated through a logistic regression including household demographic and socio-economic characteristics expected to influence both cookstove adoption and charcoal expenditure. These include the respondent's age, household size, gender of the household head, presence of children under three, educational attainment, employment status, health conditions, and a household housing and asset index, measured through access to basic household infrastructure. Nearest-neighbour matching is performed without replacement, applying a caliper of 0.2 standard deviations of the logit of the propensity score to improve match quality [5].

Following the matching procedure, Ordinary Least Squares (OLS) regression models are estimated on the matched sample to assess the relationship between cookstove adoption and weekly charcoal expenditure while controlling for residual household heterogeneity. Household demographic characteristics and housing conditions are included as control variables, while robust standard errors are used to account for heteroskedasticity. Regression models estimated on the full sample are used as robustness checks.

To complement the quantitative analysis, open-ended survey responses were reviewed and grouped into categories based on the reported use of the savings, providing contextual insights into how households reallocated the resources saved.

Although the matching strategy reduces observable selection bias, unobservable differences between adopters and non-adopters cannot be completely ruled out. Moreover, information on the use of savings is self-reported and should therefore be interpreted with caution.

3. FINDINGS

3.1 Descriptive evidence

Table 1 presents descriptive differences in weekly charcoal consumption and expenditure between Mbaula users and non-users. On average, households adopting the improved cookstove consume 3.6 kg less charcoal per week than non-adopters. This reduction translates into significantly lower weekly charcoal expenditure, with adopters spending approximately 392.9 MZN (around EUR 5.3) less than the comparison group.

	Mbaula Users	Non-Users	p-value
Charcoal Consumption			
Weekly charcoal expenditure (MZN)	200.1 (118)	593 (3769.2)	0.000*
Weekly charcoal consumption (kg)	5.5 (4.3)	9.1 (8)	0.000*
Total observations	210	179	

*p<0.05. Continuous: t-tests (logged).

Table 1. *Descriptive Statistics on Charcoal Consumption and Expenditure by Stove Adoption Status. Source: Author, 2024.*

Although these descriptive differences suggest a negative association between improved cookstove adoption and household charcoal expenditure, they do not account for systematic differences between adopters and non-adopters. The following analysis therefore estimates the relationship using a matched sample and regression models controlling for observable household characteristics.

3.2 Effect of Mbaula adoption on charcoal expenditure

Table 2 reports the main regression results estimated on the matched sample. All coefficient estimates are reported with heteroskedasticity-robust standard errors. Improved cookstove adoption is associated with a statistically significant reduction in weekly charcoal expenditure. The estimated coefficient implies that Mbaula users spend approximately 26% less on charcoal than comparable non-users, holding household characteristics constant.

Among the control variables, only household size is positively and significantly associated with charcoal expenditure, reflecting the higher cooking energy demand of larger households. The estimated effect of cookstove adoption remains robust across alternative model specifications.

Variable	Coefficient	Std. Error	p-value
(Intercept)	4.676***	0.176	$< 2.2e-16$
Mbaula user	−0.307***	0.078	$9.88e-05$
Age	0.0072*	0.0029	0.0138
Household size	0.092***	0.015	< 0.0001
Woman household head	−0.005	0.078	0.944
Child under 3	0.143	0.114	0.214
Housing asset index	0.033	0.035	0.352
Observations	312 (2 observations dropped due to missingness)		
Residual standard error	0.688 (df = 309)		
R^2	0.144		
Adjusted R^2	0.127		
F-statistic	8.635 (6, 309), $p < 0.0001$		

Notes: Weighted OLS regression on matched sample.
Robust standard errors (HC1). Significance: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

Table 2. *Mbaula effect on weekly charcoal expenditure (log), matched sample. Source: Author, 2024.*

3.3 Household use of charcoal savings

Beyond reducing household energy expenditure, lower charcoal costs may relax short-term budget constraints and allow households to reallocate resources towards other needs. Figure 1 presents the self-reported use of savings among Mbaula users.

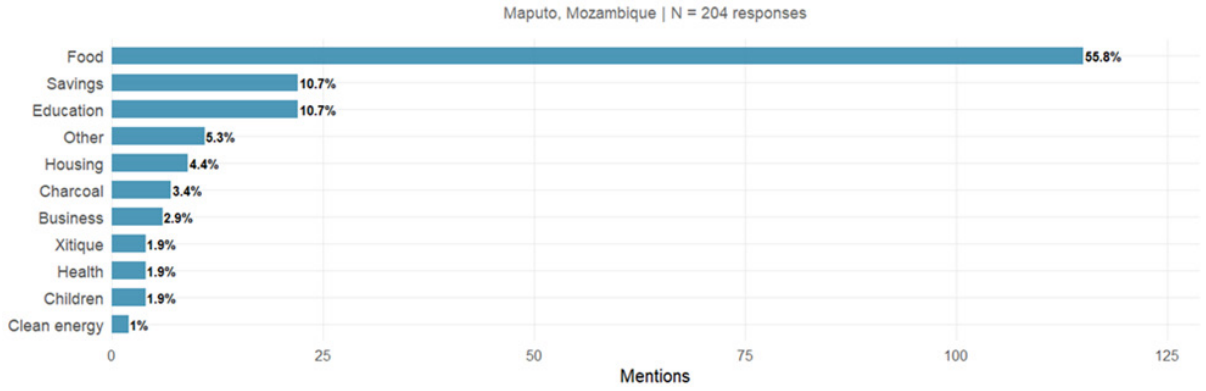


Figure 1. *How do households use savings from the Mbaula A stove? Source: Author, 2024.*

Note. *Responses are not mutually exclusive, as households could report multiple uses of the saved resources. Xitique refers to a rotating savings and credit association (ROSCA), widely used in Mozambique, in which members make regular contributions to a common fund that is allocated to each participant in turn.*

The predominance of food-related expenditure suggests that the economic benefits generated by improved cooking technologies are primarily directed towards meeting basic household needs. These findings are broadly consistent with previous evidence indicating that improved cooking technologies may contribute to household welfare not only by reducing fuel costs but also by easing budget constraints affecting food consumption and other essential expenditures [6]; [7].

Given that cooking and fuel management are predominantly female responsibilities in the study context, women are well positioned to observe changes in household fuel expenditure. Although the available data do not allow conclusions about intra-household decision-making, the reported allocation of savings

towards food and children's needs provides preliminary evidence of the broader welfare implications associated with improved cookstove adoption.

4. DISCUSSION/CONCLUSION

The findings suggest that improved cookstove adoption can contribute to more sustainable household energy transitions in urban Mozambique by improving the efficiency of charcoal use and lowering the economic burden associated with cooking fuel expenditure. The estimated reduction in charcoal expenditure indicates that improved cooking technologies may generate economic benefits for households by freeing resources that can be allocated to other essential needs.

The analysis of reported savings allocation provides further insights into the potential welfare implications of these economic gains. More than half of respondents indicated that savings were primarily used for food purchases, followed by other household-related expenses and informal savings mechanisms. While these results do not allow conclusions to be drawn regarding changes in intra-household bargaining power or women's control over resources, they suggest that improved cookstove adoption may contribute to easing short-term household budget constraints and supporting essential consumption.

These findings highlight the importance of assessing clean cooking interventions beyond technical performance and adoption rates. In rapidly urbanising contexts, where households increasingly depend on purchased fuels, the success of energy transition policies should also be evaluated through their capacity to reduce economic vulnerabilities and improve household welfare. Integrating socioeconomic dimensions into the evaluation of sustainable technologies can provide a more comprehensive understanding of how energy innovations affect everyday lives and resource allocation decisions.

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SENSITIVE HYDROSCAPES. A CIRCULAR APPROACH TO REGENERATE LAND-WATER INTERFACES OF CITY-PORT AREAS

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ABSTRACT

To adapt and mitigate water-related threats under current climate conditions, a circular regeneration of land-water interfaces plays a pivotal role. In fact, river, coastal and lake urban interfaces are subject to anthropic pressure and extreme weather events, linked to the water cycles — such as landslides, floods, river overflows, and coastal flooding — and shaping critical areas, defined in the study as Sensitive Hydroscapes. As a limited resource, water should be integrated into planning through a circular approach that reconnects water flows, spatial regeneration, and urban design. With this goal, the study proposes an approach to enact water-sensitive planning in City-Ports Areas (CPAs). The case study of Castellammare di Stabia, in the Metropolitan Area of Naples, in the South of Italy, becomes a test bed for deepening possible strategies for restoration and environmental sustainability, such as Nature-based Solutions (NbS) initiated by local stakeholders, to tackle the climate emergency.

Keywords: Circular Economy, Sensitive Hydroscapes, City-Port Areas, Nature-based Solutions.

1. INTRODUCTION

Globalisation has accelerated urban transformation processes in the Anthropocene, intensifying global crises with an ever-increasing impact on the earth's environment [1]. To address these ongoing crises, two innovative interpretative frameworks are introduced: the Neo-Anthropocene [2], to understand the present and plan responsibly for the future in a systemic way, and the Hydrocene [3], which places the role of water at the centre of the contemporary climate debate. Due to uncontrolled industrial waste [4], water resources are often neglected and polluted (Figure 1) and can become climate threats [5]. The study aims to transform water from waste/risk [6] into a resource/opportunity [7]. To this end, it proposes a *water-centric* approach [8] to urban planning and design in City-Port Areas (CPAs), reconnecting water flows with spatial regeneration. This approach draws on the strategic potential of a sustainable *circular economy* [9] [10] and supports the efficient management of the associated decision-making processes.

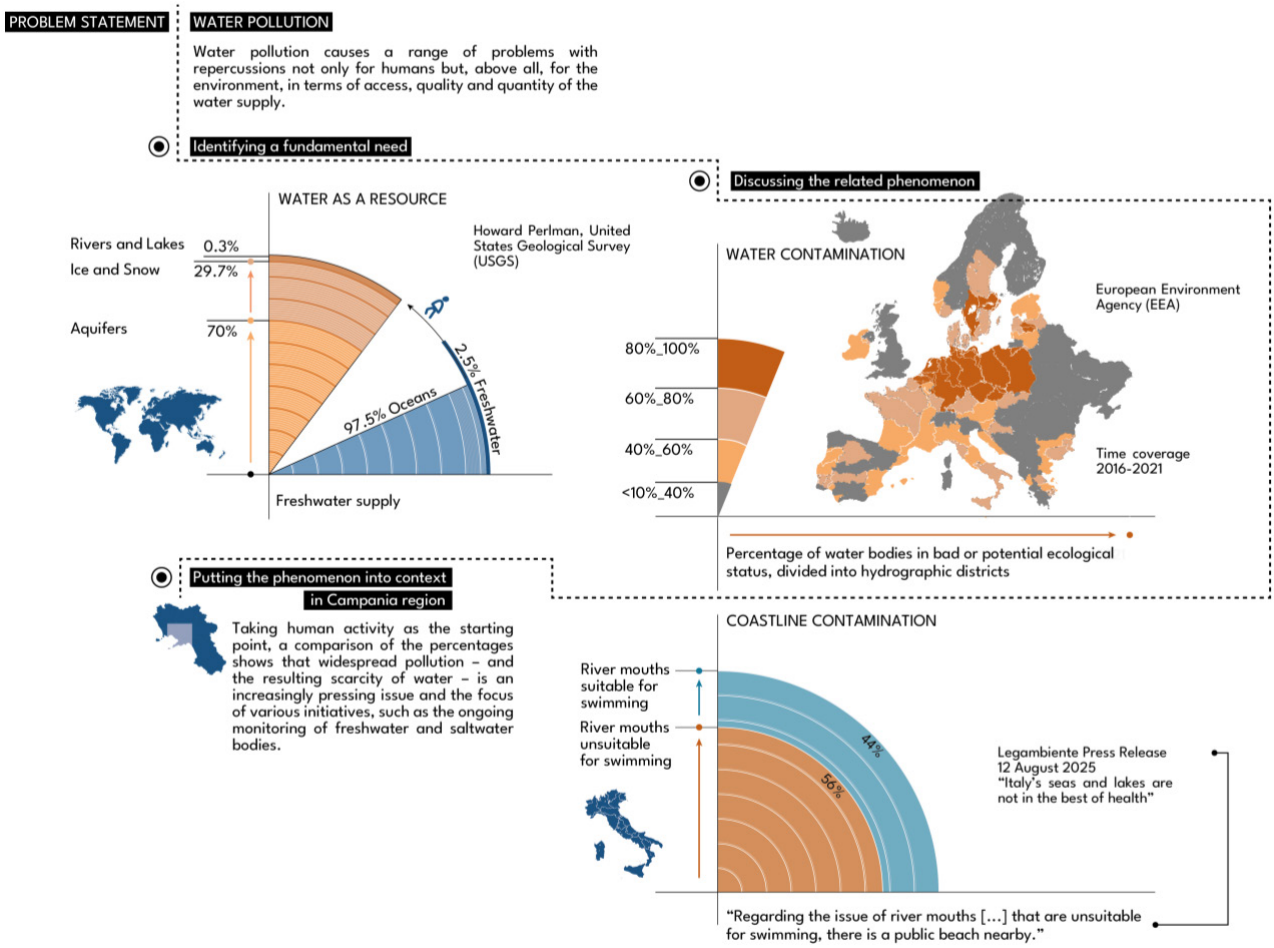


Figure 1. *Water Pollution. A comparison of quantitative data at the international, European, national (Italy) and local (Campania Region) levels, showing the relation between water and pollution.*

2. METHODS

To investigates how a circular water-centric approach can transform water-related risks into opportunities for urban planning and design in City-Port Areas (CPAs), the research proposes a four-phases methodology based on a case study in the South of Italy: the seaside and river city of Castellammare di Stabia, located in the Gulf of Naples and hosting the mouth of the Sarno River, defined as one of the most contaminated rivers in Europe [11][12].

Phase 1 - KNOWLEDGE FRAMEWORK. The knowledge base on Castellammare di Stabia was integrated through a spatially and time-sensitive investigation, implementing a historical reconstruction of water-risk events and thematic mapping with three core focuses: 1. Anthropized Urban Fabric; 2. Anthropized Impact; 3. Sensitive Urban Fabric. In particular, analysing the sequence of extreme natural events in Italy, with a focus on Castellammare di Stabia, in the Metropolitan Area of Naples, in the South of Italy, raised questions about people's perception and sensitivity to these dynamics at regulatory and social levels. The production of an 'awareness-raising' timeline - to identify and understand past events - reveals how water-hazard dynamics in sensitive contexts can affect both climate, cities, and communities (Figure 2).

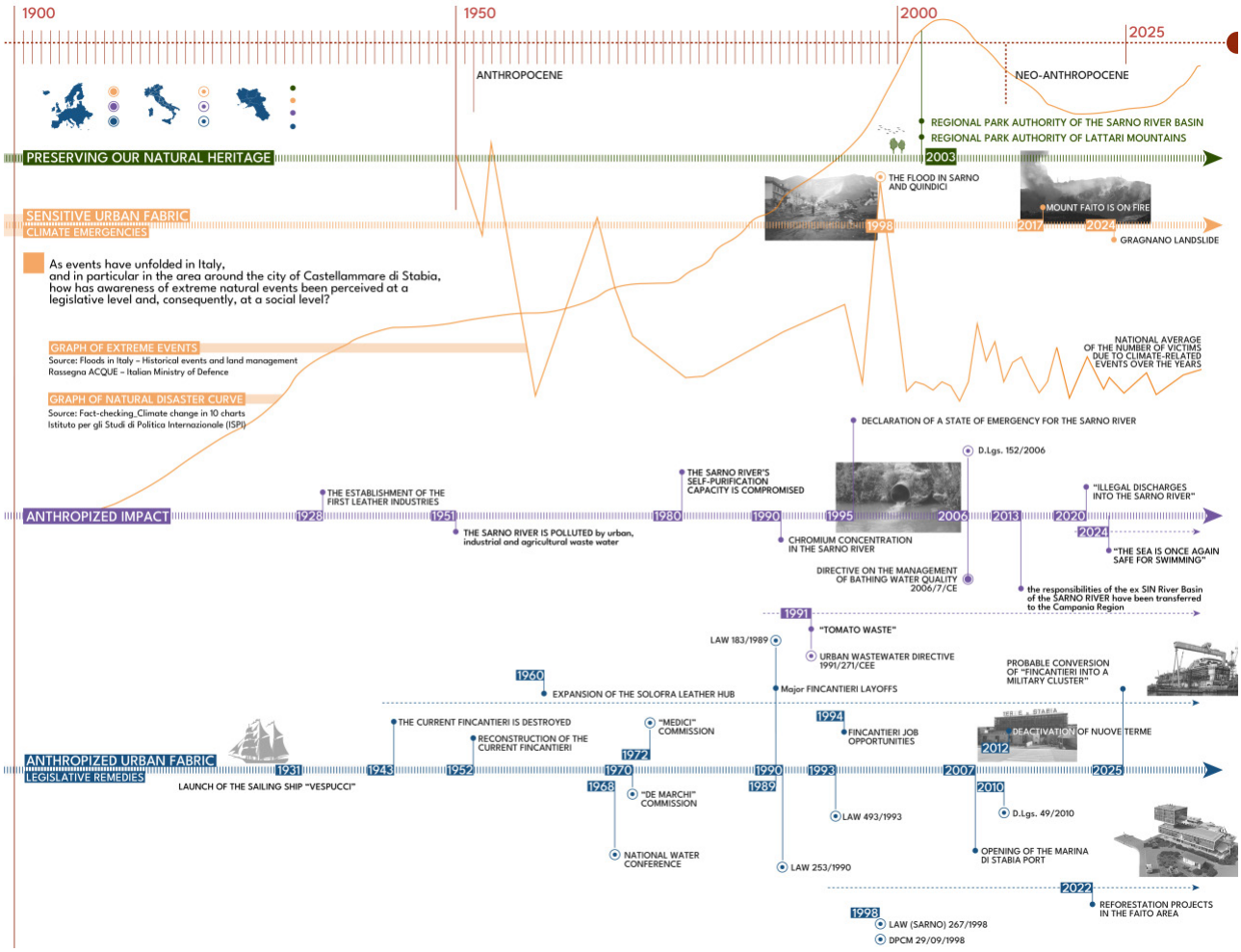


Figure 2. *"Awareness-raising" timeline. Timeline of extreme weather events at legislative and societal levels in the Pilot City of Castellammare di Stabia, with the aim of preserving the natural, urban and architectural heritage.*

Phase 2 – PROBLEM FRAMING. Within the spatial and time-sensitive investigation focusing on the relationship between Neo-Anthropocene and Hydrocene in the case study, the following research question arises: **How can critical landscapes at the land-water interfaces** [13] **of the City-Port Areas be identified and reinterpreted as hotspots for circular urban regeneration in Castellammare di Stabia?**

Phase 3 - INTERPRETATIVE FRAMEWORK. The overlap of the three spatial thematic mappings (*macro-layers*) reveals the extent to which the *Anthropised Urban Fabric* in Castellammare di Stabia has been negatively impacted by the activities of tanning and canning industries, which have exploited natural resources to the point of polluting them, turning water into a threat. The intersection between macro-layers points out critical areas at the land-water interfaces, defined as ***Sensitive Hydroscapes.***

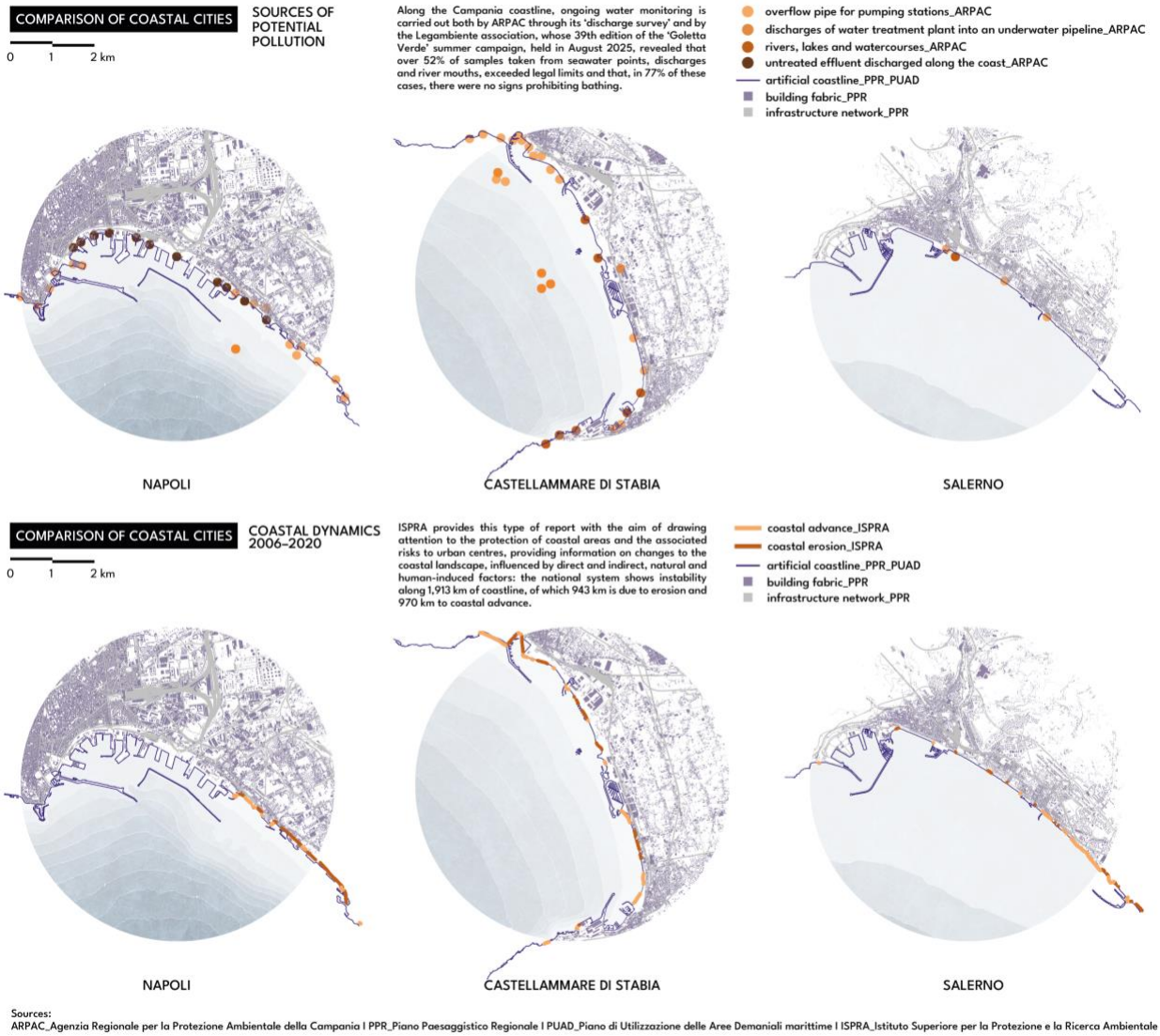


Figure 3. *Comparative analysis of CPAs in the Campania region. At the top, "sources of potential pollution" show the distribution of the areas where contamination exceeds the legal limits, as a result of human activity; at the bottom, "coastal dynamics 2006–2020" show the advance or erosion of the coastline due to human and natural factors.*

Moreover, a comparative analysis between CPAs in the region shows local vulnerability to the water cycle [6], as well as institutional monitoring of wastewater and evolution of the coastal landscape (Figure 3). To counteract the rise in climate-related emergencies, closely linked to pollution-with various repercussions such as river flooding and coastal inundation, several legislative measures have been enacted, particularly in recent years, such as the adoption of *Urgent measures for the prevention of hydrogeological risk and in support of areas affected by landslides in the Campania region* [14] and the *Flood Risk Management Plan* (Piano Gestione Rischio Alluvioni - PGRA) [15].

Phase 4 – DESIGN EXPLORATION. Adopting Castellammare as a *Pilot City* to test circular solutions in *Sensitive Hydroscapes* of CPAs, to protect public health, the proposed approach envisions design

interventions that address multi-risk mitigation in public Sensitive Hydroscapes along the land-water interface in the historic centre of Castellammare di Stabia and at the mouth of the Sarno River.

3. FINDINGS

The main result consists in the identification of the *Sensitive Hydroscapes*, defined as critical land-water interfaces where anthropogenic pressures, disrupted water dynamics, and spatial vulnerability overlap, e.g. urban landscapes subject to extreme weather events linked to the water cycle and the movement and redistribution of water, such as landslides, floods, river flooding and coastal flooding, particularly along the coastal and river interfaces of CPAs.

To regenerate these landscapes and contribute to water regulation in the face of climate-related emergencies, Nature-based Solutions (NbS) [16] can support a circular management of water flows through various methods such as moisture control and storage. In the city of Castellammare di Stabia, the work introduces urban strategies to implement several NbS, increasing the use of porous green paving, dispersing rainwater flow across surfaces at different elevations, and revitalising the system of degraded thermal springs, in a circular logic. Moreover, these strategies interact with abandoned heritage across the land-water interfaces of Castellammare di Stabia, making its open spaces or the nearest public spaces accessible, safe and water-resilient.

4. CONCLUSION

Regenerating Sensitive Hydroscapes, NbS can be integrated into projects led by local stakeholders, tailored to local biophysical, socio-economic, political and cultural conditions.

The implementation of these context-specific projects requires an in-depth understanding of the associated NbS success factors and of the Pilot City. Acknowledging scalability [17] of local initiatives as fundamental, the study proposes an awareness-raising campaign on the theme of Sensitive Hydroscapes through a widespread network of circular activities [18] implemented within Urban Living Labs [19].

Within this collaborative environment, physical and virtual research serves as a strategic tool for the urban and architectural regeneration of the built heritage of the city of Castellammare di Stabia, currently in a state of neglect, such as the former Cinema Montil, the former Magazzini Generali, the former Caserma Cristallina and the Antiche Terme Stabiane.

5. AUTHOR'S CONTRIBUTION

Conceptualization, methodology, investigation, Massimiliano Gatani, Flavio Costantino, Benedetta Pastena, Libera Amenta; data curation, M.G. and F.C.; writing—original draft preparation, M.G. and F.C.; writing—review and editing, L.A. and B.P. All authors have read and agreed to the published version of the manuscript.

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BRIDGING THE GAP BETWEEN ESG REPORTING AND CONSUMER PERCEPTION: THE CORPORATE INTEGRATED SUSTAINABILITY COMMITMENT (CISC)

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ABSTRACT

In recent years, Environmental, Social and Governance (ESG) reporting has significantly expanded the availability of corporate sustainability information. However, the complexity and heterogeneity of sustainability reports, often limit their accessibility and comparability for consumers, creating a gap between companies' sustainability commitment and its public perception. This paper proposes the Corporate Integrated Sustainability Commitment (CISC), a consumer-oriented framework that converts heterogeneous ESG information into a synthetic sustainability score ranging from 0 to 100. The framework integrates progress toward sustainability targets, ESG reporting quality, and consumer priorities. It was applied to the Italian retail sector through the analysis of the sustainability reports of Coop, Conad, and Esselunga, combined with a consumer survey. The findings demonstrate the framework's feasibility and its potential to reduce information asymmetries between companies and consumers.

Keywords: Circular Economy; ESG Reporting; Sustainability Assessment; Consumer-Oriented Framework; Information Asymmetry; Corporate Integrated Sustainability Commitment (CISC).

1. INTRODUCTION

Sustainability reporting has become a central component of corporate strategy [1], [2], driven by European regulation, growing stakeholder expectations, and the widespread adoption of Environmental, Social and Governance (ESG) principles [1], [3]. Sustainability reports are now the primary instrument through which organizations communicate their environmental, social, and governance commitments and performance. Despite the growing availability of ESG information, its accessibility and comparability remain limited [4], [5]. Sustainability reports rely on heterogeneous indicators and technical information primarily intended for investors and institutional stakeholders [3], [4]. Consequently, consumers often struggle to incorporate sustainability information into purchasing decisions, creating a persistent information gap [5], [6]. To address this challenge, this paper proposes the Corporate Integrated Sustainability Commitment (CISC), a framework that transforms ESG information into a synthetic sustainability score ranging from 0 to 100. Unlike conventional ESG ratings, the CISC combines progress

toward sustainability targets, reporting quality, and consumer priorities into a concise and comparable measure that reduces information asymmetries between companies and consumers. The framework was applied to the Italian retail sector through the analysis of the sustainability reports of Coop, Conad, and Esselunga, complemented by a consumer survey. The survey was used both to derive the consumer-oriented weighting system and to investigate the relationships between perceived sustainability commitment, perceived greenwashing, customer satisfaction, and brand loyalty [5], [7]. This study makes two contributions. First, it introduces a replicable methodology for constructing a consumer-oriented sustainability index from publicly available ESG information. Second, it provides empirical evidence supporting the theoretical assumptions underlying the proposed framework, showing that credible ESG communication is associated with lower perceived greenwashing and higher consumer satisfaction, thereby encouraging competition based not only on corporate sustainability performance but also on the quality and transparency of ESG reporting.

2. METHODS

The CISC framework follows a four-stage process: (i) identification and classification of Key Performance Indicators (KPIs) reported in sustainability reports [3]; (ii) normalization of corporate performance against declared sustainability targets; (iii) assessment of ESG reporting quality through a transparency coefficient; and (iv) aggregation of the resulting information using a consumer-oriented weighting system based on the principles of Multi-Criteria Decision Analysis (MCDA) [8]. The first three stages process objective information extracted from sustainability reports, whereas the final stage incorporates consumer preferences into the synthetic sustainability score. By integrating corporate performance, reporting quality, and consumer priorities, the framework provides a more comprehensive assessment of sustainability commitment than approaches based solely on reported ESG performance [8], [6].

Formally, the CISC score for $year_t$ is defined as:

$$CISC_t = 100 \sum_{i=1}^{n} w_i P_{i,t}^{*} \tau_{i,t}$$

Where $P_{i,t}^{*}$ represents the normalized progress of KPI i toward its sustainability target, w_i its consumer-derived weight, and $\tau_{i,t}$ the transparency coefficient. The following sections describe the operationalization of each component.

2.1 KPI extraction and classification

KPIs were systematically extracted from the sustainability reports of the selected companies [3]. Indicators suitable for longitudinal analysis were retained, while year-specific omissions or comparability limitations were subsequently accounted for through the transparency coefficient. Minor differences in terminology or measurement units were harmonized whenever objective conversion was possible. The

selected KPIs were then classified into the three ESG dimensions, forming the reference database for the CISC framework.

2.2 Target-based normalization

Because ESG KPIs are expressed in heterogeneous units, the framework applies a target-based normalization procedure. Baseline and target values were defined using corporate sustainability reports and, where necessary, recognized regulatory benchmarks, converting KPIs into comparable values on a common 0–1 scale while preserving their original meaning.

2.3 Transparency adjustment

Operationally, for each KPI_i and $year_t$ the transparency coefficient is defined as:

$$\tau_{i,t} = \begin{cases} 1 & if\ information\ is\ complete\ and\ fully\ comparable \\ 0.5 & if\ information\ is\ usable\ but\ only\ partially\ comparable \\ 0 & if\ information\ is\ absent\ or\ non-comparable \end{cases}$$

Partial comparability includes changes in scope, definition, measurement unit or reporting methodology that limit, without preventing, objective comparison, whereas $\tau_{i,t} = 0$ applies when information is omitted or such changes prevent reliable comparison. The intermediate value is applied uniformly to all cases of partial comparability, reducing discretionary assessment. Since the coefficient is applied after progress normalization, performance deterioration is captured by $P^*_{i,t}$ rather than by the transparency penalty. This ensures that transparent reporting of deterioration is not additionally penalized, whereas reported progress may be discounted when supported by incomplete or poorly comparable disclosure. The three-level structure ensures methodological consistency and replicability, while future developments could evaluate additional levels to capture different degrees of information loss.

2.4 Consumer-oriented weighting

The final stage incorporates the consumer perspective into the framework. ESG weights were derived from a consumer survey designed to estimate the relative importance assigned to different sustainability dimensions [8]. Each KPI inherits the weight of its corresponding ESG dimension, allowing the final sustainability score to reflect consumer priorities.

2.5 Final aggregation

Figure 7 summarizes the overall CISC workflow from KPI extraction to final score computation.

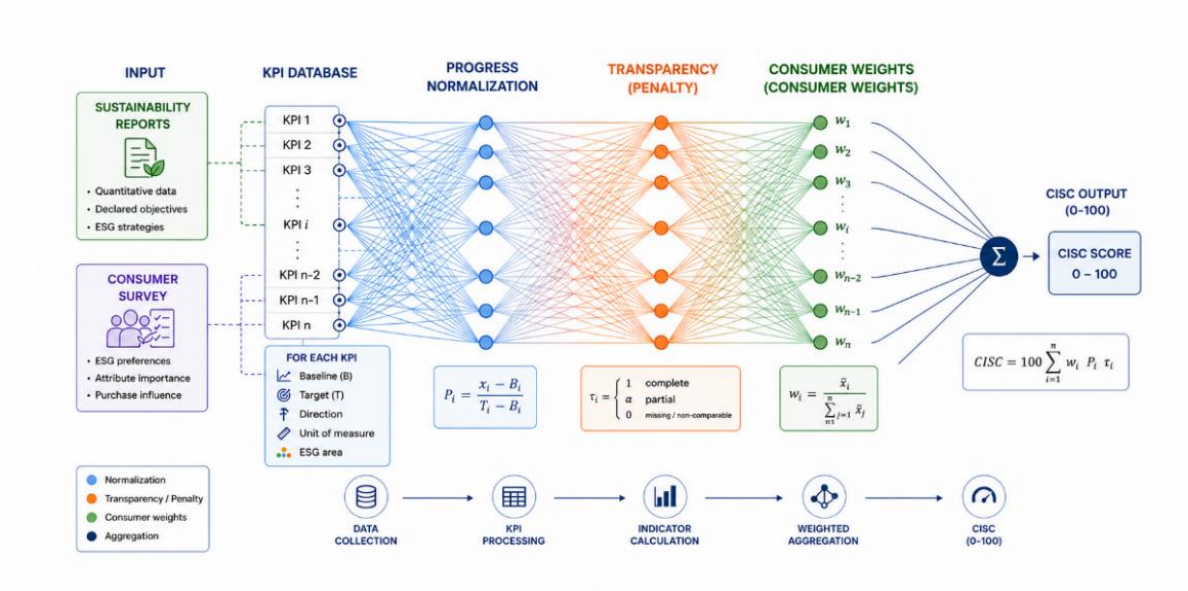


Figure 7. *Methodological workflow of the CISC framework. Source: Authors' own elaboration; graphic generated with AI assistance.*

2.6 Case study

To evaluate the empirical applicability of the CISC framework, it was applied to the Italian retail sector, focusing on three leading retailers (Coop, Conad, and Esselunga) selected for their consistent sustainability reporting and different ESG reporting approaches. Sustainability reports published between 2019 and 2024 were analyzed, excluding 2020 to minimize COVID-19-related distortions.

2.7 Data collection

The empirical analysis combined two data sources: the sustainability reports of the selected companies and a survey administered to 162 Italian consumers. Corporate sustainability reports were used to build the KPI database and calculate the CISC score. The consumer survey served two purposes: (i) to derive the consumer-oriented weighting system based on the principles of Multi-Criteria Decision Analysis (MCDA) [8], and (ii) to collect data on perceived sustainability commitment, perceived greenwashing [6], customer satisfaction [7], and brand loyalty, using validated measurement scales [9]. These variables were employed to examine the theoretical assumptions underlying the framework rather than to validate the CISC itself. Figure summarizes the role of the consumer survey in the empirical implementation of the CISC framework: construction of consumer-oriented weights (Fig.2A), and perceptual variables used in the regression analyses (Fig.2B).

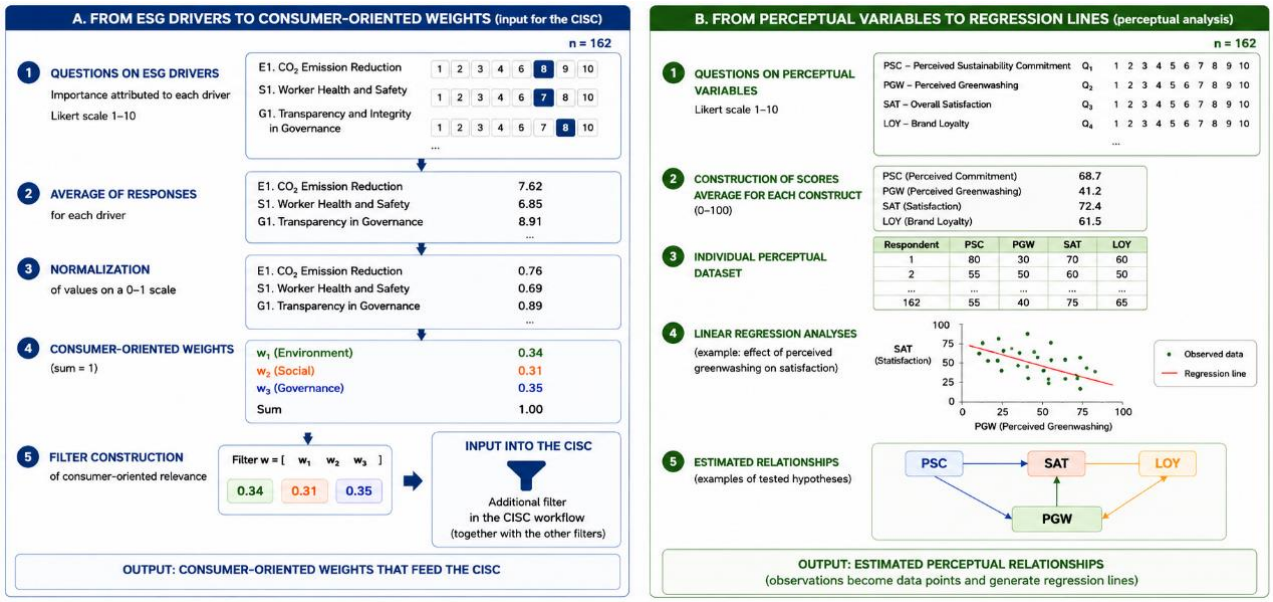


Figure 2. *Role of the questionnaire in the empirical application of the CISC framework. Source: Authors' own elaboration; graphic generated with AI assistance.*

3. FINDINGS

The CISC was calculated for Coop, Conad, and Esselunga over the study period. Figure shows the temporal evolution of the index.

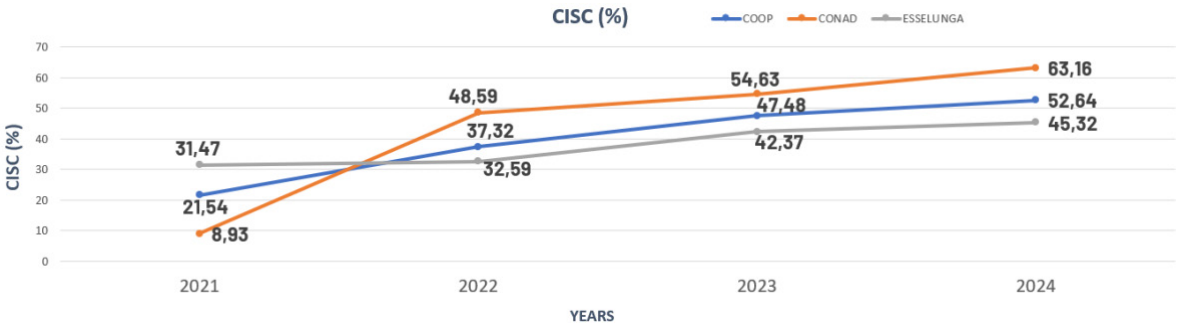


Figure 3. *Temporal evolution of the CISC score for Coop, Conad, and Esselunga (2021–2024). Source: Authors' own elaboration.*

All three retailers exhibit a progressive increase in sustainability commitment, although with different trends. Coop shows steady growth, Esselunga a more gradual increase, while Conad records the largest improvement, achieving the highest CISC score in the final year. These results indicate that the framework effectively captures both the level and the evolution of corporate sustainability commitment through a single comparable indicator.

3.1 Empirical evidence supporting the theoretical assumptions

To further assess the theoretical assumptions underlying the CISC framework, separate linear regressions were estimated for each retailer. Figure summarizes the relationships between: perceived

greenwashing and consumer satisfaction (4.A), perceived sustainability commitment and consumer satisfaction (4.B), perceived sustainability commitment and perceived greenwashing (4.C). Across all three retailers, higher perceived sustainability commitment is consistently associated with lower perceived greenwashing and higher consumer satisfaction, while higher perceived greenwashing is associated with lower consumer satisfaction. Although the strength of the relationships varies across companies, the direction of the effects remains consistent, providing empirical support for the theoretical assumptions underlying the proposed framework.

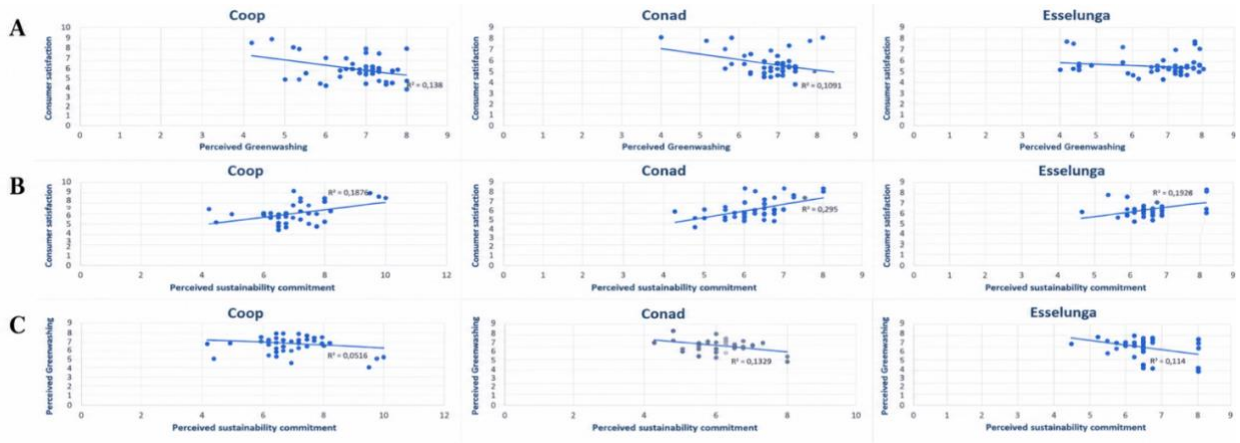


Figure4. *Linear regression analyses of the relationships between perceived greenwashing and consumer satisfaction (A), perceived sustainability commitment and consumer satisfaction (B), and perceived sustainability commitment and perceived greenwashing (C) across Coop, Conad, and Esselunga. Source: Authors' own elaboration.*

4. DISCUSSION/CONCLUSION

The empirical analysis supports the theoretical assumptions underlying the development of the CISC framework. Across all three retailers, higher perceived sustainability commitment is consistently associated with lower perceived greenwashing [5], [6] and higher consumer satisfaction [7], highlighting the importance of credible ESG communication in shaping consumer evaluations [10]. Building on these findings, the CISC provides a methodological framework for translating complex ESG disclosures into a concise and comparable sustainability measure. Rather than representing a definitive solution to information asymmetry, the framework offers a practical tool for studying, monitoring, and progressively addressing this phenomenon over time [4]. From a managerial perspective, the CISC may also encourage firms to compete not only on sustainability performance itself but also on the transparency, continuity, and quality of ESG reporting [3], making sustainability information more accessible to consumers [5], [6]. A current limitation of the framework is that KPI identification and classification were performed manually. Future research will therefore focus on automating these processes through dedicated software, enabling the CISC to become scalable, easier to update, and applicable across industries.

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IMPACT INVESTING: ANALYSIS USING THE ISM-MICMAC METHOD

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ABSTRACT

This study analyses the risks associated with impact investing, an investment approach that pursues a positive social or environmental outcome alongside a financial return. We propose the application of the ISM-MICMAC methodology to address the main difficulties typically faced by impact investing projects. The methodology combines two complementary approaches: the first structures risks into a multilevel hierarchy that highlights the relationships between variables, while the second classifies risks according to their ability to influence or depend on other factors, facilitating the identification of critical risks. The research aims to improve risk management in impact investing, providing investors with tools to identify strategic levers that can make investments more effective and sustainable, and contributes to mitigating the sector's typical difficulties by identifying possible intervention policies.

Keywords: impact investing; ISM-MICMAC analysis; impact risk; financial risk; ESG risk.

1. INTRODUCTION

Despite the growing interest of recent years, impact investments are characterised by uncertainties stemming from multiple factors, and this research aims to analyse the risks associated with these investments [1]. To address these challenges, the ISM-MICMAC method has been adopted, which brings together several techniques to obtain a more complete and detailed view. The objective is twofold: to provide a clear overview of the main risks, and to identify the most effective strategic levers to improve the performance and sustainability of impact investments. Through this research, we aim to offer investors practical tools that support more informed and conscious decisions in the context of impact investing; such a method represents a useful instrument for anticipating future scenarios and development dynamics [2].

2. METHODS

The ISM-MICMAC method is used for the analysis of complex systems and is particularly useful for understanding and structuring the relationships between the variables that affect a system. As the name suggests, the approach combines two complementary techniques, Interpretive Structural Modeling (ISM) and Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (MICMAC), which are often used together for business assessment and forecasting of future scenarios.

ISM was first proposed by Professor J. Warfield in 1973 [2], which wanted to develop an innovative method for analysing complex systems. The methodology aims to study the relationships between variables, with the ultimate objective of obtaining a hierarchical representation of the relationships between the elements of a system by ordering them according to their level of influence and dependence. The methodological process involves experts from the field, especially in the initial phases dedicated to the identification of system elements and the relationships between variables.

3. FINDINGS

This section presents the application of the ISM-MICMAC methodology described above to the case of impact investing, following the same sequence of steps.

3.1 Identification of system risks

This was achieved through a combination of secondary research, based on an in-depth literature review, and primary research through interviews and discussions with field experts, allowing the identified elements to be broadened and validated.

The literature review identified two main risk categories: financial and impact risks. Financial risks are similar to those of traditional investments but reflect the specific social and environmental characteristics of impact investing [3]. Impact risks refer to the possibility of achieving a lower-than-expected social or environmental impact [4].

To classify these risks, a Risk Breakdown Structure (RBS) was adopted. The RBS organises risks into three levels: macro-categories (Level 1), sub-categories (Level 2), and specific risks (Level 3), which represent the elements used for the subsequent data analysis.

The structure distinguishes between financial and impact risks, with particular attention to ESG (Environmental, Social, Governance) risks, as shown in Table 1.

Level 1	Level 2	Level 3
Financial risks	Financing risk	R1: Difficulty in finding financial resources for initial development due to the increasing cost of money
	Liquidity and exit risk	R2: Difficulty in liquidating investments in the long term and in exiting the investment
	Business model management risk	R3: Returns not adjusted for the financial risk incurred
		R4: Inefficient and inflexible business model that generates lower profits than expected
		R5: Overly restrictive access requirements
	Macroeconomic risks	R6: Local inflationary movements
	Market risks	R7: Relevant political, economic and social events
		R8: Reduced demand for products/services and lack of market growth
Impact risks	Results	R9: Possibility of unexpected negative impacts
		R10: Difficulty in accurately quantifying the effects of an intervention
	Execution	R11: Planned activities not performed as expected
ESG risks	Environmental	R12: Negative environmental impacts
	Social	R13: Low stakeholder engagement
	Governance	R14: Reputational damage arising from the business
		R15: Perception of impact washing

Table 1. *RBS (Risk Breakdown Structure) of the system risks.*

Financial risks are distributed across all three RBS sub-categories, which already suggests that they are not the only critical factors, but are strongly interconnected with impact and ESG risks, as confirmed by the ISM results below.

3.2 Establishing the relationships between variables (i, j)

This phase was carried out with the collaboration of experts, who assessed the weight of each relationship within the system. During the interviews, qualitative data were collected and converted into quantitative data through the scale shown in Table 2.

Strength of impact	No	Weak	Medium	Strong	Very strong
Numerical value	0	0.25	0.5	0.75	1

Table 2. *Conversion scale for the strength of the relationship between variables.*

3.3 Partitioning the reachability matrix into levels

Using matrix procedures that take into account the relationships between the risks, the digraph shown in Figure 2 was obtained.

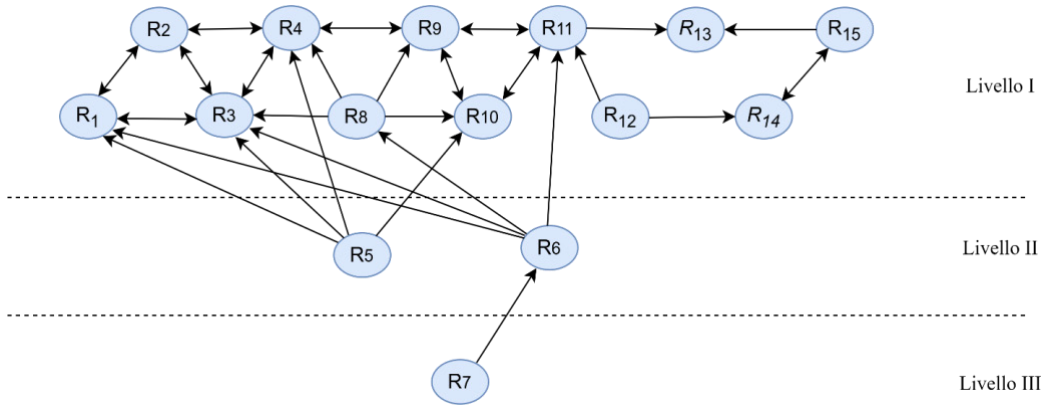


Fig. 1. *Digraph of relations between risks, organised by hierarchical level (Livello = Level).*

3.4 MICMAC analysis

After matrix procedures the micmac diagram is obtained (Fig.3).

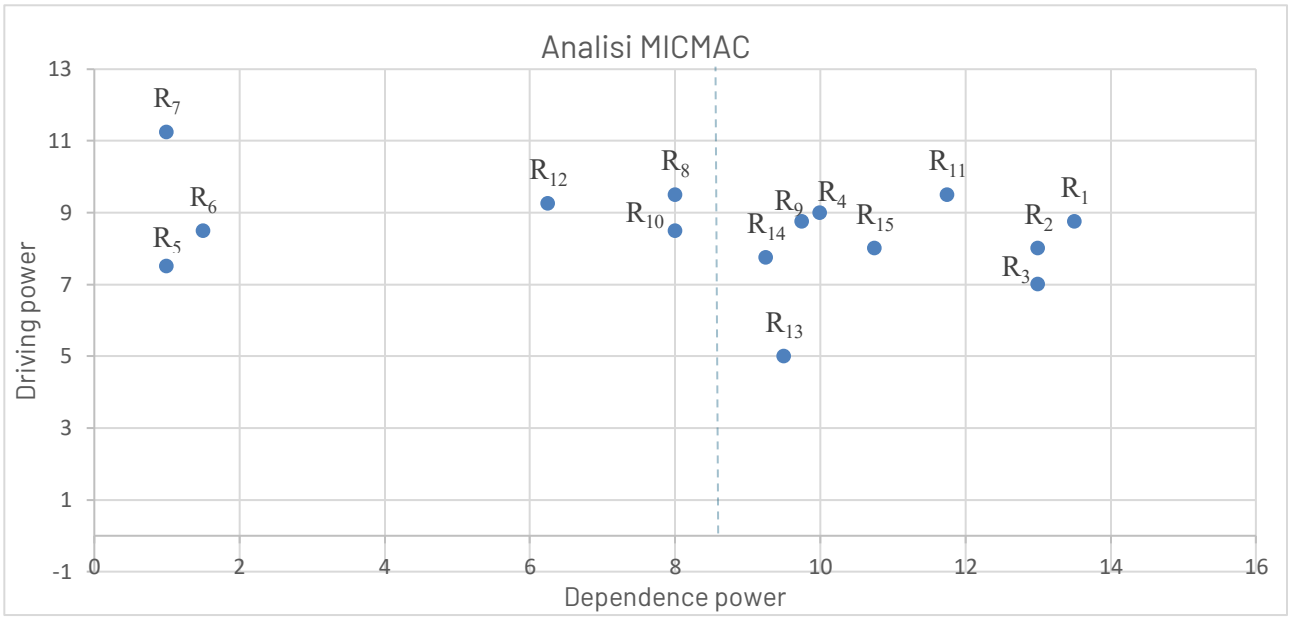


Fig. 2. *MICMAC diagram: positioning of the 15 risks according to dependence power and driving power.*

The most critical quadrant (linkage elements, Group III) includes both financial and impact risks, confirming the close connection between sustainability and financial performance. In the quadrant of autonomous elements (Group I), characterised by low influence and low dependence, only risk R5 is found; although it falls within this category, it shows a somewhat higher degree of influence than is typical for autonomous elements. This classification shows that some elements have a strong influence on the system, while others are more dependent on external variables, allowing the identification of intervention priorities and providing a basis for developing strategies to mitigate the effects of these risks on the system.

4. DISCUSSION/CONCLUSION

Once the final MICMAC diagram is obtained, it is possible to define possible intervention policies for each area of the graph, based on the position of the risks within it. Each area is associated with differentiated policies according to the criticality and influence of the factors analysed. Risks with high influence and high dependence fall into a maximum-alert zone and require immediate action; risks in the influencing-risk quadrant fall into a high-priority area requiring prompt action. A medium-priority area corresponds to the quadrant of system-dependent risks, for which planned interventions and medium- to long-term monitoring are foreseen; finally, a low-priority area, associated with the autonomous-risk quadrant, requires only periodic monitoring rather than immediate action. Table 7 summarises the possible intervention policies for each area of the MICMAC diagram.

Priority area	Risk	Possible intervention policies
Maximum alert zone	R1: Difficulty in finding financial resources	Tax relief on returns; strengthen the culture of impact investing
	R4: Inefficient and inflexible business model	Focus on training programmes; support for accelerators and incubators
	R9: Possibility of unexpected negative impacts	Implement ex-ante impact analysis; real-time data collection; improve short-term monitoring; create mitigation and response mechanisms
	R11: Planned activities not performed as expected	Simplify bureaucratic procedures; active stakeholder involvement; improve contracts; diversify activities
High priority area	R6: Local inflationary movements	More flexible pricing strategies; optimisation of operating costs
	R7: Relevant political, economic and social events	Flexible strategies; diversify the portfolio
	R8: Reduced demand and lack of market growth	Strengthen the competitive value of the offer; incentives to stimulate demand
	R10: Difficulty in accurately measuring the effects of a project	Custom KPIs
	R12: Negative environmental impacts	Conduct assessments before investing; control mechanisms
Medium priority area	R2: Difficulty in liquidating investments and exit	Create a secondary market and develop exchanges; offer gradual exit options
	R3: Returns not adjusted for the financial risk incurred	Offer guarantees or tax breaks to investors
	R13: Low stakeholder engagement	Increase transparency and communication
	R14: Reputational damage arising from the business	Transparency in data communication
	R15: Perception of impact washing	Adopt verifiable impact metrics

Table 3. *Possible intervention policies by MICMAC quadrant.*

Table 3 summarises the main risks identified and their mitigation strategies. Key challenges include difficulties in accessing financial resources (R1), which can be addressed through tax incentives and

public-private funds; rigid business models (R4), mitigated through training and incubator support; and unexpected negative impacts (R9), requiring prior assessment and continuous monitoring. Other risks, such as failure to implement planned activities (R11), inflation (R6), and political, economic and social instability (R7), can be managed through regulatory simplification, flexible strategies, financial management and portfolio diversification. Reduced demand (R8) may be addressed by strengthening market competitiveness, while difficulties in impact measurement (R10) can be reduced through advanced monitoring tools and tailored indicators. Finally, investment illiquidity (R2) can be mitigated through secondary markets and exchange platforms.

Overall, the research highlights the complexity and interdependence of risks in impact investing. The ISM-MICMAC approach identified the most influential risks and provided insights for developing effective mitigation strategies. The findings contribute to more resilient and sustainable impact investing, while future research could validate the model using a larger and more diverse expert panel and real investment portfolios.

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REALIZATION PRINCIPLE, ESG DISCLOSURE AND CIRCULAR ECONOMY IN FINANCIAL REPORTING

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ABSTRACT

This study examines the evolution of the informational paradigm within corporate reporting and its interaction with emerging sustainability frameworks, especially ESG metrics and the Corporate Sustainability Reporting Directive (CSRD) [1]. Traditionally rooted in prudence and historical cost, the realization principle has ensured reliability and capital protection by limiting the recognition of unrealized gains within financial statements. However, the transition toward comprehensive sustainability disclosure and circular economy models requires more comprehensive and forward-looking information capable of assessing social and environmental impacts. Through a conceptual analysis based on accounting doctrine, EU regulatory developments, and the author's operational experience in green public procurement, the study highlights how corporate reporting increasingly integrates non-financial metrics. Results highlight how ESG and CSRD frameworks reconfigure the overall information function of corporate reporting, linking financial performance to resource use efficiency, waste management, and circularity. The study argues that transparent sustainability communication does not weaken traditional accounting postulates, but rather integrates them, proving essential for evaluating the value generated over the long term within modern corporate systems.

Keywords: Realization Principle; ESG; CSRD; Circular Economy; Financial Reporting; Sustainability

1. INTRODUCTION

The realization principle has historically represented one of the pillars of financial reporting, ensuring that profits are recognized only when objectively realized and verifiable. This prudential approach, which originated in Article 2423-bis of the Italian Civil Code, was designed to protect corporate capital, safeguard creditors, and ensure the stability of corporate structures [2]. However, the evolution of European accounting regulations [1] and the emergence of sustainability-oriented frameworks [1], have progressively reshaped the broader informational role of corporate disclosure. The introduction of ESG metrics, the CSRD [1], and the growing relevance of circular economy models require companies to disclose environmental and social impacts that extend beyond traditional financial measures. This

section introduces the conceptual shift from a focus on a strictly financial notion of realized income to a broader interpretation of comprehensive value creation that incorporates resource efficiency, waste reduction, and long-term sustainability.

2. METHODS

The study adopts a qualitative and interpretative methodology based on three complementary sources:

1. **Doctrinal analysis** of the realization principle, historical cost, and prudential valuation rules in Italian and European accounting literature [3].
2. **Regulatory analysis** of EU sustainability frameworks, including ESG standards, the CSRD [1], and non-financial reporting obligations.
3. **Applied perspective** derived from the author's operational experience in ecological public procurement and waste-management contracts, used to contextualize how accounting principles interact with circular economy practices.

To systematically evaluate these interactions, a qualitative scoring framework (ranging from 0 to 100) was developed. This system translates fundamental regulatory milestones, disclosure obligations, and the completeness of operational data into conceptual indices, enabling a visual synthesis of structural trends in integrated reporting [1]. This triangulation allows the study to link legal-accounting theory with sustainability disclosure requirements and real-world environmental management processes [3],

3. FINDINGS

The figure1 illustrates the progressive shift from an exclusive corporate focus on financial realization to a parallel rise of sustainability-related disclosure [1].

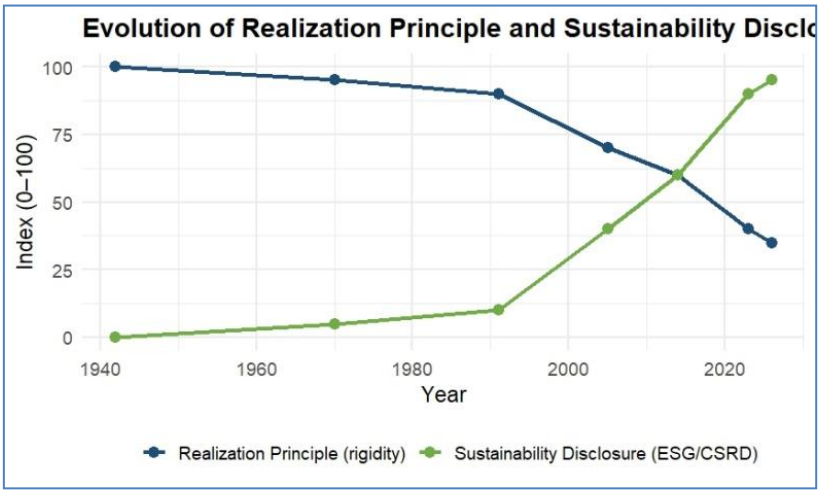


Figure 1. *Evolution of Realization Focus and Sustainability Disclosure (1942–2026)*

The diagram reported in figure 2 illustrates how traditional accounting elements and sustainability frameworks jointly contribute to integrated reporting.

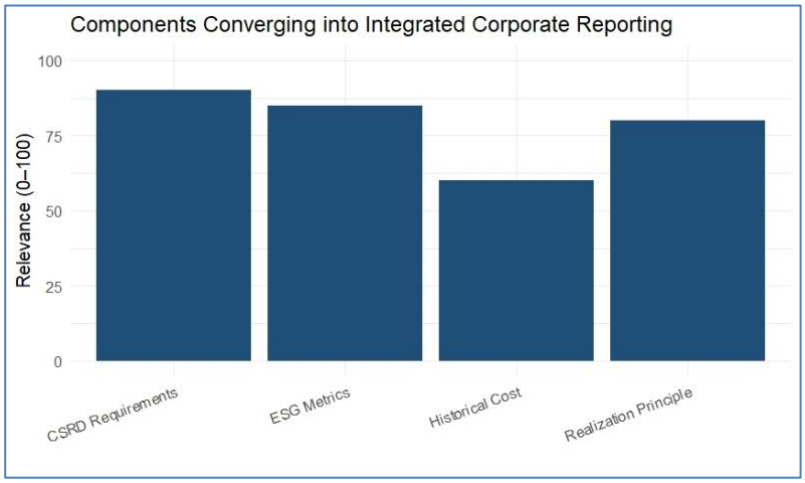


Figure 2. *Components Converging into Integrated Corporate Reporting*

3.1 Content Analysis

The analysis highlights a progressive convergence between traditional accounting principles and sustainability-oriented reporting frameworks [2, 3]. While the realization principle limits the recognition of unrealized values within the financial statements to protect capital, ESG and CSRD disclosure require companies to provide information on environmental impacts, resource use, and circularity strategies within the management report-elements that often materialize over long time horizons and cannot be captured solely through historical cost [1].

The figure 3 highlights the main circular-economy-related information streams relevant for financial and sustainability reporting.

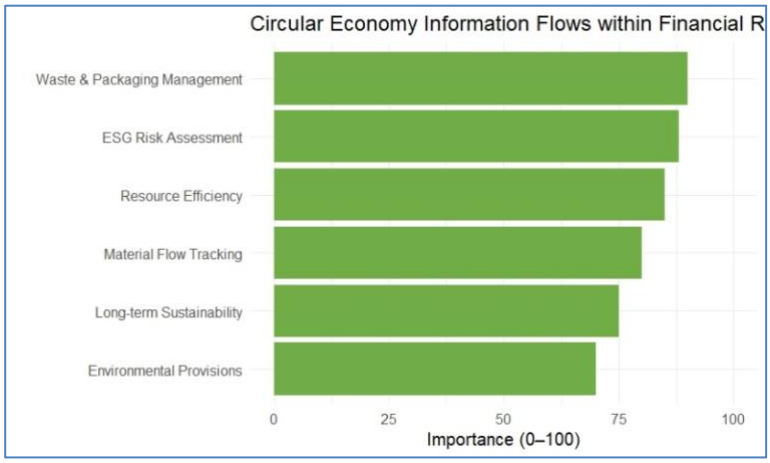


Figure 3. *Circular Economy Information Flows within Corporate Reporting*

The figure 4 summarizes limitations, opportunities and required adjustments when applying the realization principle to sustainability-related information.

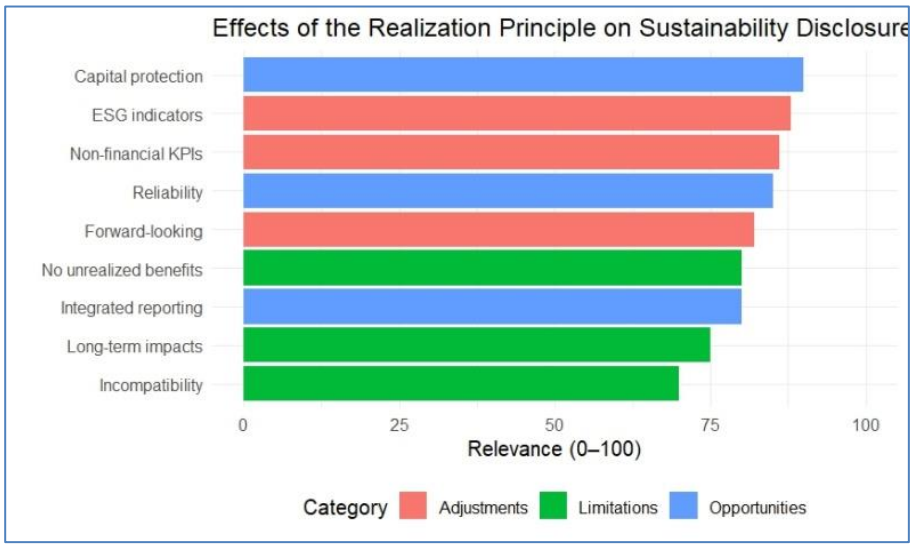


Figure 4. *Effects of the Realization Principle on Sustainability Disclosure*.

3.2 Impacts of the realization principle on sustainability disclosure

The realization principle remains essential for ensuring financial reliability, but its strict application within traditional financial statements is insufficient to represent comprehensive environmental performance [2]. Sustainability indicators such as waste reduction, recycling rates, or carbon intensity—do not correspond to realized financial transactions yet they are crucial for assessing long-term value creation. This creates a two-tier reporting system, in which financial realization coexists with non-financial materiality.

3.3 Transition toward ESG and CSRD reporting

The CSRD introduces mandatory, standardized sustainability disclosure, integrating environmental, social, and governance metrics into the overall corporate reporting framework [1]. This transition broadens the scope of corporate reporting from a static representation of realized income to a dynamic tool for evaluating risks, impacts, and future-oriented strategies. Companies are now asked to demonstrate how their business models align with circular economy principles and resource-efficient processes.

3.4 Implications for circular economy and waste/packaging management

The figure represents the sequential flow of waste and packaging data from operational processes to CSRD-compliant disclosure [1].

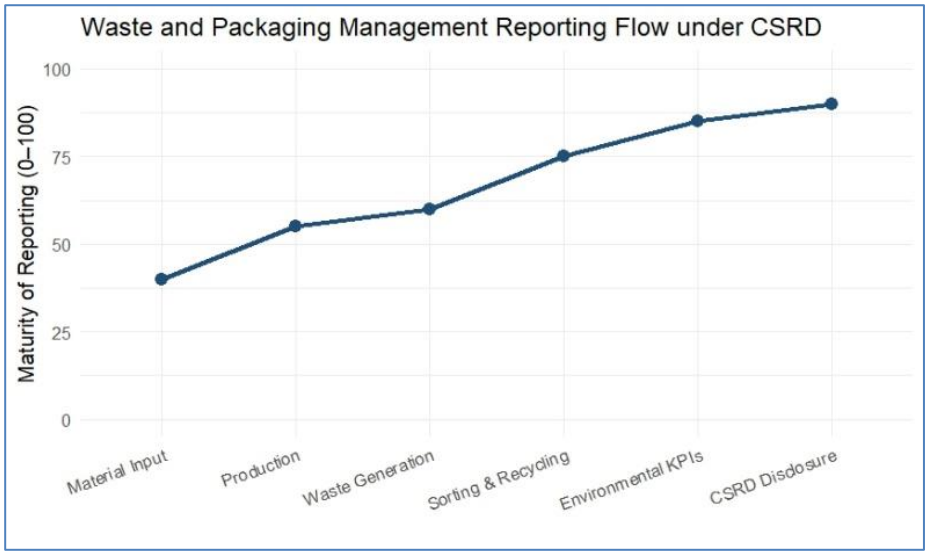


Figure 5. *Waste and Packaging Management Reporting Flow under CSRD.*

Circular economy models require transparency on material flows, recycling performance, and waste-management efficiency. These elements directly affect the credibility of environmental claims and the assessment of long-term corporate resilience. Corporate reporting, when integrated with ESG and CSRD metrics, becomes a fundamental tool for validating circular strategies, particularly in sectors such as packaging, waste collection, and ecological procurement.

4. CONCLUSION

The evolution of sustainability regulations demonstrates that corporate disclosure can no longer rely exclusively on financial metrics and historical cost to represent comprehensive corporate performance [1, 2]. Although the realization principle and historical cost remain fundamental within the financial statements to ensure reliability and capital protection [2], they must be complemented by structured sustainability disclosure capable of capturing environmental and social impacts within the integrated management report. The integration of ESG and CSRD frameworks transforms corporate disclosure into a multidimensional reporting system that links realized financial outcomes with circular economy strategies, resource efficiency, and responsible environmental management over the long term [1] The study concludes that transparent sustainability reporting is now indispensable for assessing the actual value generated by companies operating in increasingly complex ecological and regulatory contexts [3].

Disclaimer: the name of another author is withheld upon request, Giusy Amodeo Language advisor.

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THE CIRCULAR TRANSITION IN THE AGRI-FOOD SUPPLY CHAIN: DRIVERS, BARRIERS, AND THE BARILLA CASE

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ABSTRACT

This study aims to investigate the complexity of the global agri-food system, identifying it as a crucial sector in the transition towards sustainable development models. The analysis highlights how the interdependencies between the environment, health and society require a fundamental rethinking of food production, distribution and consumption, placing corporate sustainability at the heart of industrial strategies. Adopting a supply chain perspective integrated with the principles of the circular economy — from cultivation to the end-of-life management of products — the research explores how theoretical principles are translated into operational actions and the convergence between economic efficiency and environmental stewardship as a fundamental competitive dimension. In this context, the empirical analysis focuses on the case study of the agri-food company Barilla, examining its 2024 Sustainability Report to highlight the actual progress, structural barriers and operational contradictions that emerge in the application of these strategies.

Keywords: Agri-Food Companies; Agri-Food System; Barilla; Circular Economy; Sustainability.

1. INTRODUCTION

In recent years, the circular transition has emerged as the fundamental paradigm for transforming production and consumption systems from linear to regenerative [1]. In contexts now widely recognized as complex socio-technical systems, multiple actors, divergent objectives and constantly evolving non-linear dynamics coexist.

Within this holistic and integrated conceptual framework, the development of the agri-food sector requires an analytical and systemic approach based on the Triple Bottom Line principle, aimed at supporting a simultaneous assessment across three interdependent dimensions: economic, social and environmental [2].

In the European context, however, the urgent need to implement regenerative and circular models within the agri-food supply chain [4] – relating to material and resource flows – clashes with traditional industrial set-ups. The latter often remain largely inefficient and characterized by systemic weaknesses [3].

In order to test the convergence between theoretical models and their practical application in the field, this study is developed through a critical analysis of the empirical case study of the agri-food company

Barilla [5]. The results of the analysis are structured to map the operational solutions implemented across the entire value chain and, at the same time, to examine the structural limitations, systemic barriers and communicative paradoxes [6] that major players in the agri-food industry face in their complex attempt to balance economic competitiveness with the real demands of ecological regeneration.

2. METHODS

The methodological approach of this study is divided into two phases. The first phase involved a literature review conducted primarily within the Scopus academic database, using a targeted search query based on a combination of keywords such as 'circular economy', 'agri-food', 'agri-food companies' and 'sustainability'. The data obtained were analyzed, examining the temporal distribution of publications, recurring keywords and the main thematic trends.

The second phase shifts the investigation to the empirical level through the case study method. To test the practical applicability of circular models and highlight the associated operational trade-offs, the agri-food company Barilla was selected, as it is considered a highly representative player in the European sector. The documentary analysis focused on the Barilla 2024 Sustainability Report [5]. The qualitative and quantitative data thus collected were subsequently integrated and compared with the sector's main institutional reports, in order to map the actual industrial barriers and drivers and ensure a critical and objective analysis.

3. FINDINGS

The transition to a circular agri-food model promises systemic benefits that far exceed the scope for improvement offered by the traditional linear model. As illustrated in Fig. 1, a comparison between the current development scenario and the circular scenario projected for 2030 and 2050 reveals a marked divergence in terms of resource efficiency, environmental mitigation and socio-economic impacts [3].

In terms of production inputs, the circular approach enables a genuine decoupling of growth from resource consumption, driving a drastic reduction in the use of chemical fertilizers, pesticides and energy sources, coupled with highly optimized water management. This upstream efficiency gain translates downstream into a significant reduction in human pressure on ecosystems: the adoption of regenerative practices not only halves the use and degradation of agricultural soil compared with the business-as-usual scenario, but also accelerates the decarbonization of the supply chain, reducing greenhouse gas emissions to levels below those estimated for the linear pathway.

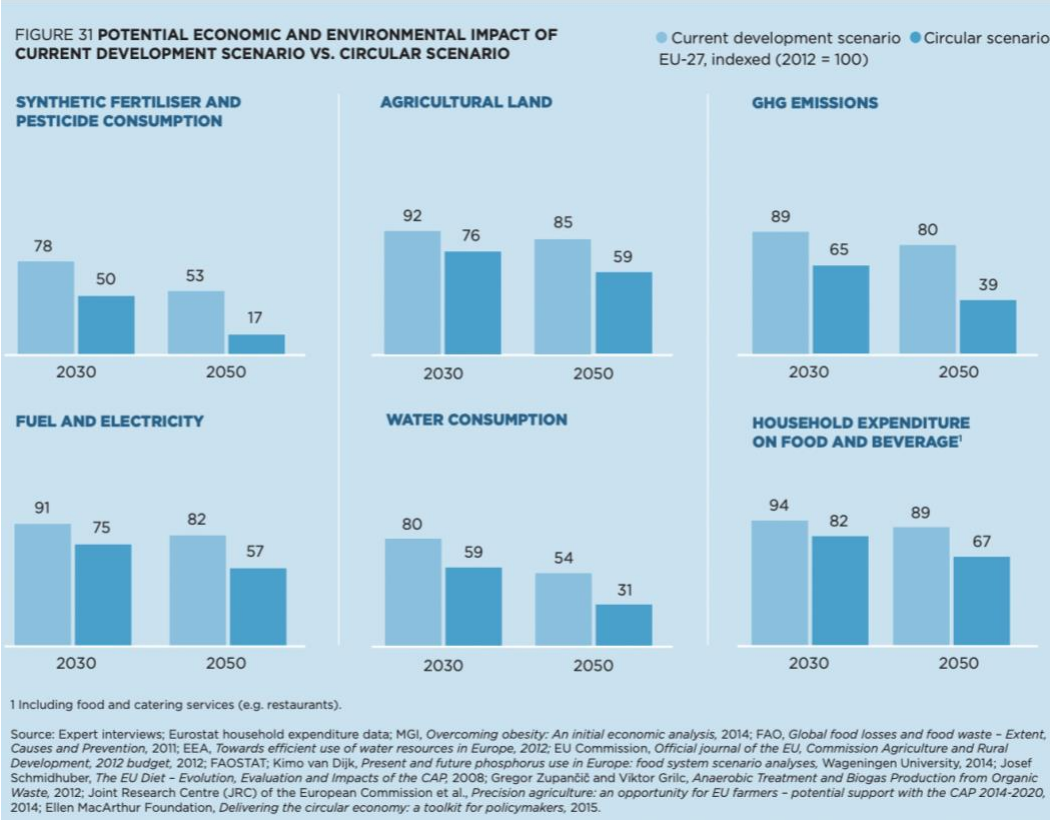


Figure 1. *Potential economic and environmental impact of the current development scenario versus the circular economy scenario.* ***Source:*** *ACTeon Environment Research & Consultancy, (2012).*

At present, agri-food systems are undergoing a complex restructuring due to unprecedented external pressures of an environmental, economic and social nature, which necessitate the development of shared strategic responses [7].

It is clear that the transition towards a sustainable and inclusive model cannot be left to the isolated initiatives of individual companies. It requires a coordinated and structured approach capable of integrating the entire value chain. In this context, although sustainability has now established itself as a crucial competitive factor in the market, the path to implementation remains heavily hampered by structural barriers such as the wide geographical dispersion of production, the length of supply chains and the heterogeneity of the stakeholders involved in terms of resources and expertise [6].

This complex interplay between drivers of change and systemic resistance is clearly reflected in the analysis presented in the Quantis Report [6], whose key factors on the forces governing sustainable transformation are summarized in Fig. 2.

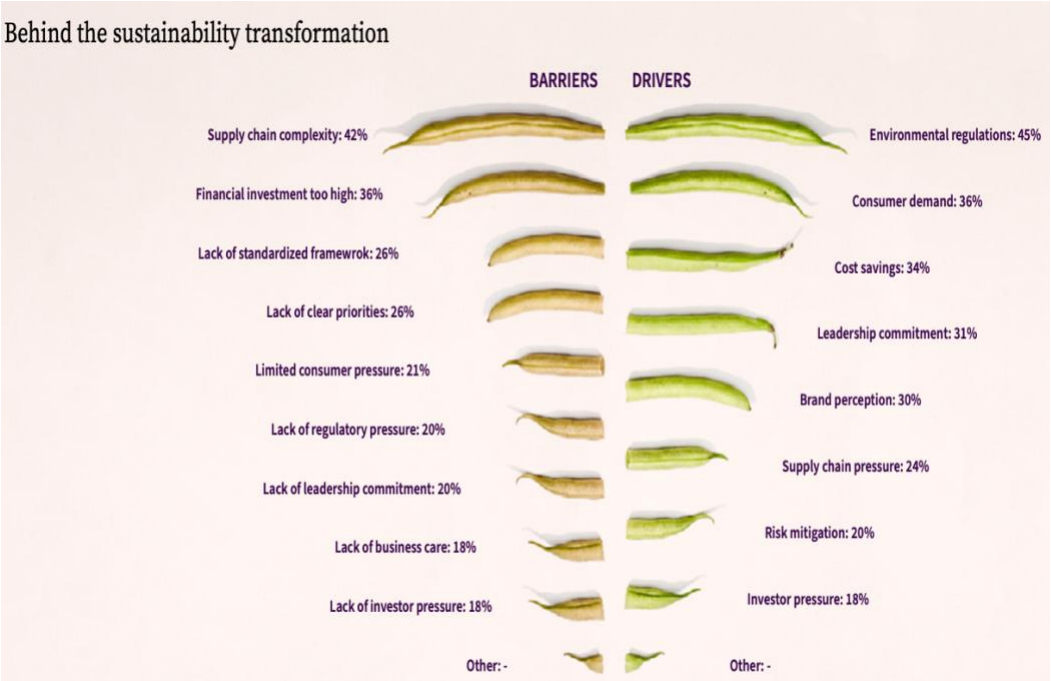


Figure 2. *Key factors driving the sustainable transformation of businesses.* ***Source****: Quantis-BCG.*

To put this coordinated approach into practice and overcome these systemic barriers, key players in the agri-food sector must systematically identify and prioritise their sustainability issues. Fig. 3 shows a significant empirical example from the Barilla Group [5], which in 2024 conducted a Double Materiality Analysis in line with the European Commission's Delegated Regulation (2023/2772) and the CSRD Directive (2022/2464). This tool serves as a genuine strategic compass, enabling the Group to assess issues that may generate positive or negative impacts – whether current or potential – on both the environment and people, taking into account short-, medium- and long-term time horizons.

The analysis is conducted from two complementary perspectives. On the one hand, impact materiality (an 'inside-out' approach) assesses the external effects that the Group's activities have on the environment and society throughout the entire value chain. On the other hand, financial materiality (an outside-in approach) considers the environmental and social aspects that may have financial consequences for the organisation. The integration of these two perspectives gives rise to the consolidated list of material issues that guides the company's strategic priorities; the results of this analysis have consequently been translated into concrete actions and programmes in line with the corporate strategy.

ESRS	Programme	Value chain
E1 - Climate change	Decarbonisation	Entire value chain
E1 - Climate change	Energy & water	Core - Production
E1 - Energy	Energy & water	Core - Production
E3 - Water	Energy & water	Core - Production
E4 - Biodiversity and ecosystems	Sustainable agriculture	Upstream - Raw materials
E5 - Resource use and circular economy	Responsible supply chains	Upstream - Raw materials
E5 - Resource use and circular economy	Sustainable packaging	Upstream - Packaging
S1 - Own workforce	Barilla People	Core - Production
S1 - Own workforce	Health and safety	Core - Production
S4 - Consumers and end-users	Nutrition and wellbeing	Downstream - Consumption
G1 - Business conduct	Responsible supply chain	Entire value chain

Figure 3. *The results of the double materiality analysis.* ***Source:*** *2024 Sustainability Report, Barilla.*

4. CONCLUSION/DISCUSSION

The results highlight the ambivalence of the global agri-food system. If, on the one hand, its carbon footprint, intensive exploitation of resources and overuse of chemical inputs make it one of the main drivers of ecological degradation, on the other hand, its pervasiveness makes it one of the most powerful levers for triggering the ecological transition [8]. In this context, the adoption of the circular economy is not merely an option for improving efficiency, but the necessary paradigm for creating a truly sustainable agri-food system.

However, as the Barilla case study reveals, translating the principles of circularity into industrial practice involves complex trade-offs. Although the company has successfully integrated sustainability into its strategy through responsible farming contracts and the reduction of packaging, a critical analysis necessitates highlighting the limitations of this transition. The main paradox lies in the clash between the production scale of a multinational corporation and the timescales of ecological regeneration: global sourcing makes it difficult to ensure full traceability of material flows and the effective closure of cycles. Furthermore, the transition to fully recyclable or compostable packaging is hampered by the fragmented nature of collection and recycling systems in various foreign markets, risking the undermining of upstream efforts and raising questions about the system's true effectiveness.

This gap between stated commitments and operational reality demonstrates how the transition to a circular agri-food model requires consistency and a long-term strategic vision capable of sustaining high initial investment. In the years to come, it will be necessary to transform sustainability from a mere competitive factor into an intrinsic and shared condition of global development.

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PORTFOLIO OPTIMIZATION INTEGRATING FINANCIAL AND ESG RISKS MULTI-RISK APPROACH

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ABSTRACT

This study proposes an innovative two-step portfolio optimization framework that integrates financial risks with Environmental, Social, and Governance (ESG) criteria. Drawing on the theory of coherent risk measures, the research moves beyond the classical mean-variance paradigm by employing Conditional Value-at-Risk (CVaR) and the Gini-type measure to capture tail risks and investor risk aversion. The methodology consists of an initial stage minimizing market risk over a ten-year horizon to identify financially robust portfolios. In the second stage, these portfolios are re-optimized to reduce ESG risk exposure using Refinitiv sustainability ratings. Empirical results on S&P 500 components demonstrate that integrating ESG factors does not compromise returns; instead, it generates resilient strategies with superior final wealth and Sharpe ratios. This study confirms that a sequential two-step approach provides an effective solution for balancing profitability with investment responsibility.

Keywords: Portfolio Optimization; ESG Integration; Coherent Risk Measures; Gini Measure; Decision-making.

1. INTRODUCTION

Modern portfolio management is undergoing a profound paradigm shift as Environmental, Social, and Governance (ESG) criteria transition from purely ethical considerations to indispensable risk management tools. As institutional investors increasingly seek to align financial targets with sustainability mandates, the challenge lies in how to integrate these non-financial metrics without compromising portfolio resilience.

However, a significant gap persists in the current literature: most ESG integration models either rely on traditional Mean-Variance frameworks, which inherently fail to capture the non-normalities and tail risks characteristic of modern markets [1], or aggregate financial and ESG objectives into a single, often ambiguous, objective function [2]. Such aggregation can obscure the specific impact of sustainability on the overall risk-return profile.

To address these limitations, this paper introduces an innovative two-step optimization framework designed to decouple and meticulously manage distinct risk dimensions. Unlike integrated models that

merge objectives, our sequential approach provides a more transparent and tail-robust decision-making framework. The primary innovation of this work lies in the application of the Gini-Type risk measure within a multi-step ESG context. While CVaR is highly effective at capturing extreme market losses [3], the Gini measure offers a more nuanced approach by simultaneously integrating tail risk sensitivity and the investor's specific risk aversion [4]. Our results offer a refined alternative to existing models, proving that a sequential methodology empowers investors with greater control over the trade-offs between profitability and sustainability.

2. METHODS

The objective of this study is to perform a two-step optimization on the components of the S&P 500 index to construct portfolios that are both financially resilient and ESG-compliant. The dataset includes historical daily adjusted closing prices and ESG scores for S&P 500 stocks from April 2011 to December 2021, sourced from Refinitiv. The optimization process is designed to decouple financial risk from sustainability risk. While this study relies on Refinitiv sustainability ratings, we acknowledge the well-documented divergence in ESG scores among different rating agencies. The variability in scoring methodologies implies that optimal portfolio allocations and resulting risk-return profiles could exhibit sensitivity to the chosen data provider. Consequently, testing this sequential framework across multiple ESG rating systems represents a valuable direction for future research to further validate its empirical robustness.

2.1 Step 1: First Optimization – Minimizing Market Risk

In the first phase, we focus on minimizing market risk using a rolling window of one year of daily returns. Portfolio risk is evaluated through three key measures: Mean-Variance (MV) [5], Conditional Value-at-Risk (CVaR) [6], and a Gini-Type measure [4]. The primary innovation is the inclusion of the linearized version of the Gini index, which is coherent with L_1-ordering and highly efficient for optimization. To capture different degrees of extreme risk and investor risk aversion, we tested all possible combinations of tail risk parameters (α and $\beta \in \{1\%, 3\%, 5\%\}$). For each daily rolling window over the 10-year period, and for every α-β combination across the risk measures, we solved the optimization problem for 40 different target returns, generating a massive and robust dataset of ex-ante optimal portfolios.

This process generates 40 optimal portfolios that form an efficient frontier, serving as the "meta-assets" for the second optimization step.

2.2 Step 2: Second Optimization – Minimizing ESG Risk

The second phase refines the 40 optimal strategies obtained in Step 1 by focusing on the minimization of ESG risk. To rigorously evaluate the impact of sustainability on portfolio performance, this step is divided into two distinct analytical approaches:

- *Step 2.1 - Fixed ESG Constraints (Static Analysis)*: We analyze the ESG characteristics of the portfolios generated in Step 1 without modifying their internal asset allocation. This serves as a benchmark to understand the integration "cost" within a static framework.
- *Step 2.2 - Dynamic ESG Optimization (Active Reallocation)*: The 40 optimal portfolios from Step 1 are treated as individual meta-assets. We allow the model to dynamically reallocate weights among these 40 portfolios to find a new efficient frontier that minimizes ESG risk relative to an ESG target.

3. FINDINGS

The empirical analysis evaluates the framework by comparing the performance of MV, CVaR, and three versions of the linearized Gini measure (Gini1, Gini2, Gini3).

3.1 Step 1 Analysis

The ex-ante analysis reveals that MV portfolios exhibit the lowest risk and highest diversification, making them suitable for conservative investors. CVaR-based strategies effectively manage extreme market fluctuations by focusing on tail risks. However, Gini-based portfolios demonstrate a unique ability to concentrate investments on high-performing assets, achieving a superior balance between risk and return during growth phases.

3.2 Step 2 Analysis: Static vs. Dynamic

The transition from financial optimization to ESG integration highlights a fundamental difference between static and dynamic approaches. In Step 2.1 (Fixed ESG Constraints), the Global Minimum (GM) risk strategy generally leads to greater wealth accumulation than the Maximum ESG (MaxESG) strategy. This suggests that static integration can occasionally act as a constraint on financial growth.

However, in Step 2.2 (Dynamic ESG Optimization), the results reverse. When ESG constraints are adjusted dynamically, the MaxESG strategy achieves significantly higher wealth levels than the low-risk strategies. For strategies using CVaR and MV, a high ESG score does not negatively impact wealth trajectories. In the case of Gini-based measures, the dynamic model consistently yields superior results, showing that portfolios with high ESG compliance are also those that exhibit the most resilient financial growth over the long term.

		Strategy			
		Step 2.1 GM	Step 2.1 MaxWealth	Step 2.2 GM	Step 2.2 MaxESG
Risk Measure	Mean-Variance (MV)	6.354	55.942	65.379	68.433
	CVaR 1%, 1%	19.672	58.203	66.046	66.439
	Gini1 1%, 1%	29.347	40.573	64.888	65.8
	Gini3 1%, 1%	29.237	43.834	65.063	65.74

Table 1: *Final Wealth comparison between Static (Step 2.1) and Dynamic (Step 2.2) Optimization.*

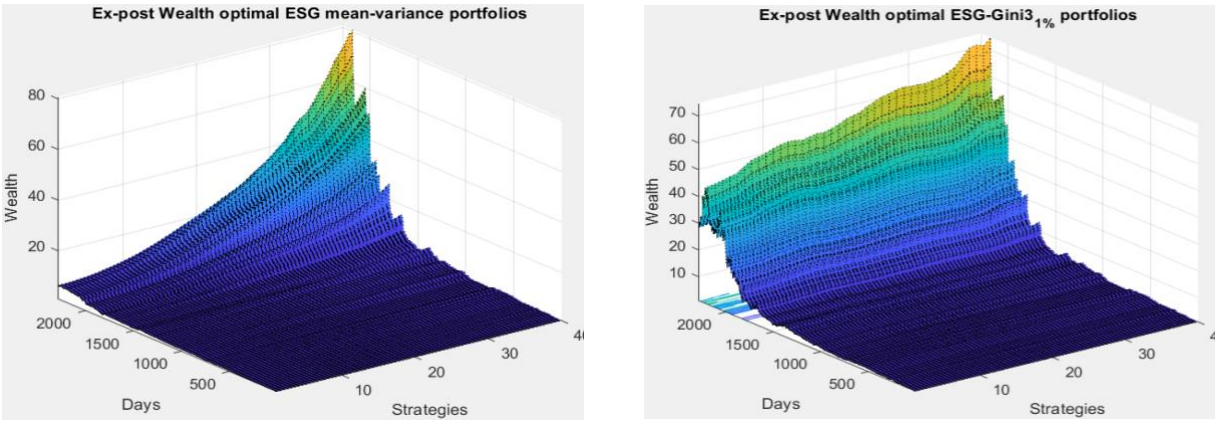


Figure 1. *Ex-post wealth evolution over time (Step 2.2). (a) Traditional Mean-Variance optimization; (b) Gini3 coherent risk measure.*

4. DISCUSSION/CONCLUSION

This study demonstrates that adding ESG factors does not penalize financial returns; rather, it strengthens the portfolio's overall resilience against market shocks. A central finding is the critical role of the Gini-type measure, which provides the most effective combination of risk mitigation, return, and sustainability. Unlike traditional models, the Gini measure allows for highly customized asset allocations that change significantly depending on the investor's specific risk aversion.

The results highlight a positive synergy between financial performance and ESG criteria: the strategies that achieve the highest wealth are frequently those with the highest ESG scores. This confirms that sustainable investing, when managed through sophisticated and coherent risk measures within a sequential framework, represents a superior approach for long-term value creation.

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PRELIMINARY ASSESSMENT OF MACHINE LEARNING MODELS FOR GRAPE POMACE SHELF-LIFE PREDICTION IN IOT MONITORING SYSTEM

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ABSTRACT

This study investigates the suitability of different machine learning models for integration into an Internet of Things (IoT)-based grape pomace monitoring system developed in an industrial context, aiming to predict shelf life and support winery by-product valorization. Because experimental measurements from the prototype were unavailable, a simulation-based workflow was implemented in Python to generate synthetic datasets representing realistic storage conditions. Several machine learning and deep learning regression models were compared, while the contribution of anthocyanin concentration as an additional predictor of grape pomace quality and shelf life was also evaluated. Results showed that nonlinear models outperformed conventional linear regression approaches, with neural network models achieving the best predictive accuracy. The inclusion of anthocyanin concentration generally improved model performance, highlighting its potential as an indicator of grape pomace stability. These findings provide preliminary guidance for predictive model selection in intelligent IoT monitoring systems and support data-driven approaches for by-product valorization.

Keywords: Grape pomace; Shelf-life prediction; Machine learning; Internet of Things (IoT); Predictive modelling; Winery by-products

1. INTRODUCTION

The wine industry is a major sector of the global agri-food economy [1], generating large quantities of by-products, with grape residues (skins, seeds, and stems) estimated at approximately 14.5 million tonnes annually in Europe alone [2]. This abundance of winery residues has stimulated increasing interest in the valorization of grape pomace, aligning with the United Nations Sustainable Development Goals [3], as a source of bioactive compounds for high-value industrial applications owing to the incomplete extraction of phenolic compounds during vinification [4]. The recovery of bioactive compounds from grape pomace requires biomass with adequate stability and shelf life [5]. However, biomass quality progressively declines during storage due to dehydration and senescence, degradation of phenolic compounds and anthocyanins driven by enzymatic activity [6], and microbial growth with

potential implications for product safety through mycotoxin production [7]. Conventional shelf-life estimation methods, including real-time accelerated, and multivariate approaches, remain limited in capturing the complexity of food deterioration processes [8]. Artificial intelligence (AI) offers a promising alternative by modelling nonlinear relationships among biochemical, environmental, and microbial variables and improving predictive accuracy [9]. Combined with Internet of Things (IoT) technologies, AI can exploit real-time sensor data to support robust modelling, shelf-life prediction, and early degradation detection [10]. In a broader perspective, the integration of IoT and AI may enhance monitoring and valorization of winery biomass across the production chain, supporting more efficient and sustainable processes [11]. This study is based on an industrial case study concerning IoT-based monitoring of grape pomace for quality and shelf-life assessment. A Python-based simulation workflow was used to generate synthetic datasets for exploratory analysis and model evaluation. Several regression models were explored and comparatively assessed, including the effect of anthocyanin concentration as an additional predictive feature. The results are structured in three steps: (i) comparison of model performance on the baseline feature set, (ii) evaluation of the impact of anthocyanin inclusion on predictive performance, and (iii) bootstrap-based statistical validation of the observed improvements.

2. METHODS

The IoT-based grape pomace monitoring prototype developed by an industrial partner was considered as the reference architecture for this study. Due to the absence of experimental measurements, a Python-based simulation workflow (v3.13.7, in Visual Studio Code) was implemented to generate and analyze synthetic datasets representing realistic storage conditions. Two datasets (A and B) were created using five input variables derived from sensor specifications: temperature (°C), relative humidity (%), light intensity, pH, and time (Unix timestamp). Dataset B additionally included anthocyanin concentration to assess its impact on shelf-life prediction. Each dataset comprised 1,000 samples, reduced to 785 after pH-based filtering. Shelf life was modeled using a multivariate regression formulation based on literature evidence [12], with predictor variables expressed as deviations from standard reference conditions, as follows:

$$shelf_life_days = 50 + 0.8 \cdot anthocyanin - 0.9 \cdot (temp - 25) - 0.5 \cdot (hum - 55) - 0.001 \cdot lux - 2.5 \cdot (pH - 6.5) + \varepsilon,$$

where ε represents a normally distributed error term and the anthocyanin component is included only in Dataset B. Data processing and visualization were performed using NumPy, Pandas, Matplotlib, and Seaborn. Exploratory data analysis on Dataset B included a Pearson correlation heatmap and a scatter plot of key relationships in the dataset. Seven regression models were developed and evaluated using an 80:20 train–test split: Multiple Linear Regression (MLR), Random Forest Regressor (RFR), Gradient Boosting Regressor (GBR), Support Vector Regression (SVR), a ResNet-based architecture, and two

Multilayer Perceptron (MLP) models implemented in Scikit-learn (Scikit-MLP) and TensorFlow/Keras (Keras-MLP). Model performance was assessed using coefficient of determination (R^2), mean absolute error (MAE), and mean squared error (MSE). Statistical significance was evaluated via bootstrap resampling (300–1000 iterations, α = 0.05) [13] complemented by data augmentation experiments introducing ±15% and ±25% perturbations to simulate measurement variability.

3. FINDINGS

3.1 Model performance comparison on Dataset A

All models are evaluated on Dataset A within the simulation framework (Fig. 1). The Keras-based MLP achieves the best overall performance (R^2 = 0.879, MAE = 2.29, MSE = 9.62), demonstrating strong capability in capturing nonlinear relationships between environmental variables and grape pomace shelf life. SVR shows comparable performance (R^2 = 0.858, MAE = 2.27, MSE = 11.3), while Scikit-MLP, GBR and RFR provide intermediate results, all outperforming the linear baseline. MLR (R^2 = 0.775, MAE = 3.43, MSE = 17.9) confirms the limitations of linear models in this context. The ResNet-based architecture achieves lower performance (R^2 = 0.786, MAE = 3.17, MSE = 17.0), indicating limited suitability for small tabular datasets. These findings indicate that Keras-MLP provides the best balance between accuracy and robustness, making it the most suitable candidate for integration into the proposed IoT framework.

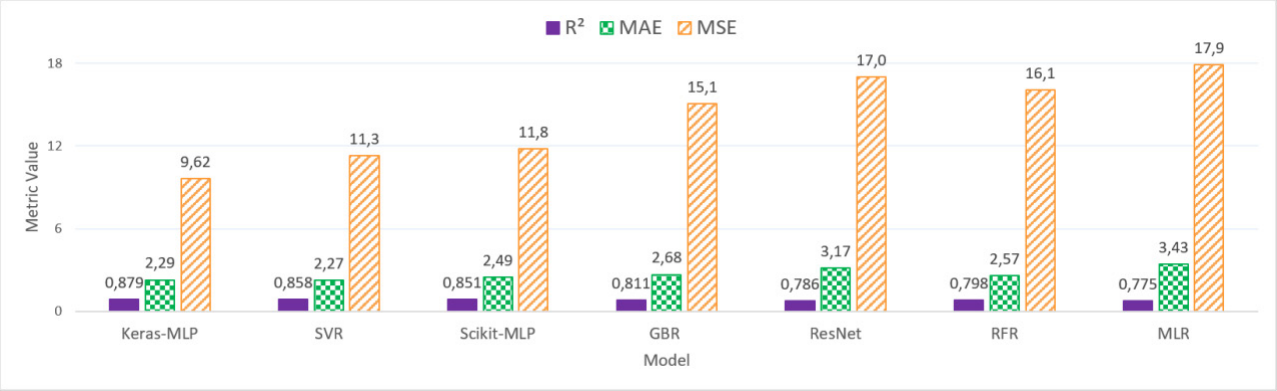


Figure 1. *Comparison of the predictive performance (R^2, MAE, and MSE) of the evaluated machine learning models on Dataset A* **(validation dataset).**

3.2 Exploratory Analysis of Anthocyanin and Its Impact on Predictive Performance

Anthocyanin concentration is introduced in Dataset B as an additional predictor due to its relevance in grape pomace valorization and its contribution to coloration and bioactive properties.

Exploratory analysis reveals a strong positive correlation with shelf life (Pearson's r = 0.85) (Fig. 2), indicating that higher anthocyanin levels are associated with longer storage stability. The scatter plot further suggests that moderate temperatures are linked to both higher anthocyanin retention and increased shelf life.

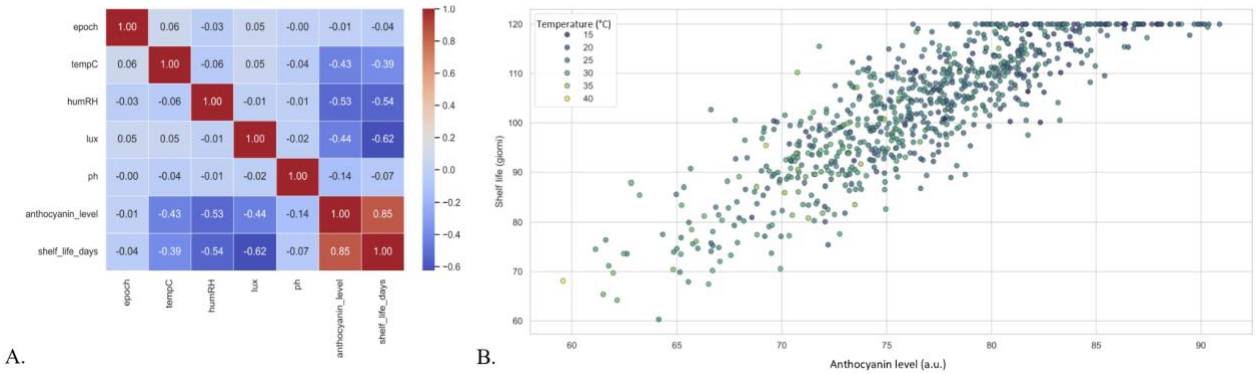


Figure 2. *Exploratory data analysis of Dataset B: (A) Pearson correlation heatmap of the analyzed variables and (B) scatter plot showing the relationship between anthocyanin concentration and shelf life.*

Figure 3 shows the evaluation of the predictive value of anthocyanin concentration, as all models are retrained on Dataset B, resulting in overall performance improvements compared with Dataset A. The Keras-MLP again achieves the highest predictive performance (R^2 = 0.890, MAE = 1.22, MSE = 3.80), while SVR yields the lowest prediction error (MAE = 0.960, R^2 = 0.858). The Scikit-MLP also performs strongly (R^2 = 0.881, MAE = 1.44, MSE = 4.14). In contrast, the ResNet-based architecture does not benefit from the additional feature and exhibits substantially lower performance (R^2 = 0.306, MAE = 4.19, MSE = 24.1). These results indicate that anthocyanin concentration improves predictive performance across most models and represents a relevant feature for shelf-life estimation, with the Keras-MLP remaining the most effective approach.

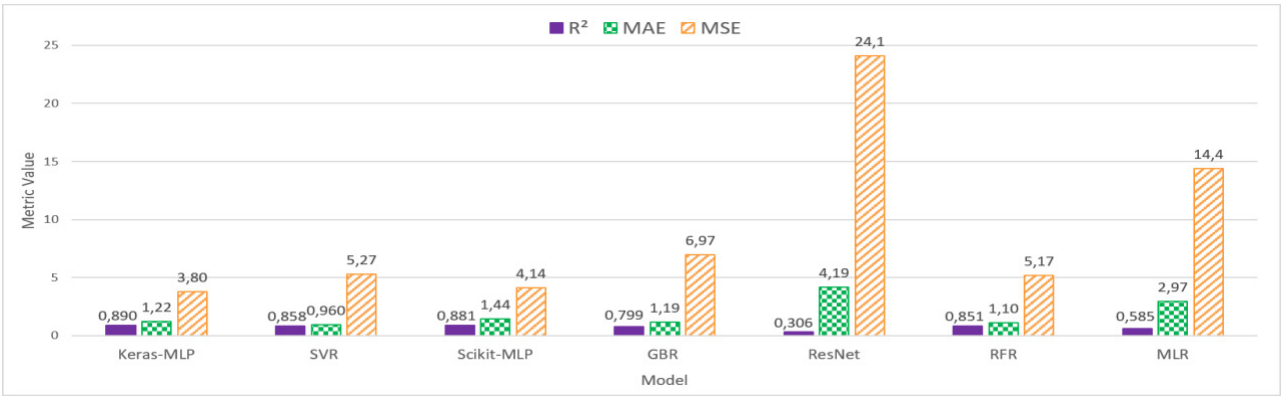


Figure 3. *Comparison of the predictive performance (R^2, MAE, and MSE) of the evaluated machine learning models on Dataset B (validation dataset).*

3.3 Bootstrap-Based Statistical Validation

Bootstrap analysis (data not shown) indicates a consistent positive effect of anthocyanin inclusion on model performance, with variability depending on noise level and model complexity. Stronger improvements are observed for non-linear models and are mainly reflected in positive ΔR^2 (R^2_{with} – $R^2_{without}$, for anthocyanin feature) whereas reductions in ΔMAE and ΔMSE (computed analogously) are

less consistent. The bootstrap distributions of ΔR^2, ΔMAE, and ΔMSE for the Keras-MLP, which shows the most stable behavior across bootstrap iterations among all models, are displayed in Fig. 4. A clear shift toward positive ΔR^2 values is observed, indicating improved predictive performance when anthocyanin is included. Although a consistent trend is observed in bootstrap analyses, statistical significance is not consistently achieved across all conditions. Further validation on experimental datasets is required to confirm the robustness and statistical relevance of the observed effects.

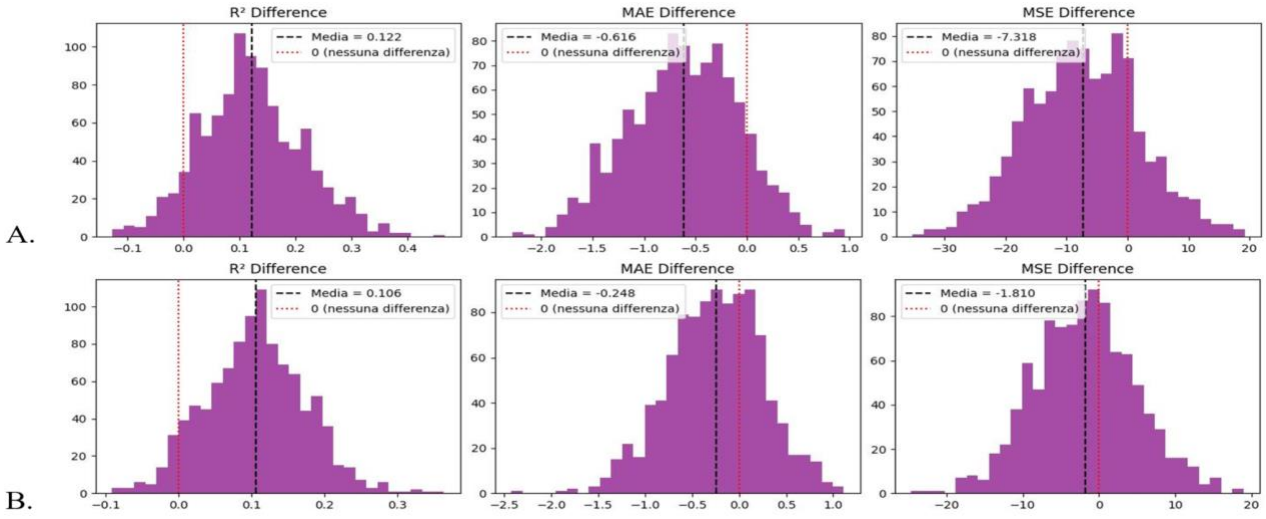


***Figure 4**. Bootstrap distributions for the Keras-MLP under (A) 25% and (B) 15% noise perturbations (1000 iterations).*

4. DISCUSSION/CONCLUSIONS

The primary aim of this study is to investigate and validate the suitability of machine learning models for grape pomace shelf-life prediction, focusing on algorithms capable of handling time-indexed environmental data within the proposed IoT-based monitoring framework. Among the evaluated approaches, the nonlinear Keras-based MLP emerged as the best-performing model. A second phase evaluates anthocyanin concentration as an additional predictive feature for shelf-life estimation and product quality assessment, due to its importance to grape pomace valorization. Results indicate a potential improvement in predictive performance; however, the analysis is based on simulated data and shows limited statistical significance under bootstrap validation, highlighting the need for confirmation using experimental datasets. Future work should focus on integrating advanced feature extraction techniques, particularly imaging-based approaches, and implementing the most effective models in low-power embedded devices for real-time industrial monitoring.

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DECARBONIZATION OF MARINE TRAFFICS: TECHNICAL-ECONOMIC AND ENVIRONMENTAL ANALYSIS

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ABSTRACT

This study highlights the big environmental pollution problem due to our wrong behaviours, with a focus on different ways of transport: land, air, sea. The purpose of the paper is to analyze damaging effects caused by transportation means and finding alternative measures to fight pollutant emissions, like green-propulsion methods and eco-friendly solutions. Also the infrastructures are responsible for alteration and degradation of the ecosystem, so it's necessary to take action on the entire cluster to achieve sustainability of transport industry.

Even if road transport represents the way with higher contaminant impact, maritime traffics play an important role because volumes of goods shipped by sea and tonnage ships are still rising. The first step towards decarbonization is to improve means, equipment and infrastructures already existing and building new ones. But the real challenge is to evaluate if green transition results into both economic and environmental benefits.

Keywords: Pollution, Ecological Transition, Sustainable Transports, Decarbonization of Maritime Traffic, Green Ports, Green Fuels, Zero and Low Emissions.

1. INTRODUCTION

Pollution is a very topical issue on which to raise public awareness. In fact, since the 1950s, industrialized countries have contributed to release toxic gases into the atmosphere with a six-fold increase in carbon dioxide [1]. Considering different economic sectors, transportation is responsible for only 14% of polluting emissions but with serious effects on human health, plant and animal species. Once emitted into the atmosphere, primary pollutants, such as carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compound (COV), primary particulates, sulphur dioxide (SO2) react chemically to produce secondary gases like ozone (O3), secondary particulate matter (PM), sulphuric acid [2].

Shifting focus to sea transport, a great obstacle to decarbonization is also represented by accidental or intentional spills in the ocean, ports and all logistic industry activities like terminal equipment,

shipyards, dry ports. Related to traffic volumes, Italian ports are classified as the most polluting in Europe [3]. Countries have implemented energy transition policies setting goals to achieve in the next few years like zero toxic emissions, use of low carbon renewable sources, Carbon Border Adjustment Mechanism (CBAM), increase in forests and green areas. Recent studies have shown if we keep exploiting the Earth to current levels, we would need other two planets within 2050 because exposure to toxic substances causes the death of million people, extinction of many animal and plant species and increase in global average temperature. [4]

2. METHODS

There are several solutions to be adopted like "clean" alternative fuels for propulsion (hydrogen, biofuel, natural gas), fuel cell electric vehicle (FCEV) and battery electric vehicle (BEV) [5], fleet and infrastructure modernization.

In the maritime sector, Countries are putting in place targeted actions to fight global warming. For example, Emission Trading System (ETS) sets maximum emission limits for ships, Emission Control Areas (ECAs) include sea stretches where navigation is only permitted to vessels with low particulate nitrogen and sulphur oxides emissions as established by MARPOL Convention, Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) allow to define sustainability parameters of naval fleets [6]. A great turning point is represented by new green fuels such as methanol produced from biomass [7], liquefied natural gas (LNG) [8], ethanol obtained from fermentation of sugar and starch, hydrogen, bio-fuels derived from used cooking oils or organic wastes, ammonia as a result of chemical reaction involving hydrogen and nitrogen. Other alternative propulsion method is electric energy (ships powered by electric engines and batteries) [9]. Solar-powered vessels and wind- powered vessels are equally revolutionary because they are able to navigate thanks to photovoltaic panels on their surfaces and special sails avoiding harmful emissions [10].

Green ports means energy efficiency of infrastructure, management of waste and noise pollution, minimizing emissions from ships at berth, technology innovation and digitalization of processes.

3. FINDINGS

Type of fuel strongly affects pollution levels. Fossil fuels are cost effective but environmentally disadvantageous, unlike green propulsion methods.

E-methanol costs around 800-1600 €/tons that exceeds methanol by 6 times (100-250 €/tons). According to estimates, this gap may decrease by 2050 to 250-600 €/tons. A 95% decrease in emissions is estimated, especially CO2 and NOx. (Fig. 1)

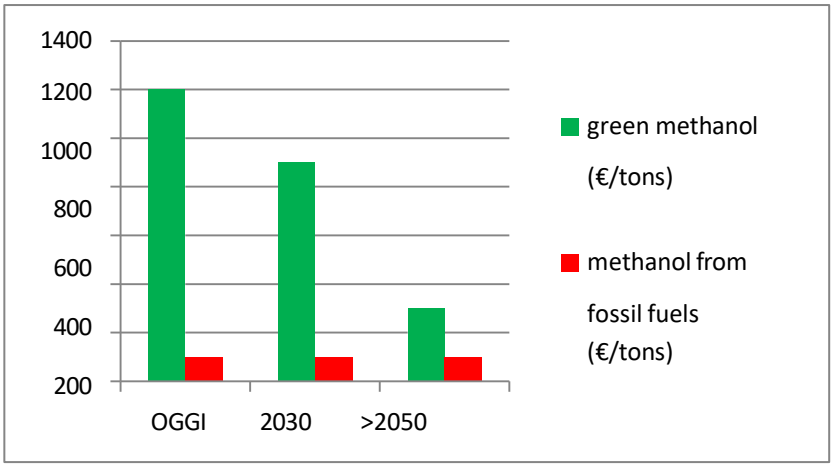


Figure 1. *Production costs of green methanol and methanol from fossil fuels (coal and natural gas). Source: author's elaboration based on link data [11]*

Also green ethanol is very expensive (4500 €/tons) with an expected reduction to 2000 €/tons in the next years. (Fig. 2)

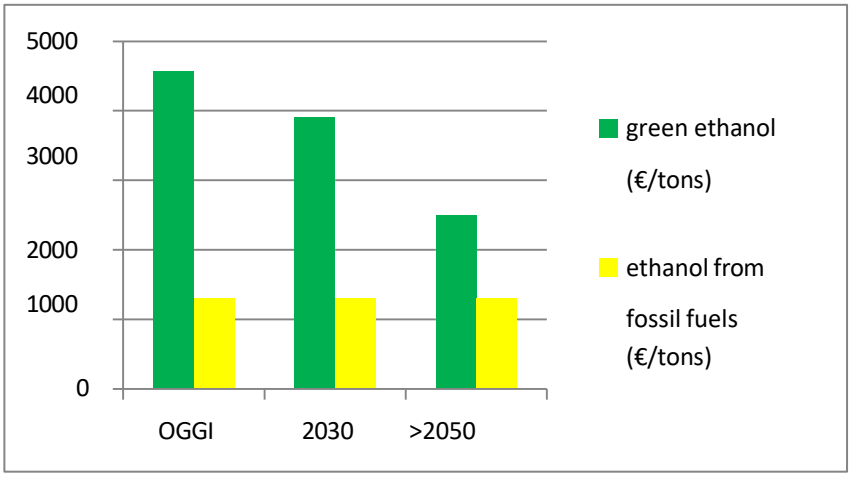


Figure 2. *Production costs of green ethanol and ethanol from fossil fuels (oil). Source: author's elaboration based on link data https://www.gazzetta.it/motori/la-mia-auto/02-11-2023/biocarburanti-una-guidacompleta-su-produzione-vantaggi-svantaggi-e-costi.shtml*

The difference in price between biofuels and heavy fuel oil is not much, considering an economic variation of about 800%-200% in the previous cases and a surcharge that fluctuates from 70% to 180% for biofuels. (Fig. 3)

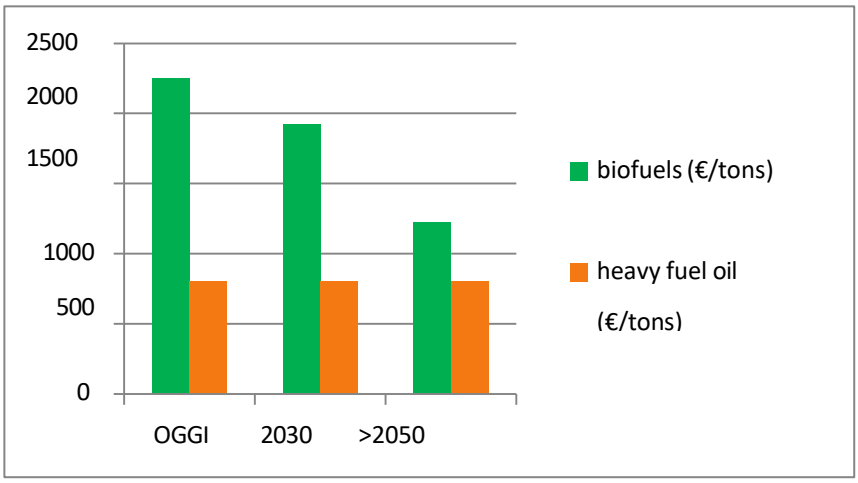


Figure 3. *Production costs of biofuels and heavy fuel oil. Source: author's elaboration based on link data https://www.pricepedia.it/it/magazine/article/2021/01/27/prezzo-del-biodieselunanalisi-econometrica; https://www.themeditelegraph.com/it/markets/2022/08/23/news/rispetto_a_luglio_il_carburante_marittimo_costa_quasi_la_meta10251348/#:~:text=Il%20prezzo%20medio%20del%20carburante,50%20doll ari%20 del%2014%20maggio*

LNG propulsion is not among the best solutions. In fact, economic and environmental advantages are inversely related. It involves high initial investments and production cost is about 50% higher than traditional fuels. Recent studies have shown an increase in emissions 2 to 5 times more polluted than conventional propulsion methods. (Fig. 4)

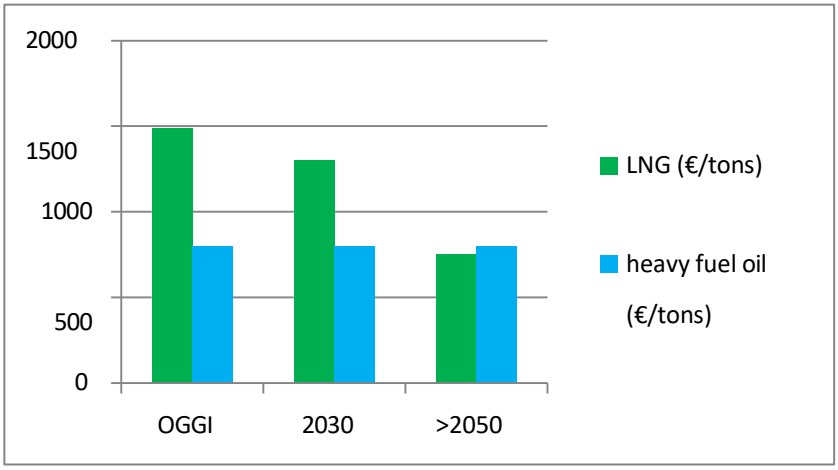


Figure 4. *Production costs of LNG and heavy fuel oil. Source: author's elaboration based on link data https://sisen.mase.gov.it/dgsaie/prezzi-settimanalicarburanti*

Ammonia might be a good compromise both in terms of economic and environmental sustainability. Its value is similar to heavy fuel oils (980 €/tons compared to 800€/tons) and a price reduction of 75% is expected in the next twenty years. (Fig. 5)

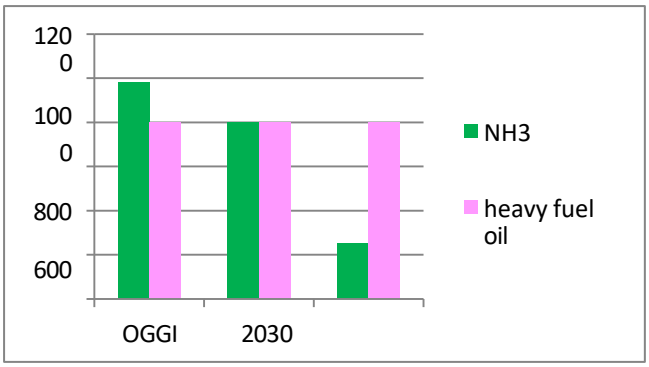


Figure 5. *Production costs of NH3 and heavy fuel oil. Source: author's elaboration based on link data https://www.rinnovabili.it/energia/idrogeno/ammoniacaverde-progetto-transfrontaliero-italiaspagna/#:~:text=Secondo%20un%20recente%20studio%20l,sopra%20i%20900%20 %*

Nowadays green hydrogen value is approximately 4000-5500 €/tons against the 2000 €/tons for hydrogen from oil and natural gas but this gap is set to fall. The emission of only water vapor into the atmosphere is the true strong point of renewable H2. (Fig. 6)

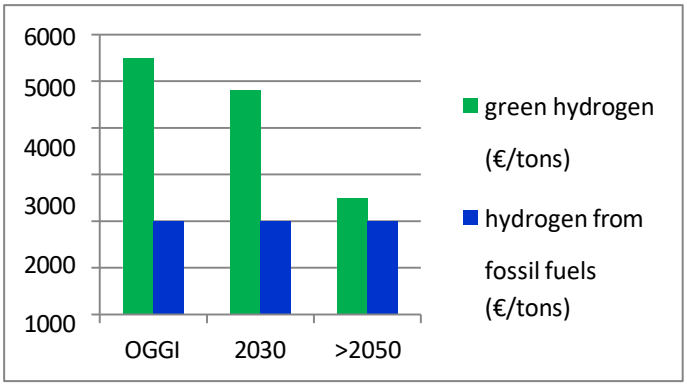


Figure 6. *Production costs of green hydrogen and hydrogen from oil and natural gas. Source: author's elaboration based on link data https://www.corriere.it/tecnologia/24_febbraio_23/l-idrogeno-verde-puo-esserecompetitivo-come-costi-lo-svela-una-ricerca-italiana-706df5e5-9c7f-4c13-8311- df908c52axlk.shtml*

Very high costs of sustainable propulsion depend on recent involvement of shipping companies in ecological transition projects. Converting existing ships to take them eco-friendly and building new ones require a huge initial investment to be amortized over the years. Management and storage of "new" fuels are aspects not to be underestimated.

The same applies to infrastructures. Several works are necessary, such as improvement of piers and docks, increased capacity of harbour ports, implementation of connections from and to the port, cold ironing and modernization measures.

Intermodal transports reduce pollution levels of 75% compared to unimodality because you can choose the most convenient way to suit your needs.

4. DISCUSSION/CONCLUSION

This paper wants to promote actions aimed at sustainable development to ensure progress without affecting life of future generations.

Overcrowding of the planet and resources over-exploitation are responsible for greenhouse effect, acidification of soil and water, changes in biodiversity, coral bleaching, eutrophication of aquatic systems, bioaccumulation and biomagnification, soil degradation, climate changes, noise pollution, trash vortex, beaching (end of life ships).

To reverse course it's necessary putting in place decarbonization actions to make the Earth a green and carbon free planet. Circular economy is the foundation of the sustainability concept. We need to focus on minimizing waste and using it to realize new products, preferring renewable sources to stop the destruction of the planet. It's impossible to make our world how it was before the climate change but we can avoid its further degradation and preserve current balances. So, decarbonization of marine traffics is the first step to take for a gradual improvement. In the passage "The Prophecy of a Cosmic Apocalypse" included in the novel "Zeno's Conscience" written by Italo Svevo, the author states to witness a rebirth it's necessary that a total destruction occurs. I wonder if our planet will face a total explosion, exactly as the Big Bang, to have a new sustainable "Earth" free of all diseases. Healing our world means protecting it from wrong behaviours of humans beings because there cannot be progress without safeguarding ecosystems.

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MAPPING THE CIRCULAR VALUE CHAIN OF WEEE-DERIVED PRINTED CIRCUIT BOARDS: CURRENT STATE AND FUTURE PERSPECTIVES

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ABSTRACT

In recent years, the growing diffusion of digital technologies and the transition to sustainable development models have made the management of Waste Electrical and Electronic Equipment (WEEE) a central issue. At the same time, the increasing demand for critical raw materials has highlighted the need to identify alternative sources to primary extraction, strengthening the role of recovery and recycling processes. In this context, electronic circuit boards (PCBs) represent a particularly significant fraction of WEEE due to their high content of strategic materials and precious metals. This paper analyzes the value chain of PCBs derived from WEEE, focusing on mapping the network of stakeholders involved. It frames this chain within the main theoretical models of circular supply chains in order to analyze its organizational dynamics and assess its potential evolutionary trajectories. The research adopts an approach that combines a review of the scientific literature, database analysis, and empirical investigation.

Keywords: Circular economy; WEEE; Printed circuit boards; Critical raw materials; Circular supply chains.

1. INTRODUCTION

The management of Waste Electrical and Electronic Equipment (WEEE) is both an environmental and industrial priority [1, 2], reinforced by the Critical Raw Materials Act [3], which aims to ensure greater security and autonomy in the supply of strategic raw materials. Among the various WEEE fractions, printed circuit boards (PCBs) play a strategic role due to their high content of precious metals and critical raw materials, such as copper, gold, silver, palladium, and rare earths. Their composition makes them a particularly interesting stream for urban mining strategies and the development of innovative processes aimed at recovering high-value components and materials [4]. The actors that carry out electronic circuit board recovery activities through multiple, non-destructive treatment options therefore play a central role in the WEEE treatment chain, contributing to increasing the recovery of critical raw materials and the value generated throughout the supply chain. In order to understand the current structure of the network of actors operating in the sector and how it can evolve by introducing innovative actors responsible for component recovery and recovery, this study aims to analyze the

electronic circuit board recovery chain derived from WEEE, with particular attention to mapping the network of actors involved. In the first part, the article explores the main theoretical models of circular supply chains proposed in the literature to analyze their organizational dynamics. In the second part, it presents the main findings from the analysis of the current supply chain configuration. Finally, the closed-loop models proposed in the literature are compared with the current supply chain configuration, highlighting possible future developments resulting from the introduction of innovative actors.

2. METHODS

The study adopts an approach that combines: i) a review of the scientific literature, aimed at comparing it with the main theoretical models of circular supply chains and defining a conceptual framework; ii) the analysis of secondary data and gray literature; and iii) an empirical investigation of the selected case study, an innovative start-up operating in the value chain of PCBs derived from WEEE through an automated recognition and disassembly/sorting process. This role places the company between the WEEE treatment activities and the subsequent phases of reuse, regeneration, and resource recovery, making it an innovative actor potentially capable of reshaping the traditional dynamics of the supply chain. The literature review was conducted by consulting the Scopus [5] and Google Scholar databases using keywords related to the topics of the circular economy and the management of end-of-life products, including circular economy, closed-loop supply chain, sustainability, reverse logistics, value recovery, and literature review. To reconstruct the spatial configuration of the WEEE- and PCB-related supply chain, the analysis distinguished between an upstream network and a downstream network. For the upstream network, data provided by the Italian WEEE Coordination Centre (CdC RAEE) were used as the reference dataset. The available data were organized and processed in an Excel database, resulting in the identification of 1,609 registered companies involved in WEEE treatment, which were then georeferenced and represented in a Geographic Information System (GIS). Unlike the upstream WEEE network, for which data from the Italian WEEE Coordination Centre (CdC RAEE) were available, the reconstruction of the downstream PCB network could not rely on a single institutional source. Therefore, an exploratory web-based search was conducted, mainly through targeted keyword searches and analysis of company websites, to identify operators potentially involved in activities following PCB separation and treatment. The search used keywords related to PCB management and valorization, including, for example, “electronic board repair and refurbishment”, “electronic component sales”, and “recovery of precious metals and critical raw materials from electronic waste”. The identified companies were screened based on the activities documented through publicly available information. Information on the type of activity, geographical location and, where available, the materials treated or recovered was collected and organized in an Excel database. This procedure

resulted in the identification of approximately 50 companies operating in different segments of the downstream network, which were then georeferenced and represented in the GIS analysis. The GIS analysis was used to standardize the geographical location of the selected companies, represent them as point features, and examine their territorial distribution within the mapped supply chain. The GIS therefore served primarily as a tool for georeferencing, spatial organization, and visualization of the selected nodes; spatial proximity was not used to infer commercial relationships or material flows that were not explicitly documented. The three central nodes highlighted in Fig. 1 were identified within the case-study analysis. The innovative start-up was considered the focal organization, while the two additional nodes, corresponding to potential competitors, were identified based on information and indications provided directly by the start-up itself. These companies were included in the GIS representation to highlight relevant actors for comparison within the downstream PCB network. The three nodes were therefore highlighted in red in the GIS map. The analysis was then further deepened through semi-structured interviews with six organizations operating in different segments of the supply chain. The collected evidence allowed us to validate and integrate the supply chain reconstruction, further exploring the relationships between the stakeholders and the dynamics of electronic circuit board valorization. Finally, the evidence collected from the secondary data and semi-structured interviews was used to develop a flowchart representing the supply chain under investigation.

3. FINDINGS

The literature review identified several "closed-loop" supply chain models, characterized by different organizational configurations that vary in terms of stakeholder integration, coordination mechanisms, and value recovery strategies. Based on the analysis of the reviewed literature, a comparison grid was developed based on a series of key parameters, aimed at highlighting similarities and differences between the various closed-loop approaches and supporting subsequent application to the empirical context analyzed (Table 1). This structure highlights how the degree of coordination between stakeholders, the degree of loop closure, and systemic breadth represent the main distinguishing features among the analyzed models.

	PRODUCTS	PROCESSES	ACTORS	RELATIONSHIPS	OBJECTIVE
REVERSE LOGISTICS (e.g., [6])	End-of-life, returned, and defective products.	Collection, transportation, inspection, sorting, repair, regeneration, remanufacturing, recycling, final disposal.	Consumers, distributors, producers, logistics operators.	Inverse relationships are mostly unidirectional.	Value recovery and regulatory compliance.
GREEN LOGISTICS (e.g., [7])	Eco-friendly materials and packaging.	Transport optimization, waste management, sustainable packaging, energy efficiency.	Suppliers, manufacturers, logistics operators, consumers.	Collaborative relationships oriented towards sustainability.	Reducing environmental impacts.
CLOSED-LOOP SUPPLY CHAINS (e.g., [8])	Recoverable, reusable, regenerable products.	Production, multi-channel sales, collection, recovery, redistribution.	Suppliers, manufacturers, online/offline retailers, consumers, recovery centers.	Integrated two-way relationships along the supply chain.	Maximizing value across the lifecycle.
DUAL-CHANNEL CLOSED-LOOP SUPPLY CHAINS (e.g., [9])	New products and remanufactured products.	Production, dual-channel sales of new products, collection, recovery, and dual-channel redistribution of remanufactured products.	Suppliers, manufacturers, online and offline distributors, consumers, collection centers, sorting centers, recovery and recycling centers.	Complex competitive/collaborative relationships between channels.	Multi-channel economic optimization.
CIRCULAR SUPPLY CHAINS (e.g., [10])	Circular products, components and materials (secondary/regenerated).	Reuse, repair, regeneration, reconditioning, cross-sector recycling.	Multi-supply chain actors, cross-sector stakeholders.	Systemic and multi-actor relationships.	Resource regeneration and long-term sustainability.
RECYCLING NETWORK (e.g., [11])	Post-consumer waste and by-products.	Separate waste collection, selection, treatment, recycling.	Businesses, local authorities, consortia, treatment plants.	Territorial relations based on cooperation and institutional agreements.	Efficient material recovery.

Table 1. *Comparison of closed-loop approaches based on key parameters.*
Source: Author's elaboration.

To reconstruct the WEEE supply chain, the stakeholders involved in both the collection and treatment of WEEE up to the separation of the PCB (so-called upstream network) and in the subsequent management and valorization activities of the PCB, up to its subsequent re-placement in a secondary market (so-called downstream network) were mapped. A total of 1,609 companies were identified in the upstream network, including 50 registered/accredited facilities, and 50 companies in the downstream network (Fig. 1).

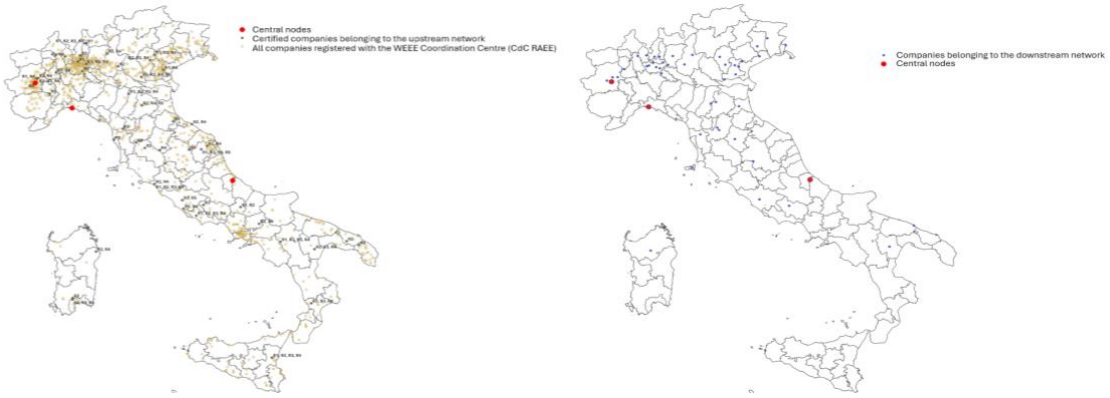


Figure1. *GIS-based representation of the WEEE printed circuit board (PCB) value chain, showing the upstream network (left) and the downstream network (right). The central nodes (red) represent the innovative start-up and two companies identified as potential competitors. In the upstream network, black dots indicate the facilities certified/accredited by the Italian WEEE Coordination Centre (CdC RAEE), whereas yellow dots represent all companies registered in the CdC RAEE database for WEEE treatment. In the downstream network, blue dots identify the remaining stakeholders involved in downstream activities. Source: Author's elaboration.*

The flowchart (Fig. 2) illustrates the main activities performed along the WEEE value chain, organized into five macro-areas. The three central sections, highlighted in different colors, constitute the focus of the analysis and describe the main phases of the supply chain covered by this work: WEEE logistics and treatment; and PCBs management. The final section also highlights, through an orange box, the role of the PCB selection and disassembly process, which acts as an intermediate node in the supply chain and enables the creation of new value chains.

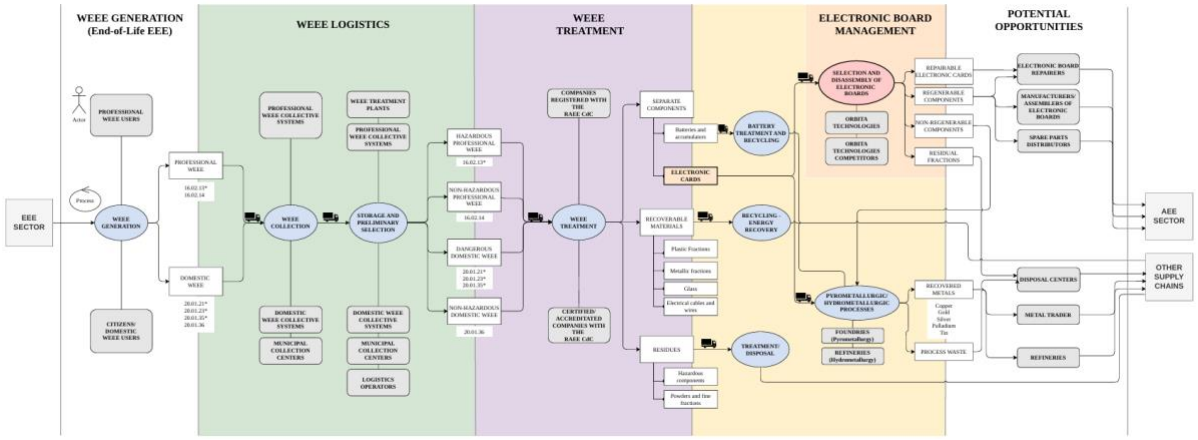


Figure 2. *Flowchart of the WEEE value chain with a focus on printed circuit board (PCB) management and value recovery flows.*
Source: *Author's elaboration.*

Finally, Table 2 compares the current supply chain configuration with an evolving scenario characterized by the presence of innovative players dedicated to the advanced valorization of PCBs. The comparison highlights a potential shift from a predominantly recycling-oriented approach to an integrated valorization of resources.

ANALYSIS DIMENSION	CURRENT CONFIGURATION	EVOLUTIONARY CONFIGURATION
Main objective	Material recovery and compliance with regulatory targets.	Maximizing the value of PCBs and components.
Treatment methods	Mainly destructive treatment (fragmentation and recycling)	Selective disassembly and targeted recovery of components and materials.
Enhancement options	Mostly recycling.	Multi-option logic: reuse, repair, reconditioning, recycling.
Valorization of PCBs	Limited, material-oriented.	High, oriented towards the recovery of components and functions.
Level of integration of the supply chain	Low, fragmented structure.	Greater integration and coordination between actors.
Role of the actors	Specialized but poorly coordinated operators.	Presence of key players with an integration and enhancement function.
Destination of flows	Diversification by material fractions (also towards other sectors).	Greater closure of the supply chain for WEEE (especially for cards).
Supply chain structure	Configuration similar to Recycling Network.	Evolution towards more integrated configurations such as CLSC and CSC.
Recovered value	Mainly material.	Higher economic and technological value.
Strategic implications	Operational and regulatory logic.	Strategic logic oriented towards long-term sustainability and the reduction of the use of virgin CRMs.

Table 2. *Evolution of the electronic circuit board supply chain between current configuration and prospective scenario. Source: Author's elaboration.*

4. DISCUSSION/CONCLUSION

The analysis highlights a supply chain characterized by a complex and partially fragmented structure, in which PCBs represent a strategic hub for the recovery of high-value-added components and, potentially, for the recovery of CRMs. The current system can be traced primarily to a "recycling network," with signs of evolution toward more circular and integrated models. Flows that are not completely closed and a prevalence of valorization processes not always oriented toward direct reintroduction into the Electrical and Electronic Equipment (EEE) sector emerge. The study revealed that an important role can be played by innovative players who perform identification and sorting activities through selective disassembly of PCBs. These players act as an intermediate hub between WEEE treatment and advanced recovery of all board components, contributing to potential supply chain developments toward more integrated models oriented toward reuse, repair, and regeneration, such as "closed-loop supply chain" and "circular supply chain." The research has some limitations related to data availability, the qualitative nature of the investigation, and its focus on the Italian context. The implications highlight the need to strengthen coordination among stakeholders, develop advanced technologies for selective recovery, and promote production models geared toward closing cycles and valorizing high-value-added components.

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