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Exploring complex industrial systems to support circular economy projects focused on the reuse of specific industrial waste categories

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Abstract

The transition from linear production models to circular economy paradigms represents one of the main challenges for contemporary industrial systems. This doctoral thesis explores complex industrial systems with the aim of supporting circular economy projects focused on the reuse and valorisation of specific categories of industrial waste as secondary resources. The research adopts a multidisciplinary approach that integrates industrial engineering, materials science and environmental assessment to identify effective strategies for the reintegration of industrial by-products into existing production processes.

The study is structured around three main industrial sectors, ceramics, polycarbonate-based products and textiles, selected for their high material intensity, significant waste generation and strong potential for circular innovation. During the first phase of the research, an extensive literature review was conducted to analyse the state of the art related to circular economy frameworks, regulatory definitions of industrial by-products and existing reuse strategies within industrial manufacturing systems. This phase enabled the development of a structured methodological framework for the assessment of waste-derived materials in complex production environments.

Subsequently, experimental laboratory activities were carried out to characterise selected industrial waste streams through thermal, chemical, mechanical and flow analyses. Specific attention was given to polycarbonate sheets waste, evaluating the suitability for reuse through material blending, process adaptation and product redesign. The results demonstrate that, with appropriate selection and characterisation, polycarbonate sheets waste can be effectively reintroduced into the production chains while maintaining functional, mechanical and aesthetic performance requirements.

In the final phase of the research, Life Cycle Assessment was applied to compare polycarbonate products manufactured from virgin raw materials with those obtained from reused industrial by-products, with the aim of quantifying environmental benefits and identifying critical trade-offs. The findings highlight significant reductions in environmental impacts, particularly in terms of resource depletion and greenhouse gas emissions, supporting the environmental viability of circular production strategies.

Overall, this thesis provides an integrated framework for the analysis and implementation of circular economy solutions in complex industrial systems, offering practical guidelines for industry stakeholders and contributing to the advancement of sustainable and resource-efficient manufacturing models.

Riassunto

La transizione dai modelli di produzione lineari ai paradigmi dell'economia circolare rappresenta una delle principali sfide per i sistemi industriali contemporanei. La presente tesi di dottorato esplora sistemi industriali complessi con l'obiettivo di supportare progetti di economia circolare focalizzati sul riuso e sulla valorizzazione di specifiche categorie di rifiuti industriali come risorse secondarie. La ricerca adotta un approccio multidisciplinare che integra ingegneria industriale, scienza dei materiali e valutazione ambientale al fine di individuare strategie efficaci per la reintegrazione dei sottoprodotti industriali nei processi produttivi esistenti.

Lo studio è strutturato attorno a tre principali settori industriali, ceramico, prodotti a base di polycarbonato e tessile, selezionati per l'elevata intensità di utilizzo di materiali, la significativa generazione di rifiuti e il forte potenziale di innovazione circolare. Durante la prima fase della ricerca è stata condotta un'ampia revisione della letteratura per analizzare lo stato dell'arte relativo ai modelli di economia circolare, alle definizioni normative dei sottoprodotti industriali e alle strategie di riutilizzo esistenti nei sistemi manifatturieri. Questa fase ha consentito lo sviluppo di un quadro metodologico strutturato per la valutazione dei materiali derivanti da rifiuti in contesti produttivi complessi.

Successivamente, sono state svolte attività sperimentali di laboratorio per caratterizzare flussi selezionati di rifiuti industriali mediante analisi termiche, chimiche, meccaniche e reologiche. Particolare attenzione è stata dedicata agli scarti di lastre in polycarbonato, valutandone l'idoneità al riutilizzo attraverso strategie di miscelazione dei materiali, adattamento dei processi e riprogettazione del prodotto. I risultati dimostrano che, attraverso un'adeguata selezione e caratterizzazione, gli scarti di lastre in polycarbonato possono essere efficacemente reintrodotti nelle catene produttive mantenendo i requisiti funzionali, meccanici ed estetici.

Nella fase finale della ricerca è stata applicata la metodologia di Life Cycle Assessment per confrontare prodotti in polycarbonato realizzati con materie prime vergini e prodotti ottenuti da sottoprodotti industriali riutilizzati, con l'obiettivo di quantificare i benefici ambientali e identificare eventuali trade-off critici. I risultati evidenziano significative riduzioni degli impatti ambientali, in particolare in termini di consumo di risorse ed emissioni di gas a effetto serra, confermando la sostenibilità delle strategie produttive circolari.

Nel complesso, la tesi fornisce un quadro integrato per l'analisi e l'implementazione di soluzioni di economia circolare nei sistemi industriali complessi, offrendo linee guida operative per gli stakeholder industriali e contribuendo all'avanzamento di modelli produttivi sostenibili ed efficienti nell'uso delle risorse.

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1. Introduction

The increasing scarcity of resources, combined with stringent environmental regulations and economic pressures on manufacturing systems, is driving industrial sectors toward more sustainable and circular production models. Within this context, the circular economy paradigm represents a fundamental transition framework aimed at decoupling value creation from resource consumption by promoting waste reduction, reuse, and valorization of industrial by-products by extending material lifecycles. Circular economy strategies such as reuse, recycling, and industrial symbiosis have been widely recognized as essential enablers for decoupling economic activities from primary resource extraction [1]. However, their effective implementation requires a deep understanding of complex production systems, material flows, technological constraints, and organizational dynamics. Several studies have explored recycling technologies and waste valorisation approaches; however, the research highlights the lack of comprehensive, system-oriented research capable of analysing industrial processes, evaluating material suitability, and supporting decision-making for reuse-oriented circular economy projects across different sectors [2, 3]. This research addresses this gap by exploring complex industrial systems to support the development and implementation of circular economy initiatives focused on the reuse of specific industrial by-product categories. The work has been conducted by combining academic investigation with direct industrial application. Over the three years of research, the activities have progressively evolved from the analysis of circular economy principles and the state of the art knowledge, to experimental material characterisation, and finally to the environmental assessment of reuse-based production scenarios.

The work adopts a systemic engineering perspective to analyse how industrial by-products can be effectively reintroduced into production cycles as secondary raw materials, maintaining functional performance while reducing environmental burden. Three main industrial sectors were considered due to their strategic relevance and material intensity: the ceramic industry, polycarbonate-based plastic manufacturing, and the textile sector. These sectors are characterized by high production volumes, significant waste generation, and strong potential for circular redesign interventions [4, 5, 6].

The research was developed progressively over the three years focusing on understanding the industrial context and defining the state of the art concerning the reuse of the by-products. Laboratory activities were conducted to characterize different waste streams, identifying properties, compatibility constraints, and potential reuse pathways. Attention was placed on material characterization, process adaptation needs, and feasibility of integration into industrial systems. Finally, the work further extends to Life Cycle Assessment (LCA) to quantitatively evaluate the environmental performance

of products manufactured using recycled or reused industrial materials, compared to those based on virgin raw materials. This provided scientifically measurable evidence of environmental benefits and potential trade-offs.

In parallel, the research examines enabling conditions, barriers, and opportunities for circular transition within industrial contexts, integrating methodological reflection with empirical evidence from real projects, scientific dissemination activities, and participation in international research initiatives.

The thesis contributes to the advancement of knowledge on circular economy-oriented industrial systems by:

- providing a structured framework for analysing complex industrial systems from a circular perspective;
- demonstrating the technical potential of selected industrial waste for reintegration into manufacturing processes;
- quantifying environmental advantages through LCA-based evaluation;
- offering methodological and practical insights to support companies in implementing circular economy strategies.

Overall, this research shows that industrial systems can evolve toward higher levels of circularity when supported by rigorous engineering analysis, material characterization, environmental assessment, and collaboration between academia and industry. The outcomes not only enhance theoretical understanding of circular industrial systems, but also deliver operational tools and evidence to facilitate real implementation of reuse-based circular economy projects in strategic manufacturing sectors.

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2. Circular Economy Foundations, Sustainability Frameworks and Regulatory Context

2.1 From Linear to Circular Industrial Systems

Over the last decades, global industrial systems have faced mounting environmental, economic, and regulatory pressures arising from material scarcity, climate change, and waste accumulation. Traditional linear production models, based on the “take–make–dispose” paradigm, have progressively demonstrated structural inefficiencies, particularly in resource intensive and manufacturing driven sectors such as plastics, ceramics, and textiles. These inefficiencies manifest as high primary resource dependence, significant energy consumption, and a persistent generation of heterogeneous waste streams that are inadequately valorized. While historically effective in supporting economic growth, this production model is increasingly incompatible with environmental constraints, resource scarcity, and climate change pressures. The rising consumption of raw materials, particularly in energy intensive and material intensive sectors such as plastics, ceramics, and textiles, has highlighted the need to decouple economic progress from the depletion of natural resources.

In this scenario, circular economy has emerged as a transformative industrial strategy aimed at decoupling economic growth from resource extraction, extending material life cycles, and promoting systemic resource optimization. Circular economy is not merely an environmental paradigm, it constitutes a complex industrial reorganization framework, requiring integration of design methodologies, material science advances, supply chain reconfiguration, regulatory evolution, and decision support tools such as LCA.

This research contributes to the transition by analysing complex industrial systems and focusing on the reuse and valorization of specific categories of industrial by-products and waste materials, such as polycarbonate scrap, textile residues, and ceramic processing by-products. Through experimental, methodological, and analytical activities carried out both in industrial and academic contexts, the work aims to develop structured approaches to enable the industrial reuse of materials previously considered waste, supporting their integration into new value chains and innovative sustainable products.

2.2 Sustainability and the Transition to Circular Industrial Models

Circular economy is structurally connected to sustainable development that establishes the need to meet current needs without compromising future generations ability to meet their own. However, while sustainability provides a strategic vision, circular economy provides operational pathways, explicitly addressing material loops, production efficiency, and industrial symbiosis mechanisms.

Modern industrial sustainability is therefore increasingly interpreted through three integrated dimensions:

- environmental sustainability, reducing ecological pressures and resource extraction;
- economic sustainability, enabling competitive advantage, manufacturing resilience, and new business models;
- social sustainability, fostering safe, inclusive, and innovation-driven industrial environments.

Within this framework, circular economy acts as a bridge between sustainability theory and industrial practice, operationalizing resource efficiency through:

- prevention and reduction of waste generation;
- reuse and remanufacturing strategies;
- material recycling and upcycling;
- design for disassembly and durability;
- systems integration and cross-sector material exchanges.

The industrial sectors examined in this research, polycarbonate processing, ceramic production, and textiles, represent relevant trials due to their material intensity, high waste outputs, and increasing regulatory and market expectations regarding sustainability.

2.3 The 2030 UN Agenda and International Strategic Drivers

The transition toward circular industrial systems is strongly aligned with global sustainability governance frameworks, particularly the United Nations 2030 Agenda for Sustainable Development. Several Sustainable Development Goals (SDGs) explicitly reinforce the relevance of circular economy strategies, including:

- SDG 9 – Industry, Innovation and Infrastructure; promoting sustainable industrialisation and fostering innovation, including advanced materials and process optimisation;
- SDG 11 – Sustainable Cities and Communities; encouraging resource efficiency in urban and industrial systems;
- SDG 12 – Responsible Consumption and Production; directly targeting waste reduction, material loop closure, and sustainable product lifecycles;
- SDG 13 – Climate Action; highlighting emission mitigation opportunities through material reuse and reduction of virgin resource extraction.

Circular economy contributes to operationalising these SDGs by embedding sustainability objectives within industrial engineering practices. The projects, conferences, and seminars undertaken during the research demonstrate continuous alignment with these goals, emphasising waste valorisation, extended producer responsibility, sustainable material design, and measurement of circularity.

These objectives frame circular economy as a structural requirement for future production systems. The studies and industrial experiments conducted align with these goals, supporting the progressive integration of reuse-oriented industrial planning and evidence-based evaluation through environmental assessment techniques.

2.4 Regulatory and Policy Framework

Circular economy implementation in industry is based on several consolidated principles:

- loop closure, ensuring materials remain within industrial cycles for as long as possible;
- resource optimization, maximizing efficiency across manufacturing systems;
- design for circularity, through material selection, modular product architecture, durability enhancement, and reparability;
- industrial symbiosis, enabling cross-sector exchanges of by-products and waste;
- systemic perspective, acknowledging interdependencies between technical processes, logistics, business models, and governance frameworks.

The transition toward circular economy is strongly guided by European and national regulatory frameworks. The European Green Deal, the EU Circular Economy Action Plan, and waste legislation packages establish obligations and opportunities for industries to reduce waste, enhance material recovery, and demonstrate environmental responsibility. These policies redefine waste not only as a disposal problem but as a potential secondary raw material, fostering transitions toward by-product classification, end-of-waste criteria, and extended producer responsibility mechanisms. Specific relevance is given to:

- definitions of by-products and end-of-waste criteria, essential to legally distinguish materials suitable for reuse from waste streams;
- Extended Producer Responsibility (EPR) schemes, which require producers to manage the environmental impact of their products throughout their life cycle;
- regulatory incentives and obligations supporting recycling rates, material traceability, and environmental performance assessment.

However, practical application requires sector specific engineering interpretation. For instance:

- in polycarbonate systems; reuse strategies must consider polymer integrity, mechanical properties retention, thermo-mechanical degradation, and compatibility with new product functions;
- in ceramic production, waste inclusion affects mixture composition, sintering behaviour, structural resistance, and aesthetic characteristics;

- in textile industry, heterogeneity of fibers, presence of contaminants, and logistical fragmentation represent critical challenges to systemic recovery.

This research addresses these complexities through both experimental material characterization and systemic industrial analysis, integrating laboratory activities, industrial collaboration, and methodological frameworks.

Moreover, the integration of LCA methodologies, as explored in the comparative analysis between virgin and recycled polycarbonate, supports compliance with regulatory demands for measurable environmental performance and contributes to scientifically grounded decision-making.

2.5 Towards a Systemic Engineering Approach

Circular economy implementation in industry cannot be approached through a purely material or technological perspective. Industrial systems are intrinsically complex socio-technical ecosystems, where technological constraints, economic feasibility, organizational dynamics, logistics, stakeholder behaviour, and policy influence coexist and interact. It requires a systemic engineering perspective considering:

- systemic mapping of industrial processes and flows;
- rigorous experimental characterisation of materials;
- integration of technical feasibility with organizational and economic sustainability;
- robust environmental assessment tools, particularly LCA.

This research explores how complex industrial systems can integrate circular economy projects focused on the reuse of selected industrial waste categories. The aim is to provide structured contributions to the practical and methodological advancement of circular economy projects emphasizing the collaboration between companies, research institutions, and regulatory stakeholders.

3. Industrial By-Products and Production Processes in Complex Industrial Systems

3.1 From waste to industrial resource

In conventional linear production systems, a wide spectrum of residual materials is generated as a result of manufacturing, transformation, finishing, and logistic processes. Traditionally classified as waste, these materials are increasingly reinterpreted as industrial by-products, representing valuable secondary raw materials capable of re-entering productive cycles through reuse, recycling, and upcycling strategies. Within the framework of the circular economy, industrial by-products do not merely constitute a disposal problem, but instead an opportunity to reduce primary resource consumption, mitigate environmental burdens, and foster innovation across supply chains.

The concept of industrial by-product is strictly linked to regulatory definitions, technical suitability, and environmental compatibility. According to European and national frameworks, a material can be classified as a by-product only when *it originates from a production process where its generation is not the primary aim, it can be used directly without extensive further processing, demonstrates technical suitability for a subsequent application, and complies with environmental and health safety requirements.*

From an engineering perspective, by-products contribute to system efficiency by:

- reducing virgin material dependency;
- enabling material circularity loops;
- lowering life cycle environmental impacts;
- supporting sustainable industrial symbiosis strategies.

The research work developed across three industrial sectors characterized by high material intensity and significant environmental burdens: ceramic manufacturing, polycarbonate-based plastic production and textile industry. These sectors were selected due to their high waste generation, technological feasibility of reuse, and alignment with EU waste hierarchy principles, EPR policies, SDGs, and current research trends.

3.2 Industrial By-Products in complex production systems

Industrial by-products can be defined as materials generated unintentionally during production processes which, although not primary products, retain suitable physical, mechanical, or chemical characteristics to be valorized in alternative applications.

According to European and national legislation, a material can be classified as a *by-product* rather than *waste* when it:

- originates from a production process primarily aimed at another product;
- can be directly used without further processing beyond normal industrial practice;
- satisfies technical quality and environmental safety requirements;
- has an identified end-use application.

The classification of a material as *by-product* rather than waste represents a crucial legal and operational threshold enabling circular transitions in industrial systems. Misclassification can lead to inefficiencies, regulatory burdens, and unnecessary disposal costs, while correct classification promotes industrial symbiosis, resource optimization, and economic competitiveness.

Industrial by-products exhibit heterogeneous characteristics depending on the originating process, production conditions, and material composition. Their valorisation potential is influenced by:

- physical properties (granulometry, density, morphology);
- mechanical behaviour (resistance, stiffness);
- chemical composition (presence of additives, stabilizers, fillers);
- thermal behaviour (stability, degradation thresholds);
- environmental compatibility (toxicity, leachability, contamination risks).

A structured engineering classification of industrial by-products includes: (i) solid by-products, such as powders, granulates, plates, scraps, and production residues; (ii) polymeric by-products, originating from thermoforming, injection moulding, cutting or disassembly of plastic components; (iii) fibrous and textile by-products, resulting from manufacturing offcuts, unsold stock, or end-of-life material recovery; (iv) composite and multilayer by-products, which pose additional technical challenges due to heterogeneous composition.

Their recognition as resources rather than waste depends on characterization activities such as mechanical testing, morphological analysis, chemical assessment, and functional performance verification. During the research, the suitability of selected by-products to be reintroduced into industrial processes has been analysed assessing both technical feasibility and environmental convenience, supported by LCA.

3.3 Ceramic Manufacturing Processes and By-Product Integration

Ceramic manufacturing is characterized by high raw material and water demand, energy-intensive processes, and significant waste generation, traditionally associated with significant environmental burdens. Multiple industrial by-products can be inserted into ceramic mixtures to partially replace virgin materials without compromising product functionality due to the intrinsic flexibility of ceramic mixtures.

Research activities focused on analysing typical ceramic raw material compositions, process phases (mixing, milling, forming, drying, firing), potential insertion stages for secondary materials.

Industrial by-products considered within the ceramic sector include powders and residues originating from processing phases or external industrial streams, provided they exhibit mineralogical compatibility with ceramic bodies.

The studies and experimental activities indicate that the integration of selected by-products in ceramic mixtures can:

- contribute to structural stability of ceramic mixtures;
- can improve or maintain mechanical performance of ceramic mixtures;
- reduce dependence on virgin raw materials;
- provide tangible environmental benefits by lowering waste disposal needs;
- align with circular economy objectives and manufacturing decarbonisation strategies.

These findings support the thesis conceptual framework: industrial processes can be re-engineered to integrate secondary materials within robust technical and regulatory boundaries supporting the transition toward eco-designed ceramic products capable of embodying circular economy principles while maintaining industrial competitiveness.

3.4 Textile Industry Processes and Waste Valorization

The textile sector represents one of the most critical industries in terms of waste generation, environmental impact, and difficulty of recycling due to high variability of fibers, blends, finishing chemicals, and contamination. Large quantities of waste and by-products are generated throughout production chains due to cutting processes, defective materials, overproduction, and end-of-life products.

Research activities contributed to identifying priority waste categories, potential recovery technologies, and process strategies capable of enhancing material return into production cycles.

Characterisation activities allow the evaluation of different materials suitability to improve recoverability. Pre-sorting and material characterization are fundamental to extend the by-products end-of-life and promoting innovative business models consistent with circular economy strategies.

3.5 Polycarbonate By-Products and Their Reuse Potential

Polycarbonate is a high-performance engineering thermoplastic widely used in automotive components, protective equipment, building applications, and consumer products due to its strength, transparency, impact resistance, and dimensional stability. However, its production is energy intensive and associated with environmental implications related to fossil resource dependency. Also,

the polycarbonate end-of-life typically follows a predominantly linear pathway, resulting in disposal and environmental burden.

Industrial processes generate significant amounts of polycarbonate by-products in the form of plates and sheets offcuts, scraps from machining and forming operations, dismantled industrial components. During the research, several types of polycarbonate plates and by-products were collected and systematically characterised to evaluate their reuse potential. Activities involved identification of physical properties, mechanical performance, degradation level, and structural suitability for new applications.

The research activity explored strategies to:

- characterize polycarbonate sheets originating from industrial discard streams;
- evaluate their mechanical, optical, and structural properties;
- define conditions for reuse without re-melting or severe degradation;
- apply reused polycarbonate in new eco-design applications (e.g., office furniture, innovative products);
- compare virgin and recycled polycarbonate through comparative LCA.

Laboratory testing confirmed that industrial polycarbonate by-products, when appropriately selected and processed, maintain performance levels compatible with functional reuse in multiple sectors as manufacturing of innovative and ecological polycarbonate plates, development of new industrial components, design-oriented applications such as sustainable office furniture. Moreover, LCA analyses reveal significant environmental advantages, particularly in greenhouse gas reduction, energy savings, and material footprint decrease.

This case highlights how complex technical evaluation, regulatory compliance and design innovation create viable industrial circular economy pathways contributing to resource preservation, energy savings, and reduced environmental impacts when compared with virgin material production.

3.6 Industrial By-Products within Complex Industrial Systems

The valorisation of industrial by-products must be understood within the broader perspective of complex industrial systems. These systems are characterised by multiple actors and interdependencies, cross-sectoral interactions, material and information flows, regulatory frameworks.

The reuse of industrial by-products also requires the development of decision-support tools, methodological frameworks, and analytical approaches able to assess technical feasibility, economic viability, environmental performance, and system impacts.

Within this context, this research followed a structured engineering methodology, integrating:

- state-of-the-art analysis through literature review and policy framework understanding;
- industrial process mapping to identify where waste is generated and how it can be intercepted;
- material characterization to ensure technical compatibility;
- experimental validation in laboratory conditions;
- environmental performance verification through LCA;
- alignment with circular economy strategies, SDGs, and industrial symbiosis logic.

The findings emerging from ceramic, polycarbonate, and textile investigations reinforce the concept of industrial symbiosis, where waste from one process becomes input to another. Such systemic perspective aligns with the thesis objective of exploring complex industrial systems to support circular economy projects and demonstrates practical applicability in real industrial contexts.

Industrial by-products represent strategic resources for advancing circular economy objectives within complex industrial systems. Their reuse requires scientific validation, technological innovation, regulatory alignment, and systemic planning. The results achieved across ceramic, polycarbonate and textile sectors demonstrate concrete potential for integrating by-products into productive processes while ensuring environmental, economic, and industrial benefits. This section consolidates the technological and systemic foundations required to understand how specific industrial waste categories can transition from disposal liabilities to strategic industrial resources.

4. Experimental Investigations and Sustainability Assessment of Industrial By-products Reuse

The experimental activities allow the evaluation of the technical feasibility, performance, and environmental potential of reusing selected industrial by-products within new or different production processes.

The laboratory phase represented a fundamental step to:

- validate theoretical assumptions emerging from literature and industrial analysis;
- characterize material properties critical to industrial reuse;
- assess performance differences between virgin materials and recycled alternatives;
- quantify environmental implications through comparative LCA.

The experimental work focused on the three main materials, ceramic industry by-products, polycarbonate sheets and derived components, textile waste materials. Each material category was studied through a structured methodology including sample selection, material characterization, process compatibility evaluation, and functional/environmental performance assessments.

4.1 Sustainability Perspective and Circular Economy Implications

Beyond technical validation, laboratory outcomes must be interpreted as enablers of systemic sustainability transformation within its three pillars.

Experimental evidence reinforces the idea that industrial systems can evolve toward closed-loop configurations, contributing to the mitigation of overall environmental impacts. The use of industrial by-products significantly reduces the consumption of natural resources, the energy requirements associated with extraction and processing, the production of waste destined for landfill and greenhouse gas emissions.

The use of industrial by-products can partially or fully replace raw materials and is often compatible with existing technologies, requiring only limited adaptations. The circular model appears not only environmentally desirable but also economically sustainable, as it generates potential savings in terms of procurement, disposal and material costs.

The transition to a circular industrial model helps foster a responsible industrial culture, contributing to the perception of reliability and sustainability of the industrial system. The development of innovative supply chains and new technological and managerial skills represent tools for cultural and professional growth.

4.2 Regulatory and Normative Considerations

Considering the regulatory aspects, laboratory activities respond to evolving European and national frameworks promoting waste valorization and secondary raw material integration. The experimental validation aligns with key policy pillars such as:

- the UN 2030 Agenda;
- the EU Circular Economy Action Plan, encouraging material recirculation;
- the Waste Framework Directive, including principles of reuse and the concept of “end-of-waste” criteria;
- sector-oriented regulatory evolutions addressing plastics, textiles, and construction materials.

Demonstrating technical suitability through laboratory verification represents a prerequisite for industrial adoption, certification processes, and conformity with product safety and quality regulations.

4.3 Methodological Framework

The methodology considered in this research consists of:

- identification and selection of industrial by-products;
- physical, chemical, and mechanical characterization; laboratory characterizations were performed to determine key properties such as granulometry, density, and composition, mechanical resistance, optical integrity, contamination level, and degradation patterns;
- assessment of process integration feasibility, tests were performed to verify compatibility with existing manufacturing systems and to identify necessary process redesign actions;
- prototype development for relevant cases;
- environmental performance evaluation; comparative LCA analyses were performed to evaluate environmental trade-offs associated with reuse strategies and support circular design decisions.

4.4 Evaluation of Ceramic Industry By-products

Ceramic sector investigations demonstrated the feasibility of incorporating specific industrial residues into different ceramic mixtures. Experimental insights indicated that selected by-product fractions can replace raw materials without compromising dimensional stability, mechanical strength, or aesthetic characteristics of the innovative ecological products. Laboratory testing included:

- granulometric distribution analysis to ensure compatibility with ceramic mixtures;
- chemical composition verification to avoid contaminant accumulation;
- processability assessment within traditional ceramic forming and firing conditions.

The results confirm the potential of closed-loop strategies within the ceramic sector. However, the direct reuse of several by-products is not always possible; different pre-treatments are frequently required allowing the feasibility of the reuse. These additional steps to the production process must be considered to assess the environmental benefits of the substitutions.

4.5 Evaluation of Textile By-products

The investigation on textile waste streams focused on their suitability within new material formulations and recovery strategies to enhance circularity within the textile sector. The investigation enabled the classification of textile fractions with appropriate mechanical and structural properties, supporting their reuse in secondary processes rather than downcycling or landfilling. Laboratory activities included material classification, contamination and compositional assessment, suitability evaluation for reprocessing. Moreover, collaborative actions will mitigate the negative environmental impact of the textile industry through the implementation of green technologies in the textile production process favouring the re-evaluation of clothing design, the reinforcement of the consumers' environmental consciousness, the standardization of guidelines, strategies and laws.

4.6 Evaluation of Polycarbonate By-products

Polycarbonate represented a central focus of the experimental research due to its technical relevance, industrial availability as a waste stream, and environmental impact profile. Laboratory activities on polycarbonate focused on secondary polycarbonate sheets originating from industrial processes. Tests demonstrated that adequately classified, cleaned, and processed recycled polycarbonate retains functional performance levels comparable to raw materials for several applications relevant to office furniture, structural components, and industrial product design.

Different categories of post-industrial and post-use polycarbonate sheets were characterized to define:

- mechanical performance variation with reuse;
- structural integrity after prior service life;
- optical degradation such as yellowing or surface alteration.

Mechanical tests highlighted acceptable tensile resistance and impact properties, while thermal stability remained within operational requirements for most envisaged uses. Moreover, preliminary blending experiments and surface processing suggested promising potential for producing innovative ecological polycarbonate sheets, confirming the possibility to be reintegrated as valuable secondary raw materials.

Comparative LCA were conducted to quantify environmental benefits associated with replacing virgin with recycled polycarbonate. Key findings highlighted that: (i) reuse and recycling

significantly reduce environmental burdens associated with raw material extraction and processing; (ii) performance retention of recycled polycarbonate enables substitution without major functional penalties.

These outcomes contributed to define eco-design guidelines and decision-support considerations for companies willing to integrate recycled polycarbonate into product development.

The results demonstrate that the selected industrial waste categories present concrete opportunities for reuse within industrial systems, provided that materials are properly characterized, process compatibility is verified, environmental benefits are quantified.

The experimental phase therefore forms a crucial connection between conceptual circular economy frameworks and applicable industrial implementation strategies, leading into the subsequent chapters, where industrial integration strategies, optimization approaches, and system-level implications are further elaborated.

5. Sustainable production of ceramic products: the use of by-products in traditional ceramic mixture

Note: This chapter is based on a published conference paper

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XXVIII Summer school “Francesco Turco” – Blue, Resilient and Sustainable Supply Chain

The ceramic industry is capable of reusing many of the by-products generated during the production, within its processes. The by-products of the production process adopted in the ceramic industry include raw and fired tile scraps, exhausted lime, washing line sludge, polishing sludge, and dried milling residues. Recent developments and innovations in the production technologies for ceramic industry allow to replace raw materials and natural resources used in the ceramic production processes with such by-products, in a circular economy perspective. Also, the adoption of a circular approach to produce ceramic products supports the reduction of other intensive activities, including the extraction of natural resources and the transport of materials. The literature analysis shows that several studies have been conducted to combine different by-products in the ceramic mixture preserving the technical and the mechanical performances of the ceramic products. The purpose of this research is to identify the most relevant by-products allowing the sustainable production of the ceramic products. The adoption of a sustainable ceramic mixture using specific by-products allows the reduction of greenhouse gas emissions (mainly carbon dioxide) requiring lower energy for the production process. However, several by-products require a pre-treatment phase before they can be added into the ceramic mixtures. Thermal pre-treatment requires additional energy and consequently higher economic charge to the ceramic production process. Hence, the pre-treatment phase may reduce the beneficial effects associated with the sustainable production of the ceramic products, i.e. the reduction of raw material extraction and the reduced production of industrial waste. This paper proposes the definition of a framework that summarizes the advantages and the disadvantages of the sustainable production of the ceramic products. This framework leads the definition of the most suitable by-product to insert in a specific sustainable ceramic mixture. This selection is supported by the evaluation of the technical and the mechanical performances and the aesthetical characteristics of the ceramic product, the energy performance of the production process and the requirement of a pre-treatment phase on the by-product. Future developments of this research will concern the selection of specific by-products for the laboratory production of a sustainable ceramic mixture in order to analyze their characteristics.

5.1 Introduction

The problems related to the scarcity of resources, the exploitation of non-renewable energy sources, the complexity of using renewable sources to preserve natural ecosystems, represent topical issues. The inefficient use of raw materials and energy from non-renewable sources are the basis of a production system that is no longer sustainable, which requires a shift from the traditional linear economy to the more sustainable circular economy [1, 2]. According to this perspective, waste acquires a new value as by-product in a new production process [3]. The interest in the implementation of this change is global, as reported in the Agenda 2030 program, a collection of 17 Goals and 169 targets to achieve in environmental, economic, social and institutional fields. Specifically, objective 12 consists in the sustainable and efficient management of natural resources, reducing the production of waste through prevention, recycling and reuse, promoting sustainable development and lifestyles in harmony with nature; objective 13 consists in countering climate change and reducing the environmental impact [12]. Environmental sustainability is closely related to the cautious use of natural resources. Giving new life to waste by using recycled materials characterized by high performance properties is a process based on the principles of the circular economy [4]. The approach is feasible to any production system and aims at minimizing the consumption of raw materials and the amount of waste in the production processes [10]. The scheme of reuse, recovery, re-manufacturing and recycling extends the waste life and functionality as much as possible, maximizing its value, reducing the consumption of energy, eliminating the disposal costs, as well as the definition of new opportunities for innovating and optimizing the production processes [5, 6]. The ceramic industry represents a model considering sustainable and circular economy. The reuse of the by-products generated during the production within its process includes raw and fired tile scraps, exhausted lime, washing line sludge, polishing sludge, and dried milling residues. Recent developments and innovations in the ceramic production technologies allow to replace raw materials and natural resources with such by-products in a circular economy perspective [8, 11]. Also, the adoption of a circular approach to produce ceramic products reduces the intensity of other activities, including the extraction of natural resources and the transport of materials. The literature analysis shows that the insertion in the ceramic mixtures of by-products generated during different production processes has been largely considered. Several studies focus on the reuse of by-products in order to preserve the technical and the mechanical performances of the ceramic products. The reuse of by-products in the ceramic production process allows the obtaining of a sustainable ceramic mixture and the realization of innovative and ecological ceramic products. Also, the reuse of specific by-products determines the reduction in energy consumption and the greenhouse gas emissions of the ceramic production process. However, a large number of by-products requires a pre-treatment phase before

the addition in the ceramic mixture, i.e. the thermal pre-treatment. This pre-treatment implies higher energy consumption that contributes to the increasing costs of the ceramic production process reducing the beneficial effects related to the use of by-products in the ceramic mixtures. This paper aims at defining the main by-products to insert in the ceramic mixtures comparing the advantages and the disadvantages of the sustainable production of the ceramic products.

5.2 Literature review

The purpose of this research is the definition of a framework to identify the most relevant by-products generated during different production processes allowing the sustainable production of the ceramic products. The ceramic industry reuses the by-products generated during the production within its process in a sustainable perspective. Following the circular economy principles, raw materials and natural resources commonly used in the ceramic production process can be replaced with such by-products considered as industrial waste. The approach allows the minimization in raw materials consumption and the reduction of the industrial waste production. The use of specific by-products also determines lower energy requirement for the ceramic production process. However, the execution of a transformation pre-treatment phase must be considered for several by-products before they can be added to the ceramic mixture. The transformation of the by-products during the pre-treatment phase represents an additional economic charge to the ceramic production process that reduces the beneficial effects of the sustainable production of the ceramic products. The framework proposed in this research consists in a path for each by-product inserted in a ceramic mixture considering the advantages and the disadvantages related to the sustainable ceramic production. The definition of the most suitable by-products to insert in a specific sustainable ceramic mixture leads the obtaining of innovative and ecological ceramic products. Many studies focus on the addition of various industrial by-products to replace typical raw materials used in the ceramic mixtures in order to fulfil innovative ceramic products with technical and mechanical properties comparable with the reference product [13]. The findings of this literature review refer to the replacement of raw materials commonly used to produce ceramic products with such by-products, i.e. cement-asbestos, man-made vitreous fibers, fly ash and bottom ash, metallurgical slag and blast furnace slag, galvanic sludge, bentonite mud, glass scraps, exhausted foundry sands and sewage sludge. These by-products have been analyzed by several researchers in order to characterize the by-products and evaluate the amount of the substitution. Cement-asbestos waste must be treated with an inertisation process to be used as a by-product. Thermal pre-treatment removes the dangerous characteristics from this material. Thermally inerted cement-asbestos shows a phase composition similar to natural clinker with a higher content of aluminium, iron and magnesium and can be used to replace raw materials in the ceramic

mixtures [14, 11, 15]. The scraps of man-made vitreous fibers, i.e. mineral wool and glass wool, are considered as hazardous waste due to the high breathability of the fibers. Therefore, the pre-treatment phase of thermal inertisation is necessary to eliminate the dangerous properties of this by-product. The inerted fibers are similar to the materials with glassy characteristics and can be used as fluxes in the ceramic mixtures [16]. Fly ash and bottom ash considered in this research are the residues of the production processes inside the thermoelectric power plants and the municipal solid waste incinerators. Several studies have considered fly ash and bottom ash as by-products to insert in the ceramic mixture both after or without a pre-treatment phase, evaluating the addition of a singular by-product or the combination with other by-products, i.e. blast furnace slag and metallurgical slag [17, 18, 19, 20, 21]. Galvanic sludge represents some industrial waste rich in heavy metals. These characteristics must be evaluated performing physical and chemical characterizations before the reuse of this by-product in the ceramic production process. The calcination pre-treatment is also necessary to eliminate the gas-forming species [22, 23]. Montmorillonite clays are characterized by a strong presence of colloidal particles and high plasticity. Adding water to bentonite clay, the mixture considerably expands its volume forming a colloidal suspension with plastic behavior. Thermal pre-treatment is also necessary to remove the percentage of water from the mud [24, 25]. Glass scraps of various origins can be used in the ceramic production process as a sintering promoting material. Various studies have proved that the use of this by-product in place of natural sand allows the reduction of the temperature normally applied to obtain the ceramic products [26, 27]. Foundry sands are used to create molds or cores for casting iron-based alloys. High quality sands are generally considered, depending on the metal under casting. After the cooling of the molten material, the mold is broken to take the metal element and the foundry sand has completed its life cycle. Exhausted foundry sand represents a high quality by-product for the ceramic production process. Therefore, the composition of the exhausted foundry sand may significantly vary according to the metallic melt. Hence, a preliminary phase of chemical characterization and particle-size analysis is necessary to identify the most suitable exhausted foundry sand to insert in the ceramic mixture [28, 29, 30]. Several studies have evaluated the insertion of the exhausted foundry sand in different ceramic mixtures testing the substitution of increasing quantities of this by-product or evaluating a combination with other by-product, i.e. sewage sludge and glass scraps [31]. In this study, the technical and mechanical performances and the aesthetical characteristics of the ceramic products, the energy performances of the ceramic production process and the execution of a transformation pre-treatment phase on the by-products are considered in order to select the most suitable by-products to use for the definition of a sustainable ceramic mixture and the production of innovative and ecological ceramic products.

5.3 Materials and method

The ceramic products are obtained from non-metallic inorganic raw materials mixed and processed by forming and heat treatment. The ceramic products represent a variety of goods with different applications depending on the characteristics of raw materials selected for the mixture and the technological production process. Raw materials involved in the process are clay, sand, kaolin and alumina, degreasers to reduce plasticity and facilitate the cohesion of the elements during the heat treatment, fluxes which reduce the level of refractoriness, raw materials for the glaze applied on the surface. The technological production process consists in the mixture preparation led to the final use of the product, forming and dehumidification to reduce the water content, firing to compact the mixture, glazing and superficial decoration. The chemical composition and the technological production process determine the porosity and the mechanical properties, impermeability, frost resistance and technical properties, as well as the aesthetic characteristics of the ceramic products. The aim of this research is to identify the main by-products generated during different production processes to obtain a sustainable ceramic mixture. The replacement of specific raw materials with the insertion of by-products supports the reduction of the industrial waste production. The definition of a sustainable ceramic mixture allows the production of innovative and ecological ceramic products without affecting the mechanical, technical and aesthetical performances of the ceramic products. The use of specific by-products also supports the reduction in energy consumption and greenhouse gas emissions of the ceramic production process. Lower energy requirement contributes to the decrement of the economic charge of the ceramic production process. Several studies focus on the characterization of the by-products and the evaluation of the substitution preserving the technical and the mechanical performances of the ceramic products [7, 9]. The literature review shows that the use of the by-products coming from different production processes has been considered in various studies. The findings refer to the definition of a sustainable ceramic mixture adding separately one by-product per time or a combination of different by-products. The sustainable ceramic mixture has been modified adding various quantities of recycled materials and reducing the amounts of natural resources to produce different ceramic products. The information obtained in this research are collected considering: (i) the typologies of by-product added to the ceramic mixture and the percentage of the substitution; (ii) the execution of a pre-treatment phase on the by-product; (iii) the typologies of ceramic product in which the by-product insertion was tested; (iv) the main results focusing on the technical and the mechanical performances of the ceramic products; (v) the energy performance of the ceramic production process. The recycled materials selected in this analysis are cement-asbestos, man-made vitreous fibers, fly ash and bottom ash, metallurgical slag and blast furnace slag, galvanic sludge, bentonite mud, glass scraps, exhausted lime, exhausted foundry sands

and sewage sludge. The by-products analyzed in this paper have been selected considering the complexity in following the landfill disposal chain of hazardous waste and the evaluation of the amount of waste produced in different production processes. The technical and the mechanical performances of the ceramic products are assessed measuring linear shrinkage, water absorption, bulk density and rupture modulus. These indicators determine information on the sintering process of the samples. Sintering is a densification process of a compound of compacted powders aimed at removing interstitial porosity and allowing the development of bonds between adjacent particles. Linear shrinkage is a measure of the percentage dimensional variation of the samples after sintering. Water absorption and bulk density refer to the quality of the samples as it is strictly related to the compactness and therefore to the mechanical strength. Rupture modulus is a specific indicator of the mechanical properties of the samples as it represents the limit load supported without cracking. The aesthetical characteristics are evaluated comparing the difference in color between the samples and the reference product. Finally, the energy performances of the ceramic production process are analyzed considering time and temperature of the heat treatment.

5.4 Results and discussion

This section introduces the results of the literature analysis on the production of innovative and ecological ceramic products obtained introducing various recycled materials in different ceramic mixtures. The research project aims at selecting specific by-products generated during different production processes to insert in the ceramic production process allowing the definition of a sustainable ceramic mixture. The findings of this analysis consists in the evaluation of the advantages and the disadvantages related to the substitution of such by-products replacing raw materials commonly used in the ceramic production process. The results are summarized in a framework considering the information collected about the main by-products, the ceramic products obtained with the substitution, and the variations on the ceramic production process.

Figure 1 shows the structure of the framework. The addition of one by-product per time or a combination of by-products, the percentage of the insertion and the requirement of a pre-treatment phase on the by-products are reported in the first section. The second section refers to the typology of ceramic product realized through the substitution, the mechanical and the technical performances and the aesthetical characteristics of the ceramic product. Finally, the third section deals with the energy performances of the ceramic production process.

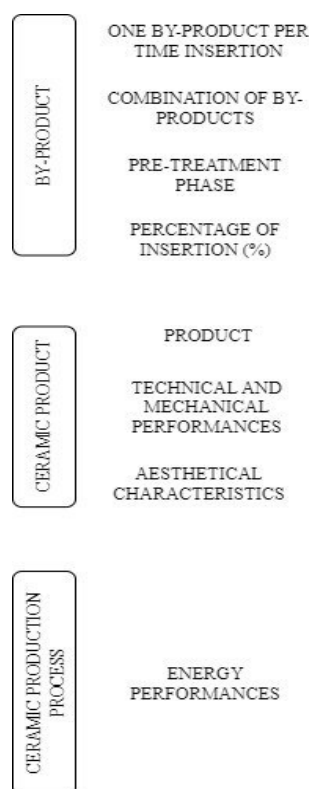


Fig. 1. Structure of the framework considering the information collected on the by-products, the ceramic products and the ceramic production process.

The selection of the recycled materials has concerned the complex theme of the hazardous waste treatment and disposal, and also the difficult management of huge quantities of waste crowding the landfill sites. The main by-products considered in this research are cement-asbestos, man-made vitreous fibers, fly ash and bottom ash, metallurgical slag and blast furnace slag, galvanic sludge, bentonite mud, glass scraps, exhausted foundry sand and sewage sludge. A large number of these selected by-products are classified under the category of hazardous waste. Therefore, a transformation pre-treatment must be implemented before the insertion of these by-products in different production processes. Generally, hazardous waste is subjected to a thermal pre-treatment in order to remove the dangerous characteristics. The thermal treatment favors the inertization of such by-products, but also requires additional energy and consequently implies higher economic charge and greenhouse gas emissions on the ceramic production process. The insertion of the by-products in the ceramic mixtures is also evaluated testing the mechanical and the technical performances and the aesthetical characteristics of the ceramic products. Linear shrinkage, water absorption, bulk density and rupture modulus of the innovative and ecological ceramic products are compared to the values of the reference products. Several studies show that the substitution of raw materials typically used in the ceramic production process with industrial by-products is analyzed in order to define the optimal amount preserving the mechanical and the technical performances. However, the substitution

generally leads the darkening of the samples without matching the aesthetical characteristics with the reference product. Specific by-products can be used in the ceramic production process as a sintering promoting material allowing the reduction of the temperature normally applied during the heat treatment. Reducing the firing temperature may determine beneficial effects on the whole ceramic production process, i.e. the reduction of firing time strictly connected to the reduction of the production costs and the greenhouse gas emissions.

Figure 2 collects the results about the insertion in the porcelain stoneware mixture of cement-asbestos, a combination of cement-asbestos and glass scraps, and man-made vitreous fibers. Specifically, cement-asbestos and man-made vitreous fibers must be subjected to a thermal pre-treatment. The danger of using fibrous materials is due to the high breathability of the fibers which can lead serious consequences on health of the operators in contact with this material. The thermal pre-treatment leads the transformation of the hazardous fibers, which lose the typical fibrous conformation allowing the reuse as by-product. The firing temperature of the thermal transformation is about 1200-1300°C [15]. This process represents a valid alternative to the hazardous waste disposal. However, it is an additional step to the ceramic production process which contributes to the increasing costs of the ceramic products. Furthermore, the thermal pre-treatment implies an increase in energy consumption of the ceramic production process and consequently higher greenhouse gas emissions. These factors reduce the beneficial effects associated with minimizing the waste sending to landfill sites.

Adding increasing quantities of inerted cement-asbestos (3, 5, 10 % wt) replacing quartz sand to the porcelain stoneware mixture, the mechanical and the technical performances are preserved [14]. Cement-asbestos (1, 3, 5% wt) and glass scraps have been used for the production of frits to insert in the porcelain stoneware mixture. Specifically, the addition of 5% wt of the new frit led to better mechanical strength, stain resistance and higher productivity. The decrement of linear shrinkage determines lower loss of material during the heat treatment [11].

Linear shrinkage, water absorption, bulk density, open porosity and crack resistance were tested after the insertion of inerted man-made vitreous fibers (3, 6, 9 % wt) in the porcelain stoneware mixture replacing fluxes. The mechanical and the technical performances of the samples are comparable to the reference product. Furthermore, the addition of inerted man-made vitreous fibers allows the reduction of the firing temperature by 40°C [16]. Reducing the firing temperature, the economic charge related to the energy consumption decrease. Also the greenhouse gas emissions connected to the ceramic production process are reduced.

Finally, the aesthetical characteristics of the samples obtained with the substitution of cement-asbestos and man-made vitreous fibers into the porcelain stoneware mixture differs from the reference product. The use of these by-products leads the realization of darker samples.

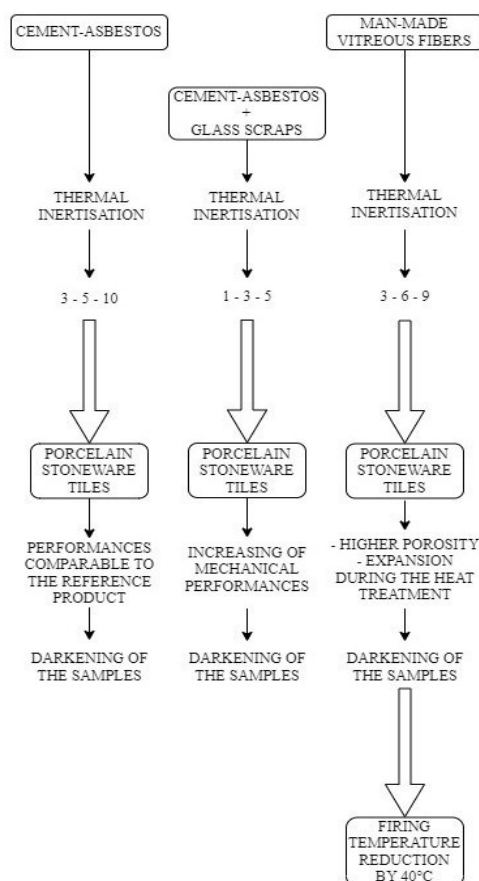


Fig. 2. Framework related to the use of cement-asbestos and man-made vitreous fibers in the porcelain stoneware mixture.

Several studies have analyzed the addition of fly ash and bottom ash to different ceramic mixtures. These by-products are generated in various production processes and are considered singularly or in combination with other by-products, i.e. furnace blast slag. The results are reported in Figure 3.

Coal fly ash shows properties similar to quartz and can be added to the ceramic mixtures as untreated by-product or after an alkali activation pre-treatment. In the second case, fly ash and bottom ash obtain properties similar to clay and feldspar. Treated coal fly ash inserted in the porcelain stoneware mixture (15, 30, 50 % wt) exhibits low firing temperature with large sintering range. Specifically, the samples show optimal post-sintering properties by the temperature of 1100°C [17]. Reducing the sintering temperature, the insertion of coal fly ash into the porcelain stoneware mixture allows the obtaining of ceramic products with good mechanical and technical performances. Furthermore, firing time and temperature are reduced. These interesting results lead the reduction of the costs connected to the energy consumption of the production process, allowing the minimization of the greenhouse gas emissions. However, the samples are darker than the reference product affecting adversely the aesthetical characteristics.

A combination of fly ash from thermal power plant and blast furnace slag from steel plant (25, 30 % wt) replaces respectively quartz and feldspar for the realization of porcelain stoneware mixture. Linear shrinkage, bulk density, water absorption and flexural strength were measured. The beneficial effects of the substitution on the mechanical performances were recorded by the temperature of 1175°C rather than 1200°C. Increasing temperature, the flexural strength drastically decreases due to the formation of glassy phases [18]. The results suggest that the appropriate regulation of firing time and temperature favors sintering avoiding excessive vitreous formation phenomena and the resistance reduction due to the higher fusibility of the mixture

Fly and bottom ash from the municipal solid waste incineration (MSI) can be inserted in the ceramic mixtures both as untreated by-product or as vitrified by-product. The use of these materials must be evaluated with mineralogical and microstructural investigations in order to define their chemical characteristics and the possible presence of hazardous fractions.

MSI fly ash was considered for the realization of the porcelain stoneware mixture (10% wt) replacing clay and feldspar. The mechanical and the technical performances of the samples are comparable to the reference product [20].

MSI bottom ash is used both treated and untreated as by-product in the porcelain stoneware mixture and in porous single firing mixture. Water absorption and linear shrinkage have been measured. Untreated MSI bottom ash, up to 5% wt, does not affect these indicators. Treated MSI bottom ash (5, 10% wt), inserted as a strong flux, favors the definition of an innovative and ecological porous single firing mixture with mechanical and technical performances comparable to the reference product. Considering the porcelain stoneware mixture, treated MSI bottom ash favors the sintering process allowing the reduction of firing time and temperature. The advantage of using treated MSI bottom ash implies the reduction in energy consumption and greenhouse gas emissions. Furthermore, the leaching tests confirm the non-hazardousness of the samples [21].

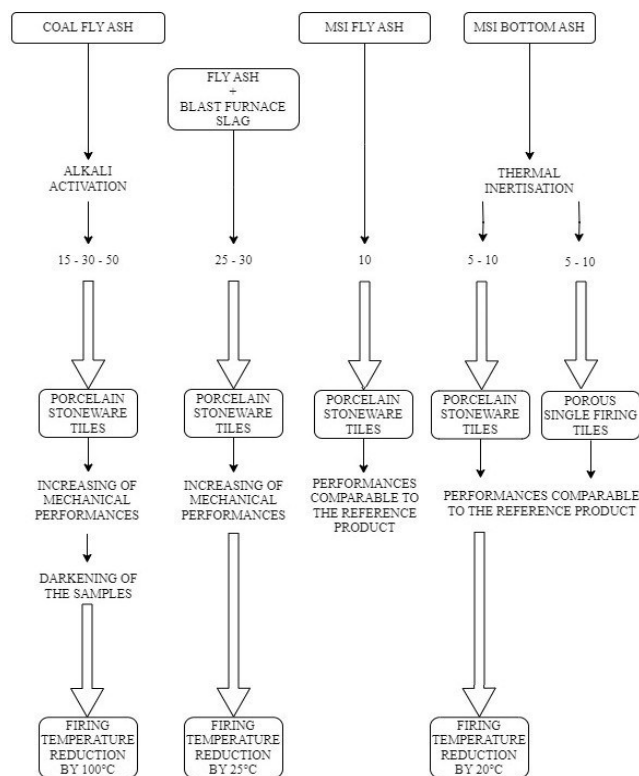


Fig. 3. Framework related to the use of fly ash and bottom ash in different ceramic mixtures.

Metallurgical slag from steel plants can be used in the formulation of glazed floor tiles mixture (8, 20%). The chemical characterization of this by-product allows the detection of any hazardous fractions. The samples with little percentage of by-product show mechanical and technical performances comparable to commercial floor tiles. However, water absorption increases with increasing addition of metallurgical slag and flexural strength decreases with increasing firing temperature [19].

The sludge produced by the physico-chemical treatment of waste water generated by electro-planting plants must be physically and chemically characterized and then subjected to calcination treatment to eliminate the gas-forming species. The treated galvanic sludge may be used as by-product in the ceramic production process in order to define the brick mixture. The inclusion of metallic elements in the ceramic mixture is ensured through the crystalline phase formation during the firing. The insertion of the treated galvanic sludge to the brick mixture, up to 15%, leads the realization of samples with mechanical and technical performances comparable to the reference product, achieving the inertization of pollutants. No significant difference in color is observed [22].

The combination of treated galvanic sludge with glass scraps is inserted in the porcelain stoneware mixture up to 20% wt. The samples meet the requirements of the mechanical and the chemical standards [23]. However, the samples made by treated galvanic sludge show a darker color than the reference standard.

The studies referred to the reuse of treated galvanic sludge, both separately and in combination, leads the obtainment of samples with good quality and the complete inertization of pollutants. The advantage is the certain reuse of hazardous waste as an alternative to disposal. However, the inertization process implies higher costs in the ceramic production process reducing the beneficial effects related to the minimization of the industrial waste production (see Figure 4).

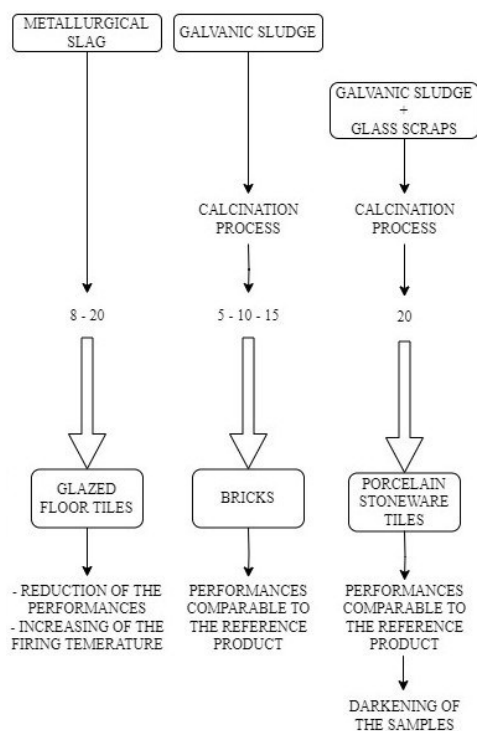


Fig. 4. Framework related to the use of metallurgical and galvanic sludge in different ceramic mixtures.

Figure 5 shows the advantages and the disadvantages of the insertion of bentonite mud in different ceramic mixtures. Montmorillonite clay is characterized by a high plasticity. The use of montmorillonite clays in the ceramic industry is strongly limited by their physical and technological behavior. Hydrating bentonite clay, the volume significantly expands forming a colloidal gel. These properties make bentonite clay suitable as a plasticizing additive for lean ceramic compositions. Calcined bentonite clay is used up to 40% wt for the formulation of a ceramic wa tiles mixture. Linear shrinkage, rupture modulus, bulk density, water absorption and humidity expansion meet the requirements for the industrial production of wall tiles. Replacing clays with heat treated bentonite gives economic beneficial effects as the costs of calcined bentonite is approximately 30% lower than clay generally used in the ceramic production process [24].

The substitution of German and Ukrainian clays in a porcelain stoneware mixture with Sardinian clay and 10% wt of various Italian bentonites is evaluated in order to reduce the costs of the ceramic products. The first mixture is obtained by the complete replacement of the German clay and partial

replacement of the Ukrainian clay (5% wt). The second mixture is formulated by the whole substitution of the Ukrainian clay. In the first case, the rheological behavior is affected by the increasing plasticity and increasing viscosity. The mechanical strength values of the dried samples are higher than the reference material; furthermore, the color of the samples is similar to the commercial product. However, the linear shrinkage is higher than the reference product [25].

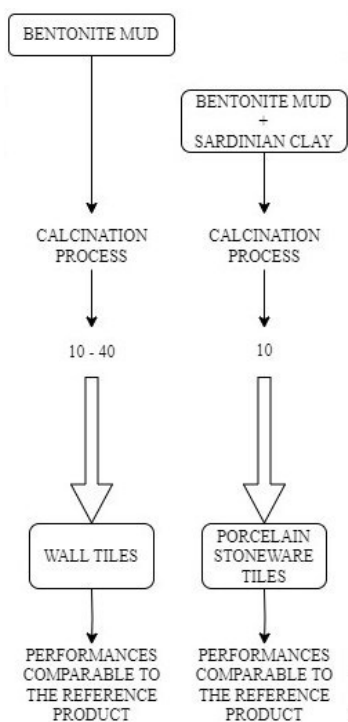


Fig. 5. Framework related to the use of bentonite mud in different ceramic mixtures.

The results related to the use of glass scraps of various origin as by-product replacing raw materials commonly used to formulate ceramic mixtures are reported in Figure 6. Glass scraps is used in the ceramic production process as a sintering promoting by-product. Various studies have proved that the use of glass scraps replacing natural sand allows the reduction of the firing temperature of the ceramic products. The advantage of reducing the firing temperature is connected to the environmental sustainability thanks to the reduction of greenhouse gas emissions and the economic savings in energy. The introduction of glass scraps is applied to the production of various ceramic mixtures, i.e. porcelain stoneware and bricks. Glass scraps represent a valid alternative to fluxes in the ceramic mixtures. Furthermore, reducing the energy consumption, the costs associated with the ceramic production process decrease.

The insertion of soda-lime-silica glass and borosilicate glass up to 41% wt is evaluated for the production of porcelain stoneware mixture. The samples are highly vitrified at a firing temperature almost 140°C lower than the normally temperature applied to the process [27].

Natural sand has been replaced by glass scraps up to 20% in ceramic tiles and bricks mixtures. The results confirm the compatibility of the by-product to the ceramic mixtures. Density, water absorption and flexural strength improve with the addition of glass scraps as the by-product contributes to the porosity reduction due to the vitreous phase formation. Thus, faster sintering allows the reduction of the firing temperature by 200°C compared to the standard [26].

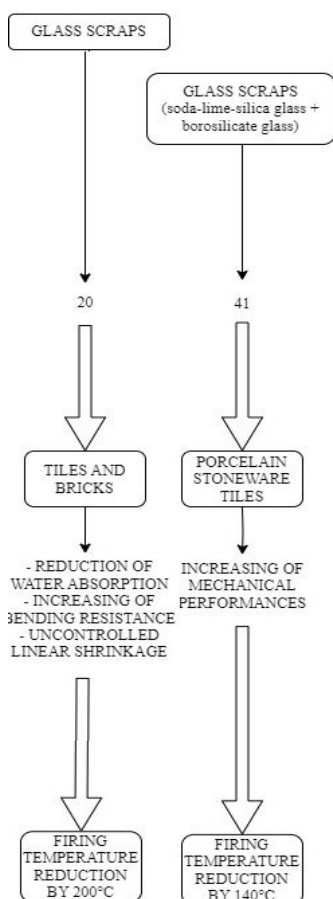


Fig. 6. Framework related to the use of glass scraps in different ceramic mixtures.

Exhausted foundry sand is a high quality by-product for the substitution of raw materials commonly used in the ceramic production process. Therefore, the chemical composition of the exhausted foundry sand may significantly vary according to the metallic melt. Chemical characterization and particle-size analysis lead the usability evaluation of various exhausted foundry sands in the ceramic mixtures. Previous studies have shown that the substitution of foundry sand in the porcelain stoneware mixture have led to the obtaining of samples with different aesthetical characteristics. Several samples are similar to the reference product while other samples present dark superficial defects.

Figure 7 collects the results about the insertion of exhausted foundry sand and a combination of exhausted foundry sand, glass scraps and sewage sludge in different ceramic mixtures. The porcelain stoneware mixture obtained by replacing clay and kaolin with foundry sand up to 15% wt shows

higher density, linear shrinkage and fire resistance. Higher water absorption and the reduction in plasticity are also detected. The color of the samples is slightly darker than the reference material [28].

Interesting results are achieved considering the substitution of clay with 15% of foundry sand in the porcelain stoneware mixture. The reduction of the firing temperature by 50 °C leads the reduction in energy consumption and greenhouse gas emissions [33].

Foundry sands can also be used for the production of bricks and tiles. Clay was mixed with different percentages of foundry sand up to 50%. The innovative samples meet the requirement for the commercial products. Decreasing the sintering temperature, the volume variations decrease, as well as the weight loss. Consequently, the mechanical performances of the samples and the productivity of the ceramic production process are improved [32].

A combination of foundry sand, glass scraps and sewage sludge from waste water treatment is considered for the formulation of the porcelain stoneware mixture. Glass scraps has positive effects on flexural strength, water absorption and firing weight loss, while foundry sand contributes to reducing linear shrinkage. The combination of 10-15% foundry sand, 15-20% glass scraps and 10% sewage sludge, at the firing temperature of 1000-1050°C, is the most suitable for the production of innovative and ecological ceramic products with performances comparable to the reference product [34].

Finally, the chemical characterization of the various exhausted foundry sands is useful to identify the by-product with the best characteristics to be used in the ceramic production process. The selected by-product can be added both separately or in combination with other by-products to formulate different ceramic mixtures. The samples show balanced technical, mechanical and aesthetic performances. The faster sintering determines the possibility to reduce firing time and temperature and consequently improve economic and environmental advantages.

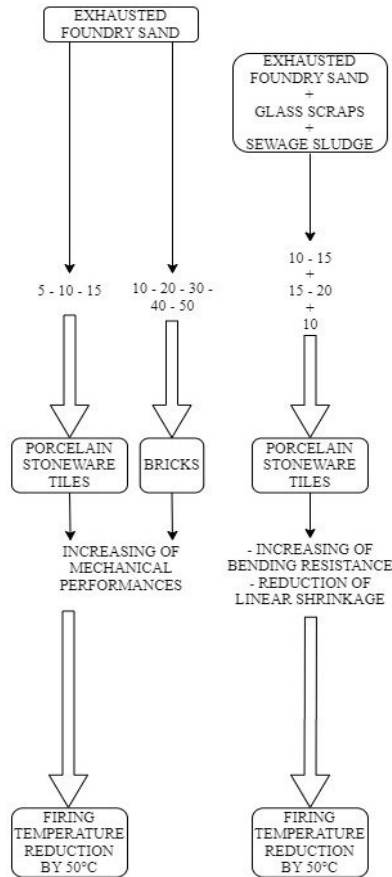


Fig. 7. Framework related to the use of exhausted foundry sand in different ceramic mixtures.

5.5 Conclusion

This paper introduces the results of a literature analysis concerning the insertion in the ceramic mixtures of various by-products generated during different production processes. The adoption of a circular approach to realize ceramic products reduces the intensity of such activities as the extraction of natural resources, the transport of materials and the energy consumption within the production process. The definition of the main by-products to replace raw materials typically used for the production of ceramic mixtures follows the principles of the circular economy aimed at extending the waste life through the reuse in different production processes. Thus, the use of by-products limits the extraction of natural resources, reduces the amount of the industrial waste and the costs for disposal. This circular perspective fits perfectly with the principles of sustainability to achieve in environmental, economic and social fields.

The collection of data studied in the literature analysis allows the definition of a framework that summarizes the advantages and the disadvantages of the sustainable production of the ceramic products. The definition of the most suitable by-product to insert in a specific sustainable ceramic mixture is supported by the evaluation of the typologies of by-product and the percentage of the substitution, the execution of a pre-treatment phase on the by-product, the typologies of innovative

and ecological ceramic product and its properties, the energy performance of the ceramic production process. The execution of a transformation pre-treatment phase must be considered for several by-products before the insertion in the ceramic mixture representing an additional economic charge to the ceramic production process. The transformation pre-treatment reduces the beneficial effects of the sustainable production of the ceramic products. The technical and the mechanical performances of the ceramic products are assessed measuring linear shrinkage, water absorption, bulk density and rupture modulus. The aesthetical characteristics are evaluated comparing the difference in color between the samples and the reference product. Finally, the energy performances of the ceramic production process are analyzed considering time and temperature of the heat treatment.

The by-products selected in this research are cement-asbestos, man-made vitreous fibers, fly ash and bottom ash, metallurgical slag and blast furnace slag, galvanic sludge, bentonite mud, glass scraps, exhausted foundry sands and sewage sludge. This selection has concerned the complex theme of the hazardous waste treatment and disposal, and also the difficult management of huge quantities of waste crowding the landfill sites. The direct use of by-products in different production processes is rarely possible. The transformation pre-treatment is generally required, mainly the thermal inertization of hazardous by-products, in order to ensure the feasibility of reuse.

Cement-asbestos and man-made vitreous fibers are considered as hazardous fibrous waste. Thus, they must be subjected to a thermal pre-treatment before they can be used as by-product in the ceramic production process. This pre-treatment provides a valid alternative to landfill disposal of hazardous waste. However, it represents an additional step to the production process with higher economic charge contributing to the increasing costs of the by-product. Furthermore, the thermal pre-treatment requires higher energy consumption affecting adversely on environmental sustainability due to the higher greenhouse gas emissions. These consequences reduce the beneficial effects of reusing the by-products instead of sending waste to landfill sites.

The chemical characterization of the by-products is essential to identify any hazardous fractions that may affect on the toxicity level. Specifically, fly ash and bottom ash must be tested before the addition to the ceramic mixtures. Metallurgical slag, blast furnace slag, galvanic sludge also must be tested with the chemical analysis.

Milling is a pre-treatment to ensure the suitable particle size fraction to insert in the ceramic mixture. Milling of glass scraps and exhausted foundry sand represents a pre-treatment phase with lower impact on the ceramic production process and the environment. Generally, the replacement of raw materials with industrial by-products coming from different production processes does not completely solve the problem of the raw materials extraction. The beneficial effects associated with

the reuse of by-products is strictly connected to the realization of innovative and ecological ceramic products formulating a sustainable ceramic mixture with materials regarded as waste to dispose.

The insertion of sintering promoting by-products in the ceramic mixture allows the production of ceramic products competitive with the commercial reference product referring to the technical and the mechanical performances, i.e. man-made vitreous fibers and glass scraps, treated fly ash and treated bottom ash. The drawback refers to the aesthetical characteristics of the samples, which are darker than the reference product. Furthermore, the partial replacement of fluxes with glassy by-products leads to improve productivity and energy savings of the ceramic production process, reducing firing time and temperature. The insertion of sintering promoting by-products allows economic and environmental benefits, in fact the costs of the ceramic production process and the greenhouse gas emissions decrease. However, the firing process must be controlled through the correct setting of time and temperature to avoid the excessive fusibility of the ceramic mixture.

Exhausted foundry sands represent a valid alternative to raw materials for the formulation of ceramic mixtures. The chemical characterization is essential to evaluate the presence of metallic traces. Exhausted foundry sands lead the decrement of sintering temperature and linear shrinkage of the samples. Furthermore, selecting the most suitable exhausted foundry sand to replace raw materials in the ceramic mixture, the aesthetical characteristics of the samples may be similar to the reference product.

The results reported in this paper mainly refer to a laboratory production of ceramic samples. Therefore, limited evidences are available considering the applications to the industrial process. Several studies deal with the insertion of industrial by-products in the porcelain stoneware mixture. Porcelain stoneware products show excellent technical and mechanical properties and high application versatility. The commercial demand for porcelain stoneware products constantly increases, thus the high application for experiments concern the study of sustainable ceramic mixtures for the production of innovative and ecological porcelain stoneware products.

Future developments of this research will detect specific by-products that fit with the aim of preserve natural resources and reduce the amount of waste in a sustainable and circular perspective. The selection of specific by-products allows the formulation of a sustainable ceramic mixture for the laboratory production in order to analyze the characteristics of the innovative and ecological ceramic product.

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6. Transforming textile waste into resources: a circular economy approach for sustainable textile production

Note: This chapter is based on conference paper

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XXIX Summer school “Francesco Turco” – Industrial System Engineering

The textile industry annually generates huge amount of textile waste contributing to environmental degradation principally related to landfill disposal or incineration. The high production of textile waste is also related to the innovations in manufacturing technology, globalized supply chains and the prevalence of online shopping. This system allows the rapid production of cheap garments favoring quick turnover. This business model, known as “fast fashion”, increases the negative impact on the environment related to the textile production processes. These practices are no longer sustainable and need to be turned into new alternative approaches as second-hand buying, choosing ethical textile productions. The transition to circular economy models that prioritize resource efficiency and waste minimization is the focus of this research. The evaluation of reusing textile waste as valuable by-products extends the material lifecycles and emphasizes the importance of closing the loop. This paper considers different strategies to reuse textile waste as by-product in a circular economy perspective. In this context, textile waste is considered as a valuable resource favoring sustainability. The evaluation of economic and environmental benefits as lower resource consumption, energy savings, and greenhouse gas emissions (GHG) mitigation are shown in this research to enforce the application of sustainable practices in the textile industry.

6.1 Introduction

The textile industry stands as a cornerstone of the global economy, driving commerce, employment, and innovation across the world. It is one of the largest manufacturing sector employing millions of people throughout the supply chain. From the creation of fabrics to the production of garments, textiles play an integral role in numerous sectors, including fashion, home furnishings, healthcare, and industrial applications generating significant value in annual incomes. Specifically, the garment sector is likely to increase due to the increasing global population and the innovation in manufacturing technologies. However, despite its economic significance, the textile industry also represents a heavy polluter considering the high water, chemical and energy requirements of the production process; i.e. the production of 1 kg of cotton takes 7 000 – 29 000 litres of water (Islam Sarker et al. 2024). The

negative estimation on the environment consists in 20% of global wastewater, 36% of carbon dioxide, 20% of waste disposal (Islam Sarker et al. 2023). One of the most pressing environmental concerns associated with the textile industry is related to the large use of harmful chemicals determining the contamination of air, water, and soil. Specifically, the use of pesticides for the cultivation of natural fibres and dyes of various origin impact significantly on human health and the environment (Jia F. et al.2020, Arshad M. Y. et al. 2023, Shamsi M. A. et al. 2023) Additionally, the disposal of textile waste poses a significant challenge. Landfilling and incineration are common practices for disposing the unwanted textiles, further exacerbating environmental degradation and contributing to greenhouse gas (GHG) emissions. Textile waste contains high energy content and can be used for heat energy generation. By the controlled burning of the textile waste during the incineration, high amount of energy is generated and can be utilized for various scopes, i.e. steam production and electricity. The promising incineration efficiency indicates a significant conversion of the textile waste energy into usable heat and electricity. Also, incineration allows the reduction of textile waste in landfills. However, burning waste to produce energy is not the ideal solution considering the increasing in the production of carbon dioxide, affecting negatively on the GHG emissions (Papamichael I. et al. 2024, Edirisinghe L. M. et al. 2023) The rise of fast fashion has intensified these environmental issues. Fast fashion, characterized by rapid production of cheap clothing, favours the quick turnover encouraging the overconsumption and the increasing of the textile waste amount. Such business model drives the customers to own larger quantities of clothes that determines the increasing of the global textile production (Loo S. L. et al. 2023). The cycle related to the fast fashion production not only accelerates resource depletion but also exacerbates negative environmental impacts connected to textile production and textile waste. These practices are no longer sustainable and a shift to the circular economy model within the textile industry is necessary. Circular economy is a valuable alternative to the traditional model of production-use-recovery and is intended to minimize the waste volume stressing the continual use of the resources through recycling, reusing, and remanufacturing. The circular economy extends the materials lifecycle as long as possible through the 10R strategies: recover, recycle, repurpose, remanufacture, refurbish, repair, re-use, reduce, rethink, and refuse (Arnold M. G. et al. 2023). The adoption of circular economy principles in the textile industry allows the mitigation of negative impacts in the environment, the preservation of natural resources and the promotion of sustainable practices throughout the supply chain (Arnold M. G. et al. 2023). The promotion of positive strategies in the textile production process leads to positive impact on human health and the environment, as reported in the Sustainable Development Goals (SDGs) of the United Nations (<https://sdgs.un.org/2030agenda>). The adoption of a circular model in the textile industry is

in line with SDG 3, good health and well-being, SDG 6, clean water and sanitation, SDG 12, sustainable consumption and production, SDG 13, climate change.

The environmental challenges posed by the textile industry require concerted efforts from all stakeholders, including governments, businesses, consumers, and social organizations. Collaborative actions will mitigate the negative environmental impact of the textile industry through the implementation of green technologies in the textile production process favouring the re-evaluation of clothing design, the reinforcement of the consumers' environmental consciousness, the standardization of guidelines, strategies and laws. Green technologies are eco-friendly approaches that encourage the sustainable development enforcing the utilization of resources and energy efficiency to reduce the negative environmental impact of the textile industry. These technologies aim at meeting the human and environmental needs by applying strategies in order to decrease pollution and increase productivity and safety. Textile manufacturing process should re-think the design of the textile products favouring recyclability and reusability, using sustainable and recyclable materials, reducing chemical use and encouraging the adoption of modular design principles with disassembly in mind (Islam Sarker et al. 2023, Furferi R. et al. 2023). Additionally, improving the consumers' knowledge about the negative effects on the environment connected to the traditional economy model and the possibility of taking alternative decisions supporting sustainability contribute to engage ethical behaviours in such activities as acquiring, consuming and disposing textile products (Shamsi M. A. et al 2023). Finally, the introduction of clear regulations and guidelines is fundamental to build a sustainable textile waste management system allowing the alignment with the SDGs and maximizing the beneficial effects connected to the transition to a circular economy perspective (Arshad M. Y. et al. 2023, Loo S. L. et al. 2023).

This paper aims at defining the state of art related to the transition of the textile industry to the circular economy in order to minimize its negative impact on human health and the environment. Fast fashion model is the principal responsible of the high volume of textile waste to dispose and the rapid consumption of raw materials, so textile recycling is fundamental to enforce the transition to a circular and sustainable business model. The main barriers and enablers are shown; finally, several case studies represent ethical examples in which textile waste is used as by-products in a circular economy perspective.

6.2 Textile production process

The textile production process involves several stages contributing to environmental impact and waste generation. Figure 1 reports the main phases of the textile manufacturing process: (i) fibre production involves the extraction of raw materials such as cotton, wool, polyester, and nylon;

environmental concerns include land use for cultivation, water consumption, pesticides and fertilizers use in the case of natural fibres, and energy consumption; (ii) yarn formation consists in spinning or twisting the fibres to obtain the yarns; energy-intensive machinery is typically used in this stage, contributing to GHG emissions; (iii) fabric production in which yarns are woven or knitted into fabric; energy and water are largely used in this phase, with additional environmental concerns related to chemical treatments for finishing; (iv) dyeing and printing involve the application of dyes to the fabric; dyeing processes often require large amounts of water and chemicals, contributing to water pollution and chemical waste; efforts to mitigate these impacts include the adoption of more sustainable dyeing methods such as waterless dyeing and the use of eco-friendly dyes; (v) finishing is applied to achieve desired properties such as softness, wrinkle resistance, and colour fastness; finishing processes may involve the use of chemicals that are harmful to human health and the environment; (vi) garment manufacturing consists in cutting and sewing the fabrics into garments; this stage also requires energy-intensive machinery and generates waste in the form of fabric scraps and offcuts.

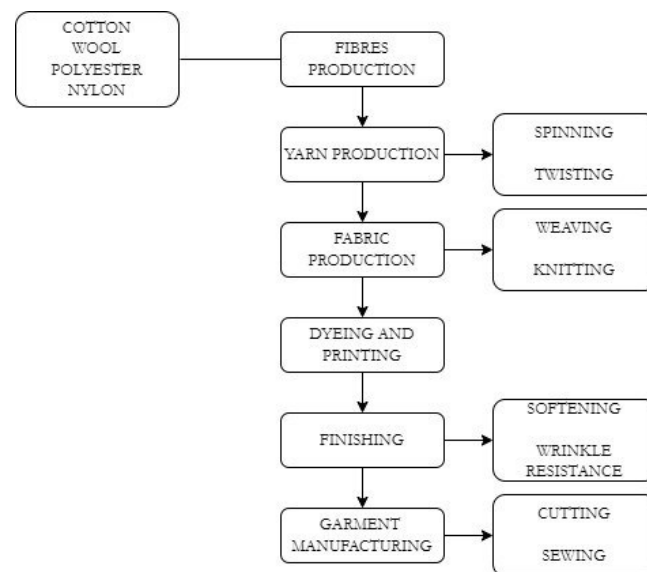


Fig. 2: Textile production process

The negative impact on the environment of the textile production process is extended on the entire production chain. Specifically, the use of chemicals in dyeing process is potentially harmful for human health and the environment. Generally, dyes used in the textile process are vat, disperse, acidic, basic, direct and sulphur dyes. Excessive use of synthetic dyes and water consumption leads to air, water and soil pollution through various toxic emissions. In a circular economy perspective, the use of sustainable dyes without toxic components affects positively on the sustainability of the

textile manufacturing process enabling the recycling of textile waste and water (Arshad M. Y. et al. 2023).

Additionally, the use of high energy-intensive machinery affects negatively on the environment contributing to the GHG emissions.

Textile waste is classified into three categories depending on the phase in which is produced: (i) production waste, from the fibres production to the dyeing and printing; (ii) pre-consumer waste, during the textile finishing process and includes fabric scraps, offcuts and defective products; (iii) post-consumer waste, generated after the products are sold and used (Edirisinghe L. M. et al. 2023). Textile waste recycling is the process of converting discarded textiles into new products, materials or fibres extending their lifecycle and reducing the environmental impact of textile production. The textile recycling processes can be grouped in two main different categories, downcycling and upcycling. Downcycling involves the conversion of textile waste into lower-value products, as shorter length of the fibres, which have limited reuse potential. Downcycling is often used for textiles that are too worn or damaged for traditional recycling. Upcycling involves the reuse of textile waste into new products with higher value or functionality than the original material., i.e. transforming old clothing into accessories, home decors, art pieces. Also, textile recycling processes may be considered as a part of an open-loop recycling or a closed-loop recycling. In the first case, the recycled materials are used in a different production process; in the second case, the recycled materials are used in the same production process as by-products (Papamichael I. et al. 2024). The reuse of textile waste as by-product favours the reduction of raw materials consumption, the minimization of textile waste production and the reduction of GHG emissions in a circular perspective.

6.3 Materials and method

This research analyses the textile production process evaluating the concerns and the strategies to facilitate the shift from the traditional business model to a circular and sustainable one. The state of art related to the textile industry has been conducted on the Science Direct and Scopus websites. Circular economy, sustainability, circular economy in the textile industry, fast fashion, use of textile waste as by-product are used as keywords in this research. The collection of data refers to the publications in the range 2000 to 2024, from which the scientific articles were selected considering the textile production and the textile waste management. Also, green practices and eco-friendly productions have been considered as model of the transition from the traditional business model to the circular and sustainable one in the textile industry. The majority of the references are related to the last years; this finding is due to the higher sensibility to the sustainability issues as reported in the Agenda 2030 of the United Nations (<https://sdgs.un.org/2030agenda>). Finally, the case studies have

been selected considering specific textile waste produced in huge quantities and difficult to manage. Several studies are considered in this research in which textile waste represents a valuable alternative to raw materials. Also, this paper focuses on the main strategies to facilitate the transition to the circular economy model highlighting the main barriers and enablers to the implementation of ethical textile production process.

6.4 Results and discussion

This section introduces the results of the literature review on the transition to circular economy models within the textile industry. The information refers to various barriers and enablers to the application of sustainable practices.

6.4.1 The textile waste recycling

Textile waste recycling holds immense potential for mitigating the environmental impact of the textile industry and fostering a more sustainable approach to textile production and consumption. However, several barriers and enablers influence the effectiveness and scalability of textile waste recycling initiatives. Textile waste recycling is fundamental for the transition of the textile industry to circularity; however, it is affected by the volume of recycled fibres produced. The higher the amount of textile waste to recycle, the higher the beneficial economic effects of the recycling process. Nowadays, the majority of global textile waste ends up in landfills or is incinerated, contributing to the GHG emissions, while recycling rates are underwhelming low (Papamichael I. et al. 2024, Edirisinghe L. M. et al. 2023). Lack of information, consumers' participation and consciousness combined with poor policies of standardization of textile waste management and absence of integrated framework contribute to low recycling rates and enforce the scarce quality perception of the textile recycled materials. All these aspects translate into low economic viability and motivation to innovate the traditional textile production process (Khan M. I. et al. 2023, Loo S. L. et al. 2023, Velichka M. et al. 2023) The integration of digital technologies into the textile production process allows the traceability of the textile products from design, through sourcing of materials and all stages of production, to delivery of the product to the consumer and disposal of the end-of-life product. Digitalization represents a valid innovation for the textile production process as it favours the sustainable development of the textile industry and increases the environmental consciousness and awareness of the consumers. The digital product passport (DPP) is a tool to enable the product traceability throughout the value chain. The DPP includes the main information concerning the materials involved in the textile process and several information related to the transport of the textile product in order to guide the consumers towards sustainable and eco-friendly decisions (Boura A. et

al. 2023). Textile recycling may refer to fabric, fibre, polymer, oligomer, or monomer recycling that can be used either in the same application (close-loop recycling) or in other applications (open-loop recycling). Generally, two or more textile recycling processes are required. Table 1 shows the advantages and the disadvantages related to the application of the different textile recycling processes.

Table 1: Textile waste recycling processes

Recycling process	Advantages	Disadvantages
Mechanical recycling	Low energy requirement	Loss of fibres quality
Thermomechanical recycling	Good fibres quality	High energy requirement
Thermochemical recycling	Good fibres quality	High energy requirement
Chemical recycling	High fibres quality	High energy, chemicals and water requirement

Mechanical recycling involves shredding or cutting textile waste into fibres or pieces, which are then processed into new products such as insulation, carpet padding, or industrial materials. This method is suitable for recycling both pre-consumer and post-consumer textile waste. The process needs low energy requirements and determines the loss of fibre quality, so it is necessary to combine the recycled fibres with virgin fibres. Thermomechanical recycling is a valid process that uses heat to melt thermoplastic textile waste such as polyesters and polyamides. Thermochemical recycling refers to gasification or pyrolysis and requires high temperature and energy input. Chemical recycling involves high investment and processing costs, high consumption of water, chemicals, and energy as well as the generation of various waste products. Chemical recycling methods include depolymerisation, dissolution, and pyrolysis (Loo S. L. et al. 2023). These recycling processes can refer to depolymerisation, dissolution, and pyrolysis. Chemical recycling allows the obtaining of more high value products comparing the process with the mechanical one. However, it requires high chemical and water consumption. The textile waste recycling is strongly dependant on the sorting phase. Proper sorting by material composition and colour before the disintegration process is essential in order to avoid the mixture of different fibres that would result in low quality yarn after spinning. Nowadays, the highly heterogeneous textile waste is commonly sorted manually considering only colour differences. Hence, the production of high value materials must be followed by automated or semi-automated selection considering the textile composition (Papamichael I. et al. 2024, Loo S. L. et al.

2023). Fibre sorting presents a challenge, specifically with mixed fibres. Mixed fibre textiles are difficult to recycle or repurpose because separating different fibre types is complex and costly. Also, the majority of textile waste presents additional decorations without any value for the textile sector, i.e. plastic and metal parts, zipper, buttons and labels (Saccani N. et al. 2023). Efforts to design textiles with easier recyclability in mind, such as using mono-materials or designing for disassembly, can facilitate the recycling process (Furferi R et al. 2022). The implementation of digitalization in the textile industry enforcing the products traceability may represent an enabler to identify the different components of the textile product allowing the components disassembling and favouring specific recycling process of the different materials (Velichka M et al. 2023).

6.4.2 Barriers and enablers to the textile industry

The main barriers and enablers of the adoption of sustainable practices in the textile industry are summarized in Table 2.

Table 2: Barriers and enablers to the textile industry transition to the circular model

Textile industry	Barriers	Enablers
Recycling process	complexity of textile waste stream lack of infrastructures technological limitation consumer behaviour	advancements in recycling technologies regulatory support industry collaboration consumer education and engagement

The principal barriers to textile waste recycling are represented by: (i) complexity of textile waste stream, textile waste streams are various and complex, comprising a wide range of materials, colors, and finishes; sorting and processing these materials pose challenges, particularly when dealing with mixed fibres or contaminated textiles; (ii) lack of infrastructures, generally the infrastructures for textile waste collection, sorting, and recycling is underdeveloped or inadequate; limited access to recycling facilities and collection points hinders the efficient recovery of textile waste; (iii) technological limitation, some recycling technologies for textiles are still in the early stages of development or require further refinement to achieve commercial viability; high costs, energy requirements, and scalability issues may avoid the adoption of advanced recycling methods; (iv) consumer behaviour, consumer attitudes and behaviors play a crucial role in textile waste recycling;

low awareness of recycling options, convenience barriers, and ingrained consumption patterns contribute to low recycling rates and high levels of textile waste generation. Also, considering the textile production process, several phases represent barriers to the shift to circular economy model. The dyeing process significantly affects the recyclability of textiles. Moreover, designing garments with colorfastness in mind can enhance the quality of recycled fibres and materials. Effective sorting and separation of textile waste are critical for maximizing recycling efficiency. Design plays a crucial role in the recyclability and sustainability of garments. Designing for disassembly, using detachable components, and avoiding complex constructions can facilitate end-of-life recycling and promote circularity. Additionally, incorporating durable and high-quality materials, such as organic cotton or recycled fibres, can extend the lifecycle of garments and reduce the need for frequent replacements, thereby minimizing textile waste generation. The main enablers of textile waste recycling consist in: (i) advancements in recycling technologies, ongoing research and development efforts are driving innovation in textile recycling technologies; emerging technologies such as chemical recycling, enzymatic processes, and advanced sorting techniques can improve the efficiency and effectiveness of textile waste recycling; (ii) regulatory support, government policies and regulations can incentivize and mandate textile waste recycling practices; extended producer responsibility schemes, landfill bans on textiles, and financial incentives for recycling initiatives can create a supportive policy environment for textile recycling; (iii) industry collaboration, collaboration among stakeholders across the textile value chain, including manufacturers, retailers, brands, and recyclers, is essential for implementing adequate solutions to textile waste management; partnerships and industry initiatives can drive innovation, scale up recycling infrastructure, and promote circular business models; (iv) consumer education and engagement; increasing consumer awareness of the environmental impact of textile industry and management and the importance of recycling is fundamental to change the behaviour and foster a culture of sustainability; education campaigns, labelling schemes, and convenient recycling options can empower consumers to make more sustainable choices.

6.4.3 Case studies

In this section several case studies are reported as examples of circular economy transition in the textile manufacturing process in order to highlight the implementation of ethical approaches within the textile waste management.

6.4.3.1 Dyeing sludge

The textile dyeing sludge reutilization has been studied in order to evaluate the potential benefits of the waste reduction and energy recovery compared to the GHG emissions. Dyeing sludge reutilization considers different strategies, as sludge to energy, sludge to brick, sludge to biochar. Textile dyeing sludge is considered as hazardous waste and the risk of organics leaching from landfills or the air pollution connected to the coal incineration power plant is relevant. In this context, alternative strategies to reuse textile dyeing sludge must be evaluated in order to reduce the negative impact on air, soil and water contamination connected to the incineration process. Sludge co-incineration in coal-fired power plants could substitute fossil fuel consumption to generate power, steam, and compressed air with the advantage of reducing GHG emissions. Sludge-to-brick is accomplished in the tunnel kiln, which has the advantages of long service life and stable performance. However, the requirement of energy during this process leads to the increasing of GHG emission reducing the beneficial effects connected to the reduction of waste disposal. Sludge-to-biochar option could generate biochar for soil amendment, bio-oil, and pyrolysis gas with low investment costs. Additionally, the risk due to the heavy metals dispersion are neutralized as the biochar matrix fixes the heavy metals included in the textile dyeing sludge. However, the long-term interaction between biochar and soil must be deeply investigated (Gong Y. et al. 2023).

6.4.3.2 Cotton

Cotton is the first natural fibre and the second most consumed fibre globally following polyester. The production of cotton fibres involves the high consumption of pesticides and fertilizers for the cultivation and dyes of various origin impact significantly on human health and the environment. Considering the environmental concerns, the recycling of cotton fibres becomes essential. The efficiency of fibre recovery from cotton fabric waste can vary depending on the specific processes and technologies employed (Edirisinghe L. M. et al. 2023). Cotton is primarily composed of cellulose and has a high valorisation capacity. It is suitable for biofuel, biochemical, and bioenergy production. However, the textile recycling rates are very low and the presence of mixed fibres makes difficult the cotton recovery from the textile waste. Enforcing more specific sorting strategies and encouraging the innovative design for disassembly, textile waste becomes homogeneous and can be considered a precious material due to its high cellulose composition and good quantity (Stella F. et al. 2024). As cotton fibres are essentially pure and natural cellulose, the fibres can be hydrolysed into bio-based building blocks such as glucose, which can then be upcycled into new high-end value-added products. However, the presence of dyes affects negatively on cotton recycling. Different strategies can be considered to repurpose or upcycle cotton waste, i.e. enzymatic hydrolysis. It is an innovative and

powerful pre-treatment; even if the chemical requirements are very low, the need of heat energy impact negatively considering the GHG emissions (Vera R. E. et al. 2022). Specifically, for cotton-denim use, reactive, direct and indigo dyes are used. These dyes must be removed from the fabric before the recovery process in order to avoid the air, soil and water pollution connected to the heavy metals dispersion. The process to remove dyes from cotton waste consists in the enzymatic degradation. This process must be monitored considering temperature and acidity parameters in order to control the dyes stability. As cotton is one of the main components of denim production, there has been an increasing pressure to the fashion industry to increase the recycling potential of cotton to answer to the shift from traditional textile production process to circular model and the market demand of denim (Shamsi M. A. et al 2023).

6.4.3.3 Denim pants, bed sheets, and silk curtains

Three different post-consumer textiles, denim pants, bed sheets, and silk curtains are used to reinforce polypropylene. The textile waste is cut into strips and sent to a co-rotating extruder and simultaneously fibrilled into fibres and compounded with the polymer. The long fibres thermoplastic process has not required any chemical or mechanical pre-treatment. The optimal percentage results in 30% of recycled fibre allowing the homogeneous fibres dispersion and distribution. The addition of recycled fibres leads to positive effects on the mechanical properties of the composite. Continuing the addition of the recycled fibre, the flowability of the blend is reduced, specifically using denim strips. The use of different textile waste changes the colour, so different coloured composites can be produced to obtain cups and bottoms (Rosenstock Voltz L. et al. 2023).

6.4.3.4 Jute and cotton

Jute and cotton waste at a ratio of 25% to 75%, respectively are used as by-products to produce composite reinforced materials with good impedance matching, high green shielding indices, reflection-absorption, light weights, corrosion resistance, flexibility, and easy processing. Electromagnetic interference shielding is a method to prevent the transfer of electrical and magnetic waves from one location to another. Conductive or magnetic material are usually used and involve the absorption or reflection of waves. Electromagnetic interference shielding materials are generally made of metal and are characterized by high electrical conductivity. Hence, carbon materials, textiles and their composites are also used due to their excellent flexibility, electrical properties, environmental friendliness, and chemical inertness. These recycled materials represent a valid alternative to heavy and expensive metals. Textiles with electromagnetic shielding functions have a significant range of applications in daily and professional use, i.e. for military and civic applications,

but also to produce super capacitors, batteries, and sensors. The use of textile waste to produce high value composite reinforced materials represents an example of circular economy model aimed at reducing the consumption of natural resources with the use of by-products that otherwise have followed the landfill disposal. This ethical and ecological behaviour contributes to the reduction of the high amount of waste in a circular and sustainable perspective (Sert S. et al. 2023).

6.5 Conclusion

This paper shows the main critical issues related to the textile production and consumption and textile waste generation. The research considers the textile production process focusing on the fast fashion model as it is strictly related to the huge quantities of textile products that become faster textile waste. By recycling textile waste, the raw material consumption and the textile waste production are minimized. The analysis of the textile production process leads to the definition of the concerns and strategies that facilitate the implementation of ethical and sustainable approaches.

The textile industry has largest economic significance, however it represents a heavy polluter considering the high water, chemical and energy requirements of the production process. Additionally, the rise of fast fashion has intensified the overconsumption and the increasing of the textile waste amount to be treated in landfill or incinerator. Collaborative actions will mitigate the negative environmental impact of the textile industry through the implementation of green technologies in the textile production process favouring the re-evaluation of clothing design, the reinforcement of the consumers' environmental consciousness, the standardization of guidelines, strategies and laws. However, several barriers and enablers influence the effectiveness and scalability of textile waste recycling initiatives. The principal barriers to textile waste recycling are represented by: (i) complexity of textile waste stream, (ii) lack of infrastructures, (iii) technological limitation, (iv) consumer behaviour. Additionally, the use of chemicals during dyeing process and the effective sorting and separation significantly affects the recyclability of textile waste. The main enablers of textile waste recycling consist in: (i) advancements in recycling technologies, (ii) regulatory support, government policies and regulations, (iii) industry collaboration, (iv) consumer education and engagement. The increase in the sustainable consumption of the consumers facilitates the decision process in favour of ecological, recycled and easy disassembled textiles. Finally, the introduction of clear regulations and guidelines and the implementation of green and eco-friendly technologies are fundamental to build a sustainable textile waste management system maximizing the beneficial effects connected to the transition to a circular economy perspective. Several case studies show the reduction of the negative impact of the textile production process on human health and the environment through the application of circular strategies. Specifically, dyeing sludge has been used

to obtain energy, bricks and biochar; post-consumer denim pants, bed sheets and silk curtains are used to reinforce polypropylene; jute and cotton wastes are used as by-products to produce composite reinforced materials representing a valid alternative to heavy and expensive metals. These examples of textile waste reuse to produce high value products aims at reducing the consumption of natural resources and the reduction of the high amount of waste in a circular and sustainable perspective. As cotton is the first natural fibre and the second most consumed fibre globally and considering its natural valuable composition, the recycling of cotton fibres becomes essential.

Future developments of this research will concern a deeper study of other business model within the textile production process. Also, cotton waste management will be analysed considering the social, economic and environmental advantages and disadvantages comparing the traditional and the circular textile production processes.

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7. Towards Ecological Polycarbonate: Strategies for Reuse and Waste Reduction in a Circular Economy Perspective

Note: This chapter is based on a conference paper

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XXIX Summer school “Francesco Turco” – Industrial System Engineering

Polycarbonate (PC) is a widely used thermoplastic. Specifically, PC sheets are used in various industries as roofing due to their durability and versatility. However, their widespread use also leads to significant waste generation. Considering PC characteristics and high availability, it presents an opportunity in the sustainability field within a circular economy approach. This paper defines the strategies allowing the reuse of PC sheet waste, with a focus on promoting waste reduction. We examine current PC waste management highlighting the environmental impact of conventional disposal methods and the need for innovative approaches to extend the materials end-of-life favoring the realization of a closed-loop system. Through an analysis of current practices, this research detects the main strategies favoring an alternative approach to PC waste disposal consisting in the reuse of PC sheet as a by-product to realize ecological products with different intended use, i. e. furnishing accessories. These strategies include designing for disassembly, establishing efficient reverse logistics channel, standardization of circular business model, considering the PC production process. Also, the detection of the technical and the mechanical performances and the aesthetical characteristic of PC waste must be analyzed to evaluate the feasibility of the reuse. By integrating these strategies, stakeholders can work towards a more sustainable PC sheet usage, minimizing environmental impact due to the quantities of PC waste production and maximizing the value derived from PC recovery as an alternative to traditional PC. Future development of this research will deal with the study of the reuse of PC waste to obtain ecological novel PC sheet through the evaluation of mechanical and technical performances.

7.1 Introduction

Plastic production has surged dramatically since its inception in the early 20th century, revolutionizing industries and daily life worldwide. The versatility, durability, and affordability of plastics have made them integral to modern society, with applications ranging from packaging and construction to healthcare and electronics [1, 2]. However, this widespread use has come at a significant cost to the environment. The exponential growth in plastic production has led to a

corresponding increase in plastic waste generation, posing serious environmental challenges. Plastic waste, notorious for its persistence in the environment, accumulates in landfills, pollutes oceans and endangers wildlife. Plastic pollution disrupts ecosystems by altering habitats, blocking waterways, and introducing toxins into the environment. Plastics degrade into smaller particles called micro-plastics through weathering and fragmentation processes. These micro-plastics permeate the environment, contaminating water, soil and air, posing risks to aquatic and terrestrial ecosystems as well as human health. In 2016, between 19 to 23 million metric tons of plastic waste were estimated to have entered the global aquatic ecosystem which represented an increase on the previous estimate of 4.8–12.7 million metric tons in 2010 [3]. The urgency to address plastic waste generation and disposal has never been greater, as the consequences of unchecked plastic pollution become increasingly apparent [4]. While plastics offer numerous benefits, their production and use have significant environmental impacts connected to the resources depletion, energy consumption and air, water and soil contamination. Plastics are derived from fossil fuels, i.e., crude oil, natural gas, contributing to resource depletion and reliance on non-renewable sources. The production process, including polymerization and plastic molding, requires substantial energy inputs, leading to greenhouse gas (GHG) emissions and exacerbating climate change. Also, several additives and chemicals present in plastics, such as phthalates and bisphenol A (BPA), can leach into the environment, posing risks to human health and wildlife. Plastic manufacturing facilities release pollutants into the air, water, and soil, posing risks to human health and ecosystems. Additionally, plastic waste, if improperly managed, contaminates terrestrial and marine environments, harming wildlife and disrupting ecosystems [5]. Plastic waste generation has reached alarming levels globally, driven by various factors ranging from consumption patterns to inadequate waste management systems. Understanding the complexities surrounding plastic waste generation and disposal is crucial for addressing the environmental and health challenges posed by plastic pollution. The main factors contribution to plastic waste generation are associated to: (i) single-use culture, bags, bottles, and packaging materials has significantly contributed to plastic waste accumulation and convenience-driven consumption habits exacerbate the problem; (ii) packaging, excessive packaging designed for short-term use and overuse of plastic materials contributing to waste generation; (iii) lack of recycling infrastructure, inadequate recycling infrastructure and low recycling rates result in a significant portion of plastic waste ending up in landfills or being incinerated, rather than being recycled or repurposed; (iv) globalization and urbanization, rapid urbanization and industrialization, coupled with globalization of consumer goods, have led to increased consumption and disposal of plastic products, particularly in densely populated urban areas [6]. Addressing the environmental impact of plastic production and use, the implementation of effective waste management strategies, investment

in recycling infrastructure, promotion of sustainable alternatives to single-use plastics, and heightened public awareness and education on plastic excessive use are necessary to reduce their negative impact on human health and the environment. Only through collaborative efforts the adverse effects of plastic pollution can be mitigated favouring the transition towards a more sustainable waste management paradigm. Among the different typologies of plastics, polycarbonate (PC) stands out as a prominent and widely utilized type. Known for its exceptional strength, transparency, and heat resistance, polycarbonate finds applications in various sectors, including automotive, electronics, and construction. Its versatility and durability make it indispensable in modern manufacturing processes [7, 8]. However, the environmental impact of PC, like other plastics, cannot be ignored. The linear economy model, take-make-dispose, typical of plastic production and consumption is inherently unsustainable. Approximately 4.92 million tons of PC are produced annually. Unfortunately, only approximately 10% of plastic waste is recycled, while the remaining portion is either incinerated, landfilled, or left to persist in ecosystems [6, 9]. Recognizing this, the plastic and PC industries are increasingly turning towards sustainability and circular economy principles. Sustainability entails minimizing resource consumption, reducing environmental impact, and promoting social responsibility throughout a product's lifecycle. Circular economy principles advocate for the continuous use and regeneration of resources, aiming at eliminate waste and maximize resource efficiency. Implementing these principles in plastic and PC industries is crucial for mitigating environmental damage, preserving natural resources, and fostering a more sustainable future. In this paper, we consider the complexities of plastic production and use examining the challenges posed by plastic waste generation and disposal. Through the evaluation of the different characteristics and applications of plastics, specifically PC and PC sheets, this paper aims at underling the need to turn to more sustainable and responsible approach to plastic and PC utilization applying the circular principles.

7.1.1 PC production process

Plastic production involves complex processes that transform raw materials into a wide array of synthetic polymers with different properties. The primary methods utilized is polymerization, where monomers, the building blocks of polymers, are chemically bonded together to form long chains or networks. Polymerization can occur through various techniques, including polymerization of monomers and condensation polymerization. In the first case, monomers such as ethylene, propylene, vinyl chloride, and styrene undergo polymerization to form polymers like polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS), respectively. The second process involves the reaction of monomers with functional groups, i.e. hydroxyl, carboxyl, that

undergo elimination of small molecules like water or alcohol to produce polymers like polyethylene terephthalate (PET) and nylon. Each type of polymers has distinct properties that makes it suitable for specific applications. Specifically, PC is a versatile and durable thermoplastic polymer. It is synthesized through a polymerization process involving bisphenol A (BPA) and phosgene or its derivatives. This process typically occurs in a controlled environment, where BPA and phosgene react to form linear PC chains. The resulting polymer can then be processed into various forms, including sheets, films, and moulded parts, to meet diverse industrial and commercial needs. PC production primarily involves the following phases: (i) synthesis of BPA from phenol and acetone through condensation reactions; (ii) polymerization, BPA and phosgene undergo a polycondensation reaction to form PC chains; (iii) processing, the PC resin is processed into desired forms using techniques such as extrusion, injection molding, or thermoforming. The main characteristics of PC consist in:

- high impact resistance, with remarkable toughness and resilience, PC exhibits resistance to impact and mechanical stress, making it ideal for safety glazing, protective equipment, and automotive components;
- transparency: with excellent optical clarity and transparency comparable to glass, PC is favoured for applications where visibility is essential, such as windows, lenses, and display screens;
- lightweights, despite its strength, PC is significantly lighter than glass, making it easier to handle and transport while reducing structural load requirements in construction and automotive applications;
- UV resistance, UV-stabilized PC formulations offer long-term resistance to UV radiation, preventing yellowing, degradation, and loss of mechanical properties when exposed to sunlight;
- heat resistance, PC maintains its structural integrity and properties over a wide temperature range, withstanding temperatures up to approximately 130°C, depending on the grade;
- chemical resistance, PC demonstrates resistance to many chemicals, including acids, bases, and solvents, enhancing its suitability for diverse industrial environments;
- thermal insulation, PC possesses inherent thermal insulation properties, contributing to energy efficiency and climate control in building applications;

easy of fabrication, PC can be easily moulded, machined, and formed into complex shapes, allowing for versatile design possibilities and efficient manufacturing processes [10, 11].

These exceptional properties lead the suitability of PC for multiple industrial, manufacturing, construction application. PC is used in automotive applications such as headlight lenses, interior trim components, and exterior body panels. Its high impact resistance, transparency, and lightweight

nature contribute to improved vehicle safety and fuel efficiency. In the electronics industry, PC finds applications in manufacturing of smartphones, laptops, and electronic housings. Its excellent electrical insulation properties, coupled with optical clarity and scratch resistance, make it an ideal material for electronic device casings and displays. PC sheets are extensively utilized in construction for skylights, roofing panels, and glazing systems. Their high impact strength, UV resistance, and light transmission properties enhance building aesthetics while providing durability and energy efficiency. PC sheets specifically designed for industrial roofing applications offer superior weather resistance, thermal insulation, and light diffusion properties. These sheets are used in warehouses, greenhouses, and agricultural structures to optimize natural light transmission and energy savings [12].

The physical and chemical properties of PC products render this material a valid option in various fields. However, its disposal presents challenges and environmental implications that necessitate careful consideration and management. PC durability and resistance to degradation pose challenges in natural decomposition processes, an improper disposal of PC waste can persist in the environment for decades, augmenting the volume of waste in landfills and the dispersion of plastics in the ecosystems. Also, despite PC is technically recyclable, challenges exist considering the separation and recovery from other mixed plastic waste due to its similar properties to other plastics. This limitation contributes to low recycling rates and results in significant quantities of PC ending up in landfills or incineration facilities. Incineration requires significant energy inputs and emits GHG and pollutants, contributing to air pollution and climate change. Finally, the breakdown PC can release BPA into the environment. BPA is a known endocrine disruptor with potential adverse effects on human health and wildlife, raising concerns about the environmental impact of PC disposal. The environmental implications of PC disposal require concerted efforts to improve recycling infrastructure, develop innovative recycling technologies, and promote circular economy principles. Strategies such as designing for recyclability, enhancing collection and sorting systems, and incentivizing sustainable waste management practices can help minimize the environmental impact of PC and transition towards a more sustainable waste management paradigm.

7.2 Materials and method

This research analyses the plastic production process focusing on the production of PC products. The concerns and the strategies in favour of the transition to the linear business model to a circular and sustainable one are evaluated considering the main characteristics and properties of PC materials and the recycling technologies to reduce plastic waste. The reuse of PC sheets waste as valuable by-products is also considered in this research in order to realize ecological products with different

intended use. The state of art related to the plastic and PC industry has been conducted on the Science Direct and Scopus websites. Circular economy, sustainability, circular economy in the plastic industry, circularity of PC industry, PC sheets, use of PC waste as by-product are used as keywords in this research. The collection of data refers to the publications in the range 2014 to 2024, from which the scientific articles were selected. The majority of the references are related to the huge amount of plastic waste produced worldwide and the principal recycling technologies of plastic waste to reduce the waste volume sent to landfills and the consumption of natural resources. This results are connected to the higher sensibility to the sustainability issues as reported in the Agenda 2030 of the United Nations [13]. Several studies are considered in this research in which PC waste is analysed in order to reach the rheological, chemical and mechanical properties supporting the reuse of PC waste as a valuable alternative to raw materials. Also, this paper shows a case study in which different scraps of PC sheets are tested to define their properties and characteristics favouring their reuse replacing raw materials as an example of circularity.

7.3 Results and discussion

This section introduces the results of the literature review on the transition to circular economy models within the plastic and PC industries. The information refers to various recycling technologies of plastic waste favouring the application of sustainable practices. Finally, the strategies of PC sheets reuse to obtain innovative and ecological PC products are reported.

7.3.1 Recycling technologies

Plastic recycling plays a fundamental role in mitigating environmental impacts associated with plastic waste accumulation. Mechanical and chemical recycling are two primary methods employed to convert post-consumer plastic waste into reusable materials. Each method offers distinct advantages and challenges, contributing to the evolving landscape of plastic recycling technologies [14, 15]. Specifically, mechanical recycling retains the inherent properties of PC while reducing the need for raw materials and diverting waste from landfills. Additionally, the distributive recycling in additive manufacturing (DRAM) represents an innovative approach to recycling plastic waste, including PC. This method holds significant promise for enhancing sustainability in both plastic recycling and additive manufacturing industries by incorporating PC directly into additive manufacturing process [16, 17]. Generally, plastic recycling still faces several challenges, including economic viability, contamination issues and lack of infrastructures and investments. Many recycling technologies, especially chemical recycling, face challenges related to cost competitiveness and scalability compared to traditional virgin plastic production. Economic issue related to plastic recycling leads to

the necessity to enforce upcycling strategies involving the transformation of plastic waste into higher-value products with enhanced functionality or aesthetic appeal. Also, the contamination of plastic waste streams with non-recyclable materials, additives, and residues hinders recycling efficiency and reduces the quality of recycled materials. These barriers affect the expansion and adoption of plastic recycling initiatives limiting the access to recycling facilities and the investments in recycling technologies. Table 1 shows the advantages and the disadvantages related to the application of the different plastic recycling processes.

Table 2: Plastic waste recycling processes

Recycling process	Advantages	Disadvantages
Mechanical recycling	Retained plastics quality	Suitable specifically for rigid plastics
Chemical recycling	Processability of mixed or contaminated plastics	High energy and economic requirement
DRAM	High flexibility in products development	Lack of infrastructures and investments

7.3.1.1 Mechanical recycling

Mechanical recycling involves physical processes to reclaim plastic waste by sorting, shredding, melting, and reforming it into new products. Plastic waste is collected from various sources and sorted based on resin type, colour, and other properties to ensure compatibility during recycling. The sorted plastic waste is shredded into smaller pieces or flakes to increase surface area and facilitate further processing. Shredded plastic flakes undergo cleaning and washing processes to remove contaminants, i.e. dirt, labels, and adhesives. Cleaned plastic flakes are melted and extruded into pellets or granules, which serve as raw materials for manufacturing new plastic products. Mechanical recycling is widely employed for rigid plastics such as PET bottles, HDPE containers, and PVC pipes. It offers several advantages, including energy savings, resource conservation, and reduced GHG emissions compared to raw plastic production.

7.3.1.2 Chemical recycling

Chemical recycling, also known as feedstock recycling or advanced recycling, involves breaking down plastic polymers into monomers or other valuable chemicals through chemical processes. Chemical recycling methods include pyrolysis and depolymerisation. Pyrolysis involves heating plastic waste in the absence of oxygen to break down long polymer chains into smaller molecules, such as gases, liquids, and waxes. These products can be used as feedstocks for the production of new plastics or other chemicals. Depolymerisation processes chemically break down plastic polymers into their constituent monomers using catalysts or solvents. The resulting monomers can be purified and reused to produce raw-quality plastics. Chemical recycling offers several advantages over mechanical recycling, including the ability to process mixed or contaminated plastic waste streams, depolymerize complex polymers, and produce high-value chemicals with potential applications beyond plastic production. Additionally, chemical recycling can complement mechanical recycling by addressing plastic waste that is currently unrecyclable through conventional methods.

7.3.1.3 DRAM

DRAM involves the integration of recycled plastic materials, such as PC, into the feedstock used in additive manufacturing, commonly known as 3D printing. The process typically consists of the following steps:

- plastic waste collection, plastic waste, including discarded PC products or scraps, is collected from various sources such as manufacturing facilities, consumer recycling programs, or post-consumer waste streams;
- sorting and pre-processing, the collected plastic waste undergoes sorting based on resin type, colour, and contamination level; pre-processing steps, such as shredding or granulation, are then performed to prepare the plastic waste for further processing;
- material extrusion/additive manufacturing, the processed plastic waste is introduced into the filament or powder feedstock used in additive manufacturing systems; through material extrusion or powder bed fusion, the recycled plastic material is deposited layer by layer to create 3D objects or components;
- quality control and testing, that measures are implemented to ensure that the recycled plastic material meets specified performance standards and dimensional accuracy.

Additive manufacturing enables the production of complex geometries and customized designs, offering greater flexibility in product development and reducing material waste compared to traditional manufacturing methods. Also, DRAM reduces the demand for raw materials by repurposing plastic waste, including PC, into new products. The use of recycled PC materials in

additive manufacturing can potentially lower production costs compared to using raw materials, contributing to economic sustainability. This practice preserves natural resources and reduces energy consumption and GHG emissions associated with traditional plastic production processes. By diverting PC waste from landfills and incineration, DRAM helps mitigate environmental pollution and reduces the environmental impact of plastic waste disposal. DRAM aligns with the principles of the circular economy by closing the loop on plastic waste, transforming it into valuable resources for manufacturing new products. Traditional recycling methods often involve downcycling or repurposing plastic waste into lower-value products, rather DRAM seeks to close the loop by transforming recycled plastics, including PC, into high-quality materials for additive manufacturing. PC represents a valid material for the reuse in additive manufacturing due to its multiple excellent characteristics. The high mechanical resistance, heat resistance, durability, transparency and versatility enhance PC specifically suitable for DRAM allowing the realization of complex and durable products. By incorporating recycled PC into additive manufacturing processes, DRAM maximizes the value of plastic waste creating sustainable solutions for both plastic recycling and manufacturing industries in a circular perspective [18, 19].

7.3.2 Strategies of PC waste reuse

PC recycling involves several pre-treatment methods and analytical techniques to assess material properties and ensure the quality of recycled products. Understanding these processes is essential for optimizing recycling efficiency and promoting sustainable plastic waste management practices [15]. Pre-treatment methods are employed to prepare PC waste for recycling by removing contaminants, improving material purity, and enhancing processability. Common pre-treatment methods include (i) sorting and cleaning, PC waste is sorted based on resin type, colour, and contamination level to ensure compatibility and consistency in recycling processes; cleaning involves removing dirt, labels, adhesives, and other impurities from the surface of PC waste through washing, scrubbing, or chemical treatments; (ii) size reduction, PC waste is mechanically shredded or granulated into smaller pieces to increase surface area and facilitate subsequent processing steps, such as melting, extrusion, or injection molding; (iii) decontamination, i.e. thermal or chemical treatments, are employed to remove residual contaminants, additives, or degradation products from PC waste, ensuring the purity and quality of recycled materials. Proper pre-treatment of PC waste is critical for maximizing recycling

efficiency, reducing energy consumption, and producing high-quality recycled products with required properties.

7.3.2.1 Thermal analysis

Thermal analysis techniques, such as thermogravimetric analysis (TGA), Fourier-transform infrared spectroscopy (FTIR) and differential scanning calorimetry (DSC), are used to characterize the thermal properties, stability, and degradation behaviour of PC materials.

TGA measures changes in weight as a function of temperature or time under controlled heating conditions. During a TGA experiment, a small sample of PC is heated gradually, and any weight loss is recorded. The temperature at which weight loss occurs indicates the onset of thermal degradation. It provides valuable information about the thermal stability, degradation temperature, and decomposing kinetics of PC materials, helping to optimize processing parameters and assess material quality. This information is crucial for understanding the thermal stability of PC and optimizing processing conditions to prevent degradation during manufacturing or recycling processes.

FTIR spectroscopy is a technique used to analyse the chemical composition and molecular structure of materials by measuring the absorption of infrared radiation. In the case of PC, FTIR analysis can provide detailed information about its chemical bonds, functional groups, and molecular structure. During an FTIR analysis of PC, the sample is exposed to infrared radiation over a range of frequencies, causing molecular vibrations characteristic of different chemical bonds. The resulting spectrum provides a unique fingerprint of the sample's molecular composition, allowing identification of specific functional groups such as carbonyl groups, aromatic rings, and carbonate linkages present in PC. By combining TGA and FTIR analysis, researchers can gain comprehensive insights into the thermal degradation behaviour and chemical composition of PC materials. This information is invaluable for various applications, including polymer characterization, quality control, and process optimization in industries such as automotive, electronics, and construction. Additionally, FTIR analysis plays a crucial role in understanding the behaviour of PC during recycling processes, guiding the development of efficient recycling technologies and promoting sustainability in the plastics industry.

DSC analysis is used to study the thermal properties of materials, including PC. DSC provides valuable insights into the thermal behavior, transitions, and stability of PC over a range of temperatures. In DSC analysis, a small sample of PC is heated or cooled at a controlled rate while measuring the heat flow into or out of the sample relative to a reference material. The difference in heat flow between the sample and the reference material is plotted as a function of temperature. DSC measures the heat flow associated with thermal transitions, such as melting, crystallization, and glass

transition, in PC samples as a function of temperature. DSC analysis enables the determination of key thermal properties, including melting temperature, heat capacity, and degree of crystallinity, which influence material processing and performance. Thermal analysis techniques play a crucial role in understanding the thermal behavior and processing characteristics of PC materials, guiding process optimization and quality control to ensure the consistency and purity of PC materials in recycling and manufacturing operations. Specifically, DSC leads the obtaining of various parameters: (i) glass transition temperature (T_g), temperature at which the polymer transitions from a glassy, rigid state to a rubbery, more flexible state; the glass transition appears as a step change in heat capacity, indicating the onset of molecular mobility in the polymer chains and is often used to characterize the mechanical and processing properties of PC; (ii) melting temperature (T_m), PC is a thermoplastic polymer that exhibits a distinct melting transition when heated above its melting temperature, the melting temperature obtained from DSC analysis corresponds to the temperature at which the crystalline regions within the PC structure melt, resulting in a peak in the heat flow curve; (iii) heat of fusion (ΔH), the amount of heat absorbed or released during the melting or crystallization of a material; in DSC analysis of PC, the area under the melting peak provides information about the energy required to melt the crystalline regions within the polymer structure; (iv) degree of crystallinity, PC typically exhibits low levels of crystallinity, by comparing the heat of fusion of a sample with the theoretical heat of fusion for 100% crystalline PC, the degree of crystallinity can be estimated.

7.3.2.2 Melt Flow index (MFI)

MFI analysis is a widely used method for evaluating the flow properties and processability of thermoplastic materials, including PC. MFI measures the flow rate of molten plastic through a standardized die under controlled conditions of temperature and pressure. The rate at which the molten polymer flows through the die is measured indicating the viscosity or melt flowability of the polymer, which influences its processing behavior in extrusion, injection molding, and other fabrication processes. This flow rate is reported in grams per 10 minutes (g/10 min) and is commonly referred to as the MFI value. MFI analysis is used for quality control purposes to ensure consistency in PC resin batches. Deviations in MFI values may indicate variations in polymer molecular weight, composition, or processing conditions, which can affect product performance and processing. MFI analysis helps optimize processing parameters such as melt temperature, screw speed, and injection pressure in plastic processing techniques like injection molding and extrusion. By adjusting these parameters based on MFI values, manufacturers can achieve desired flow behavior and product quality. Also, MFI values assist in the selection of PC grades suitable for specific applications. For example, high MFI grades are preferred for fast-cycling injection molding applications, while low

MFI grades are suitable for extrusion processes requiring precise control over flow behavior. The analysis leads to the obtaining of two parameters: melt flow rate (MFR) and melt flow index (MFI). MFR is expressed in g/10 min and represents the mass of molten PC resin that flows through the die in a specified time interval under standard conditions of temperature and pressure. Higher MFR values indicate greater flowability or lower viscosity of the molten polymer, while lower MFR values suggest higher viscosity and reduced flowability. MFI is calculated as the ratio of the MFR of the PC resin being tested to the MFR of a reference material. The MFI value provides a standardized measure of the flow properties of PC relative to other polymers or PC grades. MFI analysis enables the optimization of the processing parameters, ensures product quality, and selects suitable materials for various applications in industries such as automotive, electronics, and consumer goods.

7.3.3 Case study

The aim of this study is to evaluate the possibilities of reuse of PC sheets waste that would otherwise follow the disposal chain. Six different typologies of PC sheets and one sample of virgin grained PC have been analysed. The analysis has been conducted following several phases: (i) preliminary visual examination; (ii) characterization tests; (iii) evaluation of redeployment. The laboratory results allow the selection of the most suitable PC sheets waste to be used as a by-product in the internal production process but also in different production processes for the production of products with other intended use. The samples consist of a sample of grained material, virgin PC and six different typologies of sheets in terms of thickness, colour and shape, A, B, C, D, E, F (see Figure 1).

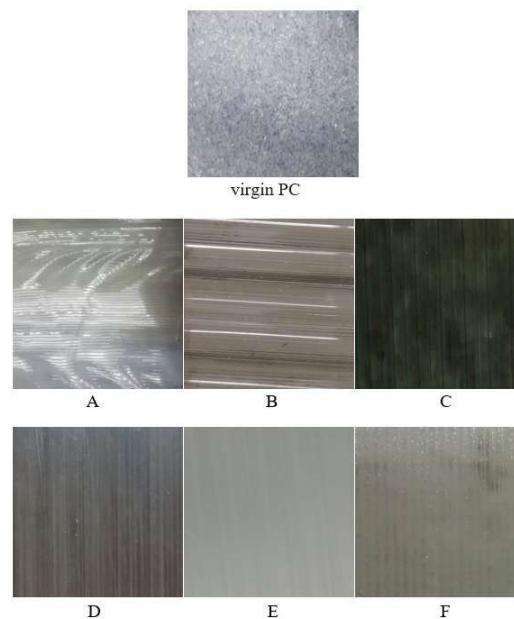


Fig. 3: PC samples

This phase allowed to define for the various types of PC the aesthetic characteristics as shown in Table 2.

Table 2: Visual examination of PC samples

Samples	Description	Visual examination
Virgin PC	Raw material	Transparent grained PC (2-3 mm)
Sheet A	Burned during production	Thin transparent sheet similar to the reference product
Sheet B	Coloured during production	Thin coloured sheet similar to the reference product
Sheet C	Exposed to environmental factors - ageing over 10 years	Honeycomb sheet considerably degraded and superficially covered by a film of residues
Sheet D	Mechanically damaged - ageing over 10 years	Honeycomb coloured sheet
Sheet E	Opal discarded from production	Honeycomb opal sheet
Sheet F	Transparent discarded from production	Honeycomb transparent sheet

The visual examination leads the first selection of the samples according to the standard colour. The characterization tests have been conducted testing the thermal properties on all samples. Table 3 shows the results relative to the glassy transition temperature for each sample.

Table 3: Thermal analysis (T_g)

Samples	T_g (°C)
Virgin PC	150.2
Sheet A	144.8
Sheet B	150.2
Sheet C	147
Sheet D	148.4
Sheet E	147.1
Sheet F	144.9

The thermal analysis showed transition temperature values compatible with those typical of the PC material; these values are similar to that of the virgin PC, except for samples A and F, whose result is lower. The execution of the IR analysis is very useful especially for the damaged plates in order to ascertain the presence of any structural and molecular differences compared to the virgin PC taken as a reference. The stability curves of slab samples are very similar to that of the virgin PC, so it is assumed that the molecular structure of slab samples and of the virgin PC is comparable. The evidence obtained from the visual examination and the thermal analysis allow a first selection of the samples to consider for the MFI analysis, specifically samples C and D. Future developments of this research will deal with the execution of the MFI analysis to complete the characterization tests. The results of the MFI analysis allow the definition of the feasibility of PC sheets waste reuse as a valuable by-product to realize innovative and ecological products preserving raw materials. In addition, the optimal percentage of by-products to be combined with the virgin PC will be defined. Also, mechanical and technical properties of the innovative and ecological samples will be detected in order to evaluate the feasibility of PC sheets waste as by-product to produce novel PC sheets.

7.4. Conclusion

Plastic production has led to widespread use across industries, but it has also resulted in significant environmental challenges, including plastic waste generation and disposal. PC, a prominent type of plastic, offers exceptional properties such as strength, transparency, and heat resistance, making it indispensable in numerous applications, including automotive, electronics, and construction. PC waste, generated from various sources such as manufacturing scrap, end-of-life products, and post-consumer plastics, presents opportunities for reuse and recycling to minimize environmental impact and promote resource efficiency. Implementing strategies for PC waste reuse can contribute to a more sustainable approach to plastic waste management. Sustainable practices, such as recycling and

circular economy principles, are essential for mitigating the environmental impact of plastic and PC industries, reducing natural resource consumption and promoting responsible waste management. Mechanical and chemical recycling methods play crucial roles in converting plastic waste into reusable materials, with advancements in recycling technologies offering opportunities for improving efficiency and sustainability. PC waste can be reused through various strategies, including mechanical recycling, upcycling, DRAM contributing to resource conservation and waste reduction efforts. Embracing sustainable practices, such as recycling, reuse, and adoption of circular economy principles, is paramount for mitigating environmental impact, preserving raw materials, and transitioning towards a more sustainable future. By prioritizing sustainability, stakeholders in these industries can minimize environmental impact, enhance resource efficiency, and promote social responsibility. The main strategies favouring the transition from the linear business model to the circular one are reported. Plastic waste reuse, specifically PC waste derived from PC sheets, is fundamental to reduce the volume of waste sent to landfills, the raw material consumption and the GHG emissions connected to the plastic production process. Finally, a case study is proposed as an example of PC waste reuse as a valuable by-product in a circular perspective. PC waste coming from PC sheets has been pretreated and analysed in order to evaluate the feasibility of reuse. The purpose is the realization of PC products with different intended use, i.e. furnishing accessories. Future development of this research will deal with the study of the reuse of PC waste to obtain ecological novel PC sheets through the evaluation of mechanical and technical performances.

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8. From waste to worth: optimizing polycarbonate recycling for eco-friendly product development

Note: This chapter is based on a published conference paper

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XXX Summer school “Francesco Turco” – Industrial System Engineering

The production of polycarbonate (PC) waste has become a pressing environmental concern due to the extensive use of PC materials across industries, including automotive, electronics, and construction. Despite its remarkable properties, such as high impact resistance, transparency, and heat resistance, PC contributes significantly to plastic waste accumulation, with only a small fraction currently being recycled. The durability of PC, while beneficial for product longevity, complicates natural degradation processes, leading to persistent waste in landfills and ecosystems. Furthermore, the breakdown of PC can release harmful substances, such as bisphenol A (BPA), posing risks to both environmental and human health. Reducing PC waste through effective reuse strategies not only minimizes landfill overflow but also preserves raw materials and lowers greenhouse gas emissions associated with virgin plastic production. This research investigates the reuse of PC sheets waste through a systematic characterization process, including thermal, molecular and flow analysis, to identify the most suitable recycled materials for eco-friendly products applications. This research identifies the ideal ratios for blending recycled PC with virgin PC to maintain structural integrity and aesthetic appeal. Additionally, the study investigates the feasibility of producing ecological PC with innovative design applications, such as eco-friendly furnishing accessories, emphasizing their mechanical performance and environmental benefits. The aim is to provide an example of ecological management of PC waste to promote circular economy principles, supporting industries in transitioning from linear production models to sustainable, resource-efficient practices, contributing to a greener future for PC applications.

8.1. Introduction

Plastic waste represents one of the most critical environmental concerns of the last century, with polycarbonate (PC) representing a significant portion due to its extensive use across various sectors such as automotive, electronics, and construction (Sitadewi et al. 2021). PC is a thermoplastic material favoured for its high impact resistance, transparency, and heat tolerance, but its resistance to degradation leads to persistent waste in landfills and natural environments. PC breakdown can release

bisphenol A (BPA), a hazardous compound posing threats to ecosystems and human health (Ye Liu et al. 2022, Prazler et al. 2022).

High versatility, durability and affordability are the main characteristics of plastic products, causing a widespread use that has a negative impact on the environment. Additionally, the single-use culture, the excessive packaging, the lack of recycling infrastructures lead to alarming amount of plastic waste generation. Also, the plastic production processes require high energy inputs that result in greenhouse gas emissions connected to the climate change (Arif et al. 2022, Liu et al. 2023). Nowadays, the majority of plastic waste is incinerated, landfilled or left in ecosystems due to the typical linear model of plastic production that is strongly unsustainable. The implementation of circular principles in plastic and PC production is mandatory to mitigate environmental damage and preserve natural resources. Plastic recycling technologies are fundamental to enforce the reuse of plastic waste as by-products to use in the same production process or to obtain products with different intended use. Mechanical recycling consists in reducing the waste size to facilitate further processing. Chemical recycling allows the possibility to process mixed plastic waste as involves the breaking down of plastic polymers into monomers. Distributive recycling in plastic manufacturing (DRAM) is an innovative approach to plastic waste recycling offering greater flexibility in product development and reducing material waste compared to traditional manufacturing methods. Also, this technology allows the reduction of raw materials demand contributing to environmental sustainability. By promoting the continuous use and regeneration of resources, circular economy aims at the minimization of waste, the maximization of resource efficiency and the preservation of natural resources (Parida et al. 2024). The reuse of PC sheet waste has been explored through preliminary visual and thermal analysis, identifying its potential as a by-product for ecological applications. Considering those findings, the aim is to promote the PC reuse by optimizing the blends between recycled and virgin PC to achieve sustainable products with reliable mechanical and aesthetic properties. This study represents a step toward circular economy implementation in the PC sector, proposing advanced strategies to reduce environmental impact and promote resource efficiency (Romani et al. 2023, Wu et al. 2024). Despite its recyclability, PC remains underutilized in circular strategies due to issues related to contamination, complex sorting, and degradation of material properties (Hoang et al. 2023). Mechanical and chemical recycling methods have shown potential, yet challenges persist in maintaining material integrity post-recycling. Recent approaches like DRAM and upcycling strategies provide innovative pathways to valorise PC waste (Ferreira et al. 2025, Reich et al. 2019, Sanchez et al. 2020). Plastic recycling is fundamental for the mitigation of the environmental impacts associated with plastic waste accumulation. However, economic issue considering the cost competitiveness of traditional plastic

production process hinders the diffusion of plastic recycling strategies and the transition from the linear business model to the circular one.

Characterization techniques allow the definition of the mechanical, chemical and aesthetic properties of plastic waste. Specifically, differential scanning calorimetry (DSC), Fourier-transform infrared spectroscopy (FTIR) and melt flow index (MFI) are essential to evaluate the feasibility of reusing recycled PC as by-product in the same production process or to produce ecological PC products with different intended use. These methods assess thermal transitions, chemical structure and flow behaviour respectively, ensuring that the recycled material meets the standards required for new applications. Additionally, several pre-treatments are required to process PC waste for recycling, i.e. sorting and cleaning, size reduction and decontamination. These pre-treatments aim at maximizing the recycling efficiency by producing high-quality by-products with excellent properties (Rosa-Saintz et al. 2023, Durante et al. 2017). The realization of ecological PC products is evaluated considering the reuse of PC sheets waste as valuable by-products. The state of art related to PC industry has been conducted on the Science Direct and Scopus websites. Circular economy in the plastic industry, circularity of PC industry, PC sheets, reuse of PC waste are used as keywords in this research. The collection of data refers to the publications in the range 2015 to 2025, from which the scientific articles were selected. The majority of the references are related to the various application of PC waste as by-product in order to enforce recycling plastic processes, the reduction of plastic waste volume sent to landfills and the consumption of natural resources. These studies support the reuse of PC waste as a valuable alternative to raw materials.

8.2 Materials and method

This paper aims at defining the most suitable PC sheet samples to use as by-product for the realization of ecological PC products with different intended use through the analysis of six PC sheets waste. The analysis of the samples follows a well-established hierarchical approach consisting in three different phases as reported in the framework of Figure 1. The preliminary visual examination allows the primary definition of the aesthetic characteristics of the samples, i.e. colour, transparency, opacity, sheet thickness variation. The characterization tests consist in the execution of the thermal analysis and the MFI analysis; in the first case, the combination of DSC performed with DSC214 Netzsch Polyma 402 and TFIR performed with Vertex 70 Bruker allows the definition of the thermal properties, the chemical composition and the molecular structure of the samples; in the second case, the flowability of the samples is detected using XNR-400C MF Indexer. Finally, the evaluation of redeployment consists in the comparison of the main results considering the colour, viscosity,

stiffness and shear strength of the various combination of the PC sheets waste with virgin PC in different ratios.

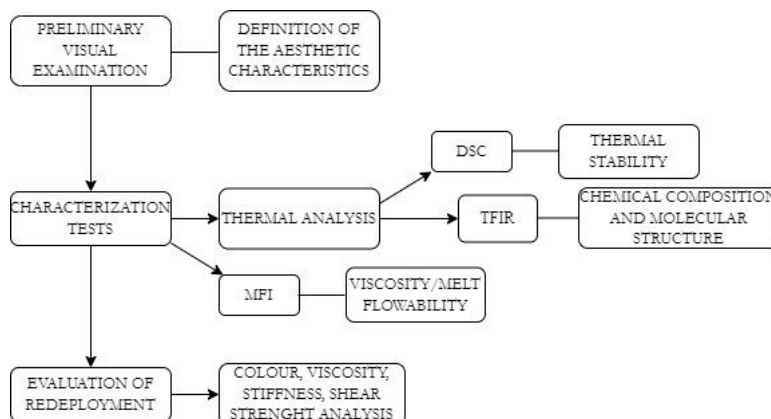


Fig. 4: Methodology of PC analysis

8.3 Results and discussion

This section introduces the results of the analysis conducted on six PC sheet samples compared to virgin PC to define the most suitable one to use as by-product. Also, the selected PC sheets have been combined with virgin PC in different ratios to evaluate the feasibility of PC sheets reuse to realize ecological products with different intended use. Two PC sheets (C and D) were identified as suitable candidates for reuse based on thermal and molecular characteristics similar to virgin PC. Sheet D demonstrated the highest potential due to its mechanical integrity and visual appearance. MFI values were higher for the PC sheets waste than for virgin PC, indicating some degradation but remaining within processable limits. Blending trials were performed in various ratios; the blend of Sheet D and virgin PC in the ratio of 30:70 provided optimal performance, combining structural quality and acceptable aesthetics.

8.3.1 Case study

The feasibility of PC sheets waste reuse as by-product has been validated for the production of ecological furnishing components. The results demonstrate that with proper selection and preparation, PC waste can be reintroduced into production without compromising product quality. This has direct implications for manufacturers seeking to integrate circular economy principles by reducing raw materials consumption and environmental impact. Virgin PC and six types of PC sheets (A, B, C, D, E, F) have been analysed in this research (see Figure 2). The samples present different thickness, colour and shape and have been selected considering the industrial availability of the products. The preliminary visual examination and the characterization tests have been performed to select the most suitable PC sheets to consider for the final phase of the investigation, the evaluation of redeployment. Each phase of the analysis is explained in the following sections.

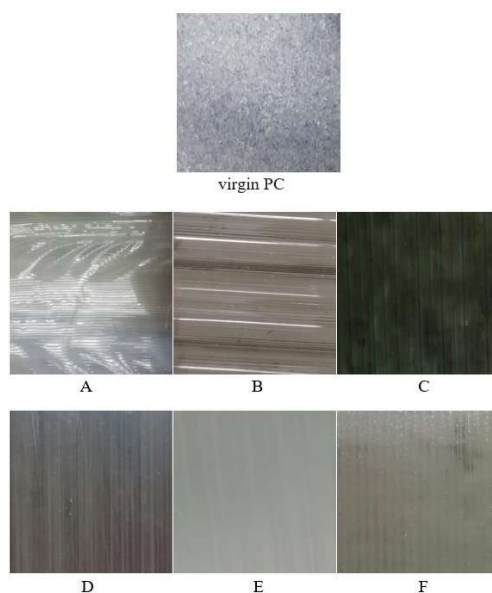


Fig. 2: PC samples

8.3.1.1 Preliminary visual examination

The results of the preliminary visual examination are reported in Table 1. Virgin PC is a transparent grained raw material in the range of 2-3 mm typically used to produce PC sheets for the construction sector. Sheet A is a burned scrap during the production process, it is thin and transparent, very similar to the reference material. Sheet B is a thin and coloured scrap similar to the reference material. Sheet C is a honeycomb scrap covered by a film of residues and considerably damaged as a consequence of the exposure to environmental factors for more than ten years. Sheet D is a honeycomb-coloured scrap mechanically damaged and used for over ten years. Sheet E and Sheet F are both honeycomb scraps discarded from production respectively opal and transparent. The significant colour deviation of Sheet B compared to virgin PC allows the first selection of the samples; however, DSC and TFIR analysis have been conducted for all PC sheets waste.

Table 3: Preliminary visual examination of PC samples

Samples	Description	Visual examination
Virgin PC	Raw material	Transparent grained PC (2-3 mm)
Sheet A	Burned during production	Thin transparent sheet similar to the reference product

Sheet B	Coloured during production	Thin coloured sheet similar to the reference product
Sheet C	Exposed to environmental factors - ageing over 10 years	Honeycomb sheet considerably degraded and superficially covered by a film of residues
Sheet D	Mechanically damaged - ageing over 10 years	Honeycomb coloured sheet
Sheet E	opal discarded from production	Honeycomb opal sheet
Sheet F	transparent discarded from production	Honeycomb transparent sheet

8.3.1.2 Characterization tests

The first part of the characterization tests consists in combining the results of the DSC and TFIR to reach the thermal behaviour and the molecular structure of the PC sheets waste. A small piece (1-2 cm) of the PC samples has been obtained from each sheet to measure the transition temperature from a rigid state to a flexible one and the absorption of infrared radiation.

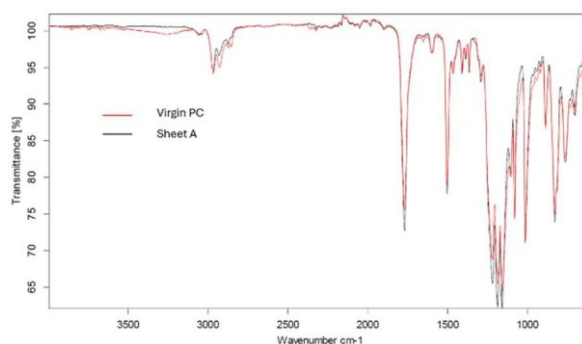
Thermal stability, chemical composition and molecular structure represent the results of the examination. The comparison of DSC and TFIR analysis allows the selection of the PC sheets to consider for the second part of the characterization tests. The MFI analysis has been performed on virgin PC and two selected PC sheets previously processed into granules.

The glassy transition temperature (T_g) of each sample is reported in Table 2. The results reported in this research represent the average value obtained from five measurements on each sample. Sheets A and F show lower T_g values (144.8°C and 144.9°C respectively) compared to virgin PC (150.2°C). These findings indicate potential material degradation. Sheets B and C showed significant colour deviation and surface contamination respectively; however, the T_g values are the same for sheet B and similar for sheet C (147°C) to the virgin PC one. Sheets D and E show T_g values (148.4°C and 147.1°C) similar to the reference material.

Table 2: Thermal analysis (T_g)

Samples	T_g ($^{\circ}\text{C}$)
Virgin PC	150.2
Sheet A	144.8
Sheet B	150.2
Sheet C	147
Sheet D	148.4
Sheet E	147.1
Sheet F	144.9

The structural degradation of the PC sheets is evaluated through the FTIR analysis. Figures 3-8 show the comparison between the stability curve of each PC sheets sample and the virgin PC one reported in the same graphs. The results related to the structural and molecular composition of the PC sheets are useful especially for the damaged scraps. Specifically, by comparing the results of sheets C and D with the virgin PC stability curve, it is possible to highlight the main differences connected to the environmental exposure and the mechanical stress. The stability curves of PC sheets are very similar to the virgin PC one taken as reference, so the molecular structures are comparable. These results highlight that the level of degradation has not significantly affected the molecular structure of the PC sheets waste, even though the exposure to environmental and mechanical stress. Considering the preliminary visual examination and the first part of the characterization tests, the findings allow the selection of the most suitable PC sheets waste to consider for the execution of the MFI analysis. Finally, these selected PC sheets have been tested in blending with virgin PC for the evaluation of redeployment.

**Fig. 3:** IR comparison – virgin PC and Sheet A

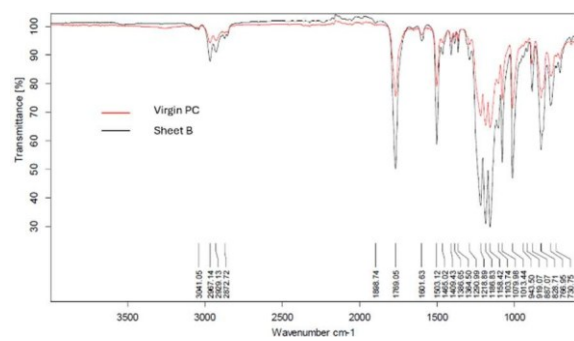


Fig. 4: IR comparison – virgin PC and Sheet B

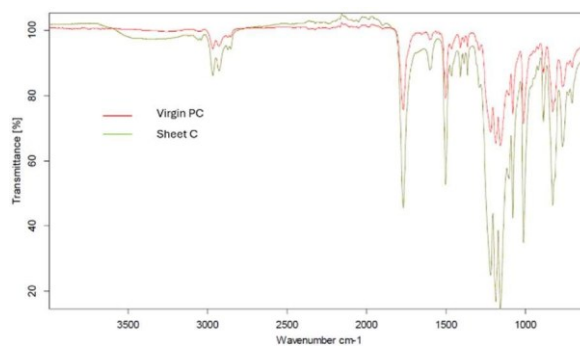


Fig. 5: IR comparison – virgin PC and Sheet C

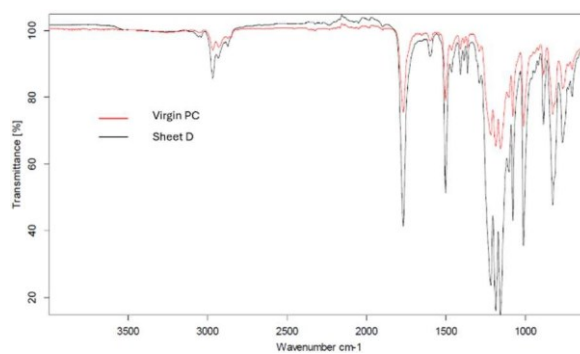


Fig. 6: IR comparison – virgin PC and Sheet D

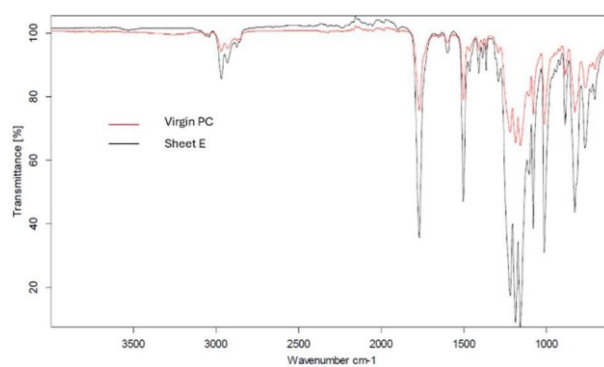


Fig. 7: IR comparison – virgin PC and Sheet E

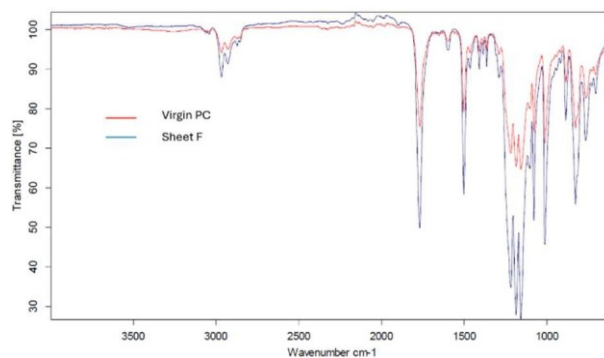


Figure 8: IR comparison – virgin PC and Sheet F

Sheets A and F have been discarded due to their level of degradation as shown by the T_g values, significantly different from the virgin PC one. Sheet B shows a relevant colour deviation from the reference material, and this affects the aesthetic characteristics of the ecological PC products eventually realized with this scrap. Sheets C, D and E present T_g values similar to the virgin PC one, even if a film of residues cover the surface of sheet C. Specifically, sheet E is a scrap discarded from production and is highly utilized as by-product in the same production process. Sheets C and D are both damaged for the long exposure to environmental and mechanical factors respectively, thus they consist in high volume of PC sheets waste sent to landfill. The aim of this research is the definition of the most suitable PC sheets waste to use as by-product for the realization of ecological PC products with different intended use. The case study represents an example of circular approach applied to the plastic and PC industries. Considering these aspects, the provenance, the availability and the thermal and chemical properties of the analysed PC sheets waste, the selection of the samples for the execution of the second part of the characterization tests refers to sheets C and D. The MFI analysis is useful to evaluate the flow properties of thermoplastic, especially PC. The flow rate of the molten PC gives information connected to the processability and the consistency of the material. Several pre-treatments are necessary for the samples suitability; specifically, washing, drying and shredding have been performed in order to clean and reduce the size of the samples. Sheets C and D have been processed into granules of 2-3 mm obtaining samples of 10-15 gr (see Figure 9).



Fig. 9: Grained sheets C and D

The results of MFI analysis on virgin PC and sheets C and D are reported in Table 3. The MFI values for sheets C and D are very similar (12.39 and 12.33 respectively) and considerably different from the virgin PC taken as reference (8.29). These findings are connected to the level of structural degradation of the sheets which affect the viscosity and the processability of the selected PC sheets waste.

Table 3: MFI analysis

Samples	MFI
Virgin PC	8.29
Sheet C	12.39
Sheet D	12.33

8.3.1.3 Evaluation of redeployment

The characterization tests performed on virgin PC and all PC sheets allow the selection of materials to use for the evaluation of redeployment. Sheets C and D have been selected to perform several pre-treatments to ensure the suitability of the samples for the MFI analysis. Finally, sheets C and D were blended with virgin PC in different increasing ratios in order to evaluate colour, viscosity, stiffness and shear strength of the different prototypes of ecological PC. Specifically, the blends of sheet C and virgin PC are in the ratios of 10:90, 20:80 and 30:70; the blends of sheet D and virgin PC are in the ratios of 5:95, 10:90, 20:80, 30:70 and 50:50. The blends of sheet D and virgin PC are higher than the blends of sheet C and virgin PC due to the superior aesthetic properties of sheet D; thus, the colour of the ecological PC products eventually obtained with this scrap result strictly similar to the colour of the reference material. The main results of the analysis conducted on the blended samples of sheet C and virgin PC are shown in Tables 4.

Table 4: Blending test results (sheet C: virgin PC)

Blending ratios	Stiffness	Viscosity	Shear resistance	Colour
10:90	Increased	Increased	Moderate	Yellow-green tint, surface streaks
20:80	Moderate	Moderate	Increased	Intensified colour, strong streaking
30:70	High	High	High	Darker coloration

As the percentage of granular sheet C increases, the stiffness and the viscosity increase. The formation of surface streaks is significantly more pronounced by reducing the percentage of virgin PC. The colour trend of the blends exhibits a yellow-green tint even at minimal ratios, becoming more intense as the proportion of sheet C increases. Figures 10-12 show the appearance of the resulting blended samples.



Fig. 10: Blended sample 10:90 (sheet C : virgin PC)



Fig. 11: Blended sample 20:80 (sheet C : virgin PC)



Figure 12: Blended sample 30:70 (sheet C : virgin PC)

The main results of the analysis conducted on the blended samples of sheet D and virgin PC are shown in Tables 5.

Table 5: Blending test results (sheet D: virgin PC)

Blending ratios	Stiffness	Viscosity	Shear resistance	Colour
5:95	Slightly increased	Slightly increased	Increased	Transparent
10:90	Moderate	Moderate	Increased	Slightly darker, visible streaks
20:80	Increased	Increased	High	Light yellow tint, surface streaks
30:70	High	High	High	Yellow tint, surface streaks
50:50	Very high	Very high	Very high	Dark yellow tint, moderate streaking

The samples obtained with sheet D exhibit a rise in viscosity as the percentage of granular sheet D increases, which consequently leads to greater stiffness. The increased viscosity contributes to the formation of surface streaks, while the enhanced stiffness improves the blends shear resistance. The colour of the blends becomes darker as the proportion of virgin PC decreases, although the blends remain sufficiently transparent as shown in figures 13-17.

**Fig. 13:** Blended sample 5:95 (sheet D : virgin PC)**Fig. 14:** Blended sample 10:90 (sheet D : virgin PC)



Fig. 15: Blended sample 20:80 (sheet D : virgin PC)



Fig. 16: Blended sample 30:70 (sheet D : virgin PC)



Fig. 17: Blended sample 50:50 (sheet D : virgin PC)

The comparison of the blends obtained by mixing virgin PC in different ratios with sheets C and D clearly indicates that sheet D is the most suitable PC waste to use as by-product. Sheet C, conversely, exhibits a high level of degradation, resulting in low-quality blends with aesthetic characteristics significantly deviating from the reference material considering the colour, even at minimal inclusion ratios. Among the five blends of sheet D, the 30:70 (sheet D : virgin PC) ratio shows the best results considering the amount of incorporation, aesthetic properties (colour and surface integrity), and mechanical performance. This blend offers an optimal solution, enabling substantial PC waste recycling without significantly compromising mechanical and aesthetic properties.

8.4. Conclusion

This study comprehensively addresses the feasibility of reusing PC sheets waste through detailed visual inspection, thermal and molecular characterization, and practical redeployment tests. The research contributes meaningfully to the development of sustainable plastic products by proposing a viable model for incorporating PC waste into new applications considering circular economy principles.

Initial analysis demonstrates that not all PC waste exhibits the same level of recyclability. Through preliminary visual examination, DSC and FTIR characterization, sheets C and D are identified as the most promising candidates for reuse, having thermal properties and molecular structures closely aligned with those of virgin PC. Also, sheets C and D are both damaged for the long exposure to environmental and mechanical factors respectively, thus they consist in high volume of PC sheets waste sent to landfill. Considering this factor, the selection of PC sheets waste to evaluate for redeployment represents an example of circular approach applied in the plastic industry, specifically in PC sector. Although, sheet C shows considerable surface degradation, its structural integrity allows for further investigation. Sheet D, conversely, exhibits both thermal stability and superior aesthetic properties, making it particularly suitable for blending trials.

MFI analysis reveals that sheets C and D have higher flow rates than virgin PC, indicating some degradation of polymer chain due to environmental exposure and mechanical damage. Nonetheless, their values remain within a workable range for blending, especially when pre-treatment processes such as cleaning, drying, and shredding are applied to enhance material consistency and cleanliness. The blending tests provide insight into the mechanical and aesthetic properties of the various ratios of sheets C and D with virgin PC. Blends containing sheet D outperform those with sheet C considering stiffness, viscosity, shear resistance, and colour. Notably, the 30:70 blend ratio (sheet D : virgin PC) emerges as the optimal solution, delivering a strong balance between recycled content and desirable product properties. This blend maintains adequate transparency, reduced surface streaking, and shows excellent mechanical performance, validating its suitability for use in the production of eco-friendly PC furnishing components.

Conversely, sheet C, due to its higher level of degradation and notable colour deviations, generates blends with compromised visual appeal and mechanical reliability, even at lower inclusion ratios. As a result, its application potential is more limited and would require further processing or pigmentation to meet aesthetic standards.

Overall, the findings confirm that targeted selection and characterization of PC sheets waste, combined with appropriate processing and blending strategies, can significantly reduce the demand for virgin plastics while enabling the development of high-quality, sustainable products. This

approach supports waste minimization, resource efficiency, and the broader adoption of circular economy models in industrial plastic applications.

Future developments of this research will include full mechanical testing, pilot scale manufacturing and life cycle assessment (LCA) to quantify environmental benefits and scalability.

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9. Energy Performance, Environmental Impact, and Life Cycle Assessment of Circular Industrial Strategies

The transition from linear production models to circular industrial systems requires robust quantitative evidence demonstrating not only technical feasibility but also environmental effectiveness, economic viability, and regulatory coherence. This section provides an integrated assessment of energy performance, greenhouse gas emissions, cost–benefit implications, and LCA outcomes associated with circular economy strategies based on the reuse of selected industrial by-products.

The analyses provide decision-support evidence essential for assessing the feasibility, scalability, and sustainability of circular economy projects within complex industrial systems. By integrating energy, environmental, and economic indicators, the aim is to connect the technical feasibility and the strategic industrial implementation.

9.1 Energy Performance Evaluation

Energy consumption represents one of the most significant contributors to environmental impact across industrial value chains. Several studies demonstrate that the reuse of industrial by-products leads to substantial energy savings, primarily due to the avoidance of energy-intensive upstream processes such as raw material extraction, synthesis, and primary transformation.

Specifically, the investigation highlights that: (i) ceramic manufacturing processes incorporating industrial residues exhibit reduced energy requirements associated with raw material preparation and waste treatment; (ii) textile recovery pathways reduce energy consumption by limiting the production of virgin fibers and related chemical processing; (iii) recycled polycarbonate applications show a marked reduction in cumulative energy demand compared to virgin polycarbonate, as polymerization and refining phases are partially or fully bypassed.

These findings confirm that circular economy strategies contribute to energy efficiency improvements across industrial value chains, supporting decarbonization objectives and industrial competitiveness.

9.2 Greenhouse Gas Emissions and Climate Impact

Greenhouse gas emissions, specifically carbon dioxide (CO₂), is usually evaluated to assess the climate change implications of circular versus linear production scenarios. The comparative assessments conducted within this research refers to the comparison between the production of virgin polycarbonate and recycled polycarbonate sheet. The results consist in:

- significant CO₂ emission reductions as recycled materials replace fossil-based raw materials;
- the reduction of energy-intensive upstream processes contributes directly to lower Global Warming Potential (GWP);
- waste diversion from landfill further mitigates emissions related to disposal and material degradation.

These outcomes directly support SDG 13 (Climate Action) of the UN 2030 Agenda and align with European decarbonization targets outlined in the European Green Deal. By demonstrating measurable emission reductions, the analyses provide scientific evidence to support the integration of circular economy strategies into climate policies.

9.3 Life Cycle Assessment as a Decision-Support Tool

LCA was employed as the primary methodological framework to ensure a holistic evaluation of environmental impacts across the entire life cycle of products and processes. Conducted in accordance with ISO 14040 and ISO 14044, the LCA considered all relevant stages:

- raw material extraction and processing;
- manufacturing and transformation stages;
- transportation and logistics;
- end-of-life scenarios.

The comparative LCA analyses, focusing on virgin and recycled polycarbonate, demonstrated that circular production models achieve lower cumulative energy demand due to avoided raw material processing, reduced greenhouse gas emissions associated with decreased fossil resource consumption, improved resource efficiency and material circularity indicators.

These results validate the environmental effectiveness of circular economy strategies and support their adoption within industrial systems, especially when combined with appropriate material selection and process optimization.

9.4 Circular Strategies, Sustainability Assessment and Cost–Benefit Considerations

The analyses conducted in this research align with current European and national regulatory frameworks promoting circular economy principles by demonstrating how circular industrial systems can reduce environmental footprints while maintaining economic performance:

- the EU Circular Economy Action Plan, which encourages the use of secondary raw materials;
- the Waste Framework Directive, emphasizing waste prevention, reuse, and recycling;
- several SDGs, including SDG 8, SDG 9, SDG 12 and SDG 13.

The results confirm that circular industrial systems based on by-products reuse can simultaneously reduce environmental impacts, enhance energy efficiency, maintain or improve economic performance. This systemic evaluation reflects the complexity of industrial systems and underscores the necessity of multi-criteria assessment frameworks to guide the transition toward sustainable production models.

Economic sustainability is a fundamental pillar of circular economy implementation. Circular strategies, while requiring initial investments in material sorting, processing, and quality control, offer significant medium and long-term economic advantages, including:

- costs associated with raw material extraction;
- savings from high energy demand for raw material treatments;
- potential reductions in waste management and disposal costs.

By demonstrating economic feasibility alongside environmental benefits, circular economy projects may consistently be integrated into industrial decision-making processes. This research supports the role of LCA as a decision-support tool for policy compliance and industrial innovation.

Circular economy strategies based on the reuse of industrial by-products yield measurable environmental and economic benefits, including reduced energy consumption, lower CO₂ emissions, and favorable cost–benefit profiles. When interpreted within a sustainability and regulatory framework, these results confirm the strategic role of circular industrial systems in advancing climate objectives, resource efficiency, and sustainable development.

Furthermore, the integration of LCA and cost–benefit analysis provides robust scientific evidence supporting the transition from linear to circular industrial systems.

10. Comparative Life Cycle Assessment of Virgin and Recycled Polycarbonate Sheets: Integrating Experimental Validation for Circular Material Applications

The transition toward circular production systems requires robust quantitative evidence demonstrating the environmental and technical feasibility of replacing virgin polymers with recycled alternatives. This study presents a comparative Life Cycle Assessment (LCA) of polycarbonate (PC) sheets manufactured from virgin raw material and from recycled polycarbonate (rPC) derived from post-industrial waste streams. The environmental analysis is complemented by experimental results obtained from laboratory investigations aimed at optimizing recycling pathways and evaluating the mechanical and thermal performance of rPC sheets. The LCA was conducted in accordance with ISO 14040 and ISO 14044 standards, considering cradle-to-grave system boundaries and focusing on key impact categories, including cumulative energy demand, global warming potential, and resource depletion. The inventory data for the recycled scenario (scenario B) were informed by process parameters and material performance outcomes derived from laboratory trials, where rPC was processed through controlled regranulation and sheet manufacturing procedures. The results indicate that scenario B achieves a substantial reduction in environmental impacts compared to the virgin counterpart, primarily due to the avoidance of energy-intensive polymerization and raw material extraction stages. Laboratory characterization confirmed that the recycled sheets meet functional requirements for secondary applications, demonstrating comparable mechanical strength and thermal stability within defined tolerance ranges. The integration of LCA and experimental validation provides a comprehensive assessment framework supporting the adoption of rPC in industrial applications. The findings highlight the potential of optimized recycling processes to contribute to resource efficiency, emission reduction, and circular economy implementation within the plastics sector. This study thus offers both methodological and applied insights for advancing sustainable material strategies in polymer-based product development.

10.1 Introduction

The increasing pressure on natural resources and the growing environmental burden associated with polymer production have intensified the need for sustainable material management strategies within the plastics sector [4]. Polycarbonate (PC), widely used for its excellent mechanical strength, transparency, and thermal stability, is a high-performance engineering polymer whose production is intrinsically energy-intensive and reliant on fossil-based feedstocks. As global demand for PC continues to rise across construction, electronics, automotive, and consumer goods industries, the

environmental implications of its life cycle, particularly in terms of greenhouse gas (GHG) emissions and resource depletion, have become a matter of increasing concern [1]. In this context, circular economy principles advocate the transition from linear “take–make–dispose” models toward closed-loop systems that prioritize waste prevention, material reuse, and recycling [5, 8]. Among the various strategies proposed for polymer circularity, mechanical recycling of PC represents a promising pathway, particularly for post-industrial waste streams characterized by relatively high material purity and consistent composition. However, despite its potential, the large-scale adoption of rPC in high-value applications remains limited, primarily due to uncertainties regarding material performance, process optimization, and the actual magnitude of environmental benefits [7, 9]. Life Cycle Assessment (LCA) has emerged as a key methodological tool for evaluating the environmental performance of recycled materials in comparison with their virgin counterparts [2]. By quantifying impacts across the entire product life cycle, LCA enables the identification of environmental hotspots and supports evidence-based decision-making in material selection and process design. Nevertheless, LCA results are strongly influenced by technological assumptions and process parameters, making it essential to integrate environmental modeling with experimental validation of recycled material properties [6]. Within this framework, recent research has highlighted the importance of coupling environmental assessments with laboratory investigations to ensure that recycled polymers meet the functional requirements of target applications. In particular, optimizing recycling pathways, through controlled reprocessing conditions, material characterization, and performance testing, can enhance the quality and reliability of rPC, thereby expanding its potential industrial use [3]. Such integrated approaches are essential for bridging the gap between theoretical environmental benefits and practical feasibility. The present study aims to contribute to this research field by performing a comparative LCA of PC sheets produced from vPC and from rPC derived from post-industrial waste streams. The environmental assessment is complemented by laboratory results obtained from optimized recycling trials, in which mechanical and thermal properties of recycled sheets were evaluated to determine their suitability for secondary applications. By combining environmental and experimental perspectives, the study seeks to provide a comprehensive evaluation of the sustainability potential of rPC sheets. Specifically, the objectives of this work are threefold:

- to quantify the environmental impacts associated with vPC and rPC sheet production through a standardized LCA framework;
- to assess the technical performance of rPC sheets based on laboratory characterization;
- to discuss the implications of integrating rPC into industrial production systems from a circular economy perspective.

Through this integrated approach, the research aims to generate robust scientific evidence supporting the transition toward more sustainable polymer value chains, demonstrating how optimized recycling processes can contribute to emission reduction, resource efficiency, and the broader implementation of circular economy strategies in the plastics industry.

10.2 Materials and Method

This study adopts an integrated methodological framework combining experimental evidence and LCA to compare the environmental performance of two PC sheet production scenarios. The first scenario (scenario A) represents a conventional sheet manufactured from 100% vPC, while the second scenario (scenario B) considers a blended formulation composed of 70% vPC and 30% rPC derived from post-industrial waste streams.

The methodological approach builds upon the experimental findings reported in a previous study [10], which provided the technical basis for defining the recycled material properties, processing parameters, and feasibility of incorporating rPC into sheet manufacturing. The laboratory results confirmed that the selected recycled fraction could be processed under standard extrusion conditions while maintaining functional performance within acceptable tolerance ranges. These outcomes were therefore used to define scenario B modeled in the environmental assessment.

The functional unit (FU) adopted for the comparative analysis is one PC sheet with standard dimension (2100x6000x10 mm), ensuring equivalence between scenario A and scenario B. The FU was selected to enable a consistent comparison of environmental impacts based on identical functional output.

A cradle-to-grave system boundary was applied, encompassing the following life cycle stages:

- production of raw materials (vPC and rPC granulate);
- transportation of materials to the manufacturing facility;
- sheet extrusion process;
- ancillary energy consumption and process inputs;
- end of life consisting in incineration process.

The packaging and the use phases were excluded from the system boundaries, as both scenarios are assumed to provide equivalent performance, consistent with the laboratory validation results.

Primary inventory data were provided directly by the industrial partner supplying the PC materials and production information. These data included:

- transportation distances and modes for raw materials and recycled feedstock;
- energy consumption associated with extrusion and sheet manufacturing processes;
- operational parameters for recycling and regranulation processes.

Secondary background data for upstream processes, including vPC production and energy supply, were sourced from the databases available within the SimaPro LCA software environment.

The inventory for scenario B incorporated the material and energy requirements identified during laboratory trials, ensuring consistency between experimental processing conditions and environmental modeling assumptions.

The LCA was conducted in accordance with ISO 14040 and ISO 14044 standards [11] using SimaPro software. The impact assessment focused on key environmental indicators relevant to polymer production, including climate change, Cumulative Energy Demand (CED), abiotic resource depletion, selected midpoint indicators reflecting emissions and resource use.

Allocation procedures for recycled material were applied based on a cut-off approach, in which the rPC entering the system carries only the environmental burdens associated with collection, sorting, and reprocessing, while the upstream impacts of the original product life cycle are excluded.

The laboratory analyses played a crucial role in defining the feasibility and modeling assumptions of scenario B. In particular, experimental characterization of mechanical properties, thermal stability, and processing behavior confirmed that a 30% recycled content could be incorporated without requiring substantial process modifications.

Consequently, identical extrusion parameters and product specifications were assumed for both scenarios, ensuring comparability of results.

Furthermore, material efficiency factors and process yields observed during laboratory trials were used to refine the inventory model, improving the representativeness of the environmental assessment.

The study relies on a combination of primary industrial data and secondary database information. Data quality was assessed in terms of temporal, geographical, and technological representativeness. While primary data ensured high reliability for manufacturing processes, uncertainties remain associated with background datasets and scaling laboratory observations to industrial production conditions.

A sensitivity analysis was therefore conducted to evaluate the influence of key parameters, such as energy consumption and recycled content ratio, on the overall environmental results.

The integration of laboratory validation, primary industrial data, and standardized LCA modeling provides a robust methodological basis for evaluating the environmental implications of incorporating rPC into sheet production. This approach ensures that the comparative assessment reflects both technical feasibility and realistic industrial operating conditions, enabling a comprehensive evaluation of circular material strategies within the PC value chain.

10.3 Results and Discussion

The case study focuses on the production of a full-scale PC sheet used in industrial and construction applications. The sheet dimensions and mass correspond to the FU modeled in the LCA, enabling a direct translation of environmental results into an industrial context.

The production system analyzed includes raw material supply, sheet extrusion, and finishing operations, with operational data provided directly by the manufacturing company. The inclusion of primary industrial data enhances the representativeness of the results and ensures alignment with real production conditions.

The comparative analysis demonstrates that the ratio 30: 70 respectively of rPC and vPC configuration achieves a noticeable reduction in environmental impacts without requiring significant process modifications. From an industrial perspective, this result is particularly relevant, as it indicates that environmental improvements can be achieved through material substitution alone, without major technological investments.

The case study further highlights that the environmental benefits scale proportionally with the recycled content, suggesting that higher substitution rates could lead to additional impact reductions, provided that material performance requirements are maintained.

10.4 Case Study

The comparative LCA evaluated the environmental performance of two PC sheet production scenarios (see Fig. 1)

- scenario A, a reference configuration based on 100% vPC;
- scenario B, a circular configuration composed of 30% rPC and 70% vPC.

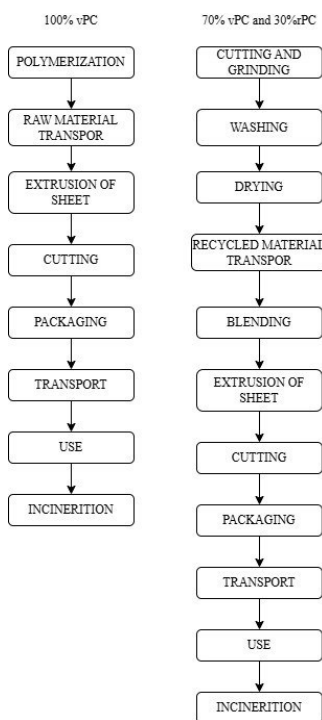


Fig. 1 – vPC and rPC production process

The analysis was conducted using the inventory parameters which integrates material flows, energy consumption, transportation distances, and end-of-life assumptions within the Simapro modeling environment.

The FU corresponds to a PC sheet measuring 2100×6000×10 mm (1.7 kg/m²), equivalent to approximately 21.42 kg of material per sheet produced by extrusion (see Tab. 1).

Table 1: Functional unit and production process

	Quantity	Mass (kg)	Mass – functional unit (kg)	Material	Material (Simapro)	Processing	Process/processing (Simapro)
vPC	1	21.42	21.42	vPC	Polycarbonate {RER}, market for	extrusion	Extrusion of plastic sheets and thermoforming, inline {RER}, market for, inline
rPC	0.3	6.43	6.43	rPC	Polycarbonate , recycled {RER}, market for	extrusion	Extrusion of plastic sheets and thermoforming, inline {RER}, market for extrusion of plastic sheets and thermoforming, inline

	0.7	14.99	14.99	vPC	Polycarbonate {RER}, market for	extrusion	Extrusion of plastic sheets and thermoforming, inline {RER}, market for extrusion of plastic sheets and thermoforming, inline
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Overall, the results show a consistent reduction in environmental impacts for scenario B across the main indicators considered, confirming the environmental advantage of integrating secondary raw materials into PC sheet production.

Material production emerged as the dominant contributor to total environmental impacts in both scenarios, as reported in Tab. 2. In scenario A, the environmental burden is largely driven by the energy-intensive polymerization stage associated with vPC production. According to the inventory data, polymerization energy demand represents the largest share of cumulative energy consumption, reflecting the intrinsic resource intensity of virgin polymer synthesis.

In scenario B, the partial substitution with rPC significantly reduces the upstream burden. Since recycled material carries only the impacts associated with reprocessing (cutting and grinding, washing, and drying), the avoided production of vPC leads to a substantial decrease in cumulative energy demand and GHG emissions.

Table 2: Material production and energy demand

	Consumption (kWh)	Consumption per functional unit (kWh)	Process	Process (Simapro)
vPC	27 per kg (polymerization)	578.34	heat energy (industry)	heat, district or industrial, natural gas {RER}, market group for heat, district or industrial, natural gas
	60 per ton (extrusion)	1.29	heat energy (industry)	heat, district or industrial, natural gas {RER}, market group for heat, district or industrial, natural gas
rPC	60 per ton (extrusion)	0.39	heat energy (industry)	heat, district or industrial, natural gas {RER}, market group for heat,
		0.9		

				district or industrial, natural gas
	0.138 per kg (cutting – grinding, 30%)	0.89	heat energy (industry)	heat, district or industrial, natural gas {RER}, market group for heat, district or industrial, natural gas
	65 per ton (washing, 30%)	0.42	heat energy (industry)	heat, district or industrial, natural gas {RER}, market group for heat, district or industrial, natural gas
	0.25 per kg (drying, 30%)	1.61	heat energy (industry)	heat, district or industrial, natural gas {RER}, market group for heat, district or industrial, natural gas
	27 per kg (polymerization, 70%)	404.84	heat energy (industry)	heat, district or industrial, natural gas {RER}, market group for heat, district or industrial, natural gas

The extrusion phase contributes a comparatively smaller share of total impacts as identical processing conditions were assumed for both scenarios. However, the recycled pathway includes additional pre-treatment steps such as cutting and grinding, washing, and drying.

Although these operations introduce additional energy requirements, their contribution remains significantly lower than the avoided impacts of vPC production, confirming the net environmental benefit of recycling.

Table 3 shows the transport impacts, modeled using heavy-duty diesel freight transport, represent a secondary contribution to overall environmental performance. The results indicate that transport-related emissions remain marginal compared to material production impacts, even when accounting for different supply routes for virgin and recycled feedstocks.

This finding suggests that the environmental performance of PC sheets is primarily determined by material origin rather than logistics, within the transport distances considered.

Table 3: Environmental impact related to transport

	Route (km)	Route per component (kg/km)	Transport	Process (Simapro)
vPC	250	5355	truck 44 t	transport, freight, lorry, >32 metric ton, diesel, EURO 3 {RER}
rPC	100 (30%)	642.6	truck 44 t	transport, freight, lorry, >32 metric ton, diesel, EURO 3 {RER}
	250 (70%)	3748.5	truck 44 t	transport, freight, lorry, >32 metric ton, diesel, EURO 3 {RER}

Both scenarios assume an identical end-of-life treatment consisting of 100% incineration, ensuring comparability of results (see Tab. 4). Consequently, differences in environmental performance between the two scenarios are attributable exclusively to upstream processes.

The inclusion of end-of-life impacts nevertheless highlights the importance of considering future circular strategies, such as multiple recycling loops evaluating the corresponding feasibility of multiple loops reuse.

Table 4: End-of-life treatment

	End of life	Process	Process (Simapro)
vPC	incineration	incineration	municipal solid waste (waste scenario) {IT}, treatment of municipal solid waste, incineration
rPC	incineration	incineration	municipal solid waste (waste scenario) {IT}, treatment of municipal solid waste, incineration

The results highlight three key insights:

- material production dominates environmental impacts, making recycled content the most effective lever for improvement;

- recycling-related processing impacts are relatively minor, confirming the environmental efficiency of mechanical recycling pathways;
- industrial implementation is feasible, as demonstrated by the case study based on real production data.

Together, these findings reinforce the role of rPC as a strategic pathway toward more sustainable polymer value chains and demonstrate the value of integrating laboratory experimentation with LCA modeling (see Figures 2 and 3).

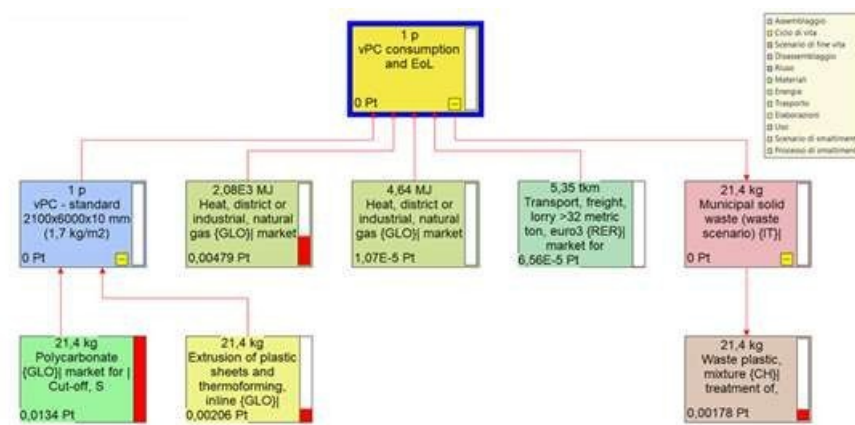


Fig. 2 – Production process of vPC

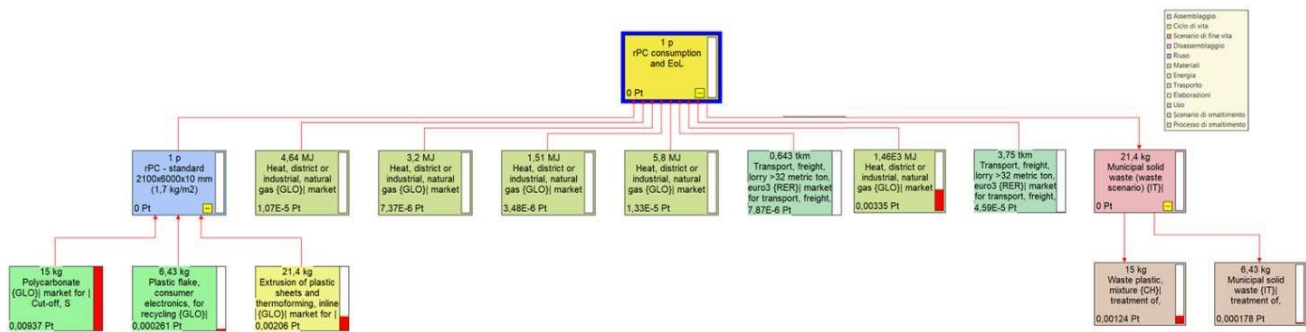


Fig. 3 – Production process of rPC

The comparative results presented in Figure 4 confirm that incorporating rPC leads to a measurable reduction in key environmental indicators, particularly:

- Global Warming Potential (GWP), due to reduced fossil energy consumption in raw material production;
- Cumulative Energy Demand (CED), reflecting the avoided polymerization energy;
- resource depletion, as recycled material reduces dependence on virgin feedstock.

These findings are consistent with the laboratory outcomes reported in a previous study, which demonstrated that rPC can be processed without significant performance losses.

The case study confirms that rPC can be effectively integrated into existing production systems, contributing to resource efficiency and emission reduction. The integration of experimental validation with LCA results therefore provides strong evidence supporting the technical and environmental feasibility of recycled-content PC sheets as a viable strategy for reducing the environmental footprint of polymer-based products, particularly in sectors characterized by high material demand.

Moreover, the use of primary industrial data demonstrates the feasibility of applying LCA as a decision-support tool in real manufacturing environments, enabling companies to quantify the environmental benefits of circular strategies and support sustainability-oriented decision-making.

Select	Impact category	Unit	vPC consumption	rPC consumption
<input checked="" type="checkbox"/>	Climate change	kg CO ₂ eq	348	256
<input checked="" type="checkbox"/>	Ozone depletion	kg CFC11 eq	1,26E-5	9,46E-6
<input checked="" type="checkbox"/>	Ionising radiation, HH	kBq U-235 eq	4,2	4,08
<input checked="" type="checkbox"/>	Photochemical ozone formation, HH	kg NMVOC eq	0,609	0,457
<input checked="" type="checkbox"/>	Respiratory inorganics	disease inc.	1,55E-5	1,13E-5
<input checked="" type="checkbox"/>	Non-cancer human health effects	CTUh	2,15E-5	1,63E-5
<input checked="" type="checkbox"/>	Cancer human health effects	CTUh	2,17E-6	1,65E-6
<input checked="" type="checkbox"/>	Acidification terrestrial and freshwater	mol H ⁺ eq	0,897	0,674
<input checked="" type="checkbox"/>	Eutrophication freshwater	kg P eq	0,0175	0,0161
<input checked="" type="checkbox"/>	Eutrophication marine	kg N eq	0,167	0,128
<input checked="" type="checkbox"/>	Eutrophication terrestrial	mol N eq	1,77	1,35
<input checked="" type="checkbox"/>	Ecotoxicity freshwater	CTUe	167	200
<input checked="" type="checkbox"/>	Land use	Pt	174	160
<input checked="" type="checkbox"/>	Water scarcity	m ³ depriv.	55,3	40,2
<input checked="" type="checkbox"/>	Resource use, energy carriers	MJ	3,81E3	2,78E3
<input checked="" type="checkbox"/>	Resource use, mineral and metals	kg Sb eq	0,000273	0,000253
<input checked="" type="checkbox"/>	Climate change - fossil	kg CO ₂ eq	347	256
<input checked="" type="checkbox"/>	Climate change - biogenic	kg CO ₂ eq	0,259	0,2
<input checked="" type="checkbox"/>	Climate change - land use and transform.	kg CO ₂ eq	0,0471	0,0458

Fig. 4 – Comparative LCA vPC and rPC

10.5 Conclusions

This study aims at evaluating the environmental and technical implications of integrating rPC into sheet production through a combined experimental and LCA approach. The research provides a comprehensive assessment of the sustainability potential of recycled-content PC sheets within an industrial context.

From a methodological perspective, the research demonstrates the value of coupling laboratory validation with LCA modeling. The experimental findings, derived from optimized recycling trials, confirmed that PC containing a recycled fraction can be processed under standard extrusion conditions while maintaining functional performance suitable for secondary applications. These results provided the technical basis for defining a realistic recycled-content scenario, ensuring that the environmental assessment reflects feasible industrial conditions rather than theoretical assumptions.

The comparative LCA analysis highlighted that material production is the dominant contributor to environmental impacts across the life cycle of PC sheets. The substitution of vPC with rPC resulted in a consistent reduction in key environmental indicators, particularly cumulative energy demand and GWP. These improvements are primarily connected to the avoidance of energy-intensive polymerization processes and reduced dependence on fossil-based feedstock. Although recycling operations introduce additional energy requirements, their contribution remains significantly lower than the avoided impacts of vPC production, confirming the net environmental advantage of scenario B.

The case study based on industrial-scale production further reinforced these findings by demonstrating that a 30% recycled content can be integrated into existing manufacturing systems without significant process modifications. This result is particularly relevant from a practical standpoint, as it indicates that environmental improvements can be achieved through incremental changes in material sourcing rather than major technological investments. The analysis also suggests that higher recycled content could lead to additional environmental benefits, provided that performance requirements and quality standards are maintained.

From a broader sustainability perspective, the study confirms the role of rPC as a key enabler of circular economy strategies within the plastics sector. By reducing resource consumption, energy demand, and GHG emissions, recycled-content sheets contribute to more sustainable material cycles and support the transition toward low-impact production systems. Furthermore, the integration of primary industrial data demonstrates the applicability of LCA as a decision-support tool for evaluating circular strategies in real manufacturing environments.

Despite these positive outcomes, the study also acknowledges certain limitations, including the focus on a single product type, assumptions related to system boundaries, and uncertainties associated with background datasets. Future research should therefore explore alternative end-of-life scenarios and broader system boundaries to further refine the environmental assessment.

Finally, this research provides robust scientific evidence that incorporating rPC into sheet production is both technically feasible and environmentally beneficial. The integrated approach adopted, combining laboratory experimentation, industrial data, and LCA, offers a replicable framework for assessing circular material strategies and supports the wider adoption of recycled polymers in high-value applications. By demonstrating measurable environmental improvements without compromising product performance, the study contributes to advancing sustainable and circular practices within polymer-based manufacturing systems.

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11. Critical Discussion and System-Level Implications

The implementation of circular economy strategies within industrial contexts requires more than isolated technical solutions. It demands a system-level understanding of environmental effectiveness, economic viability, and regulatory compatibility. The results in this research have been obtained by adopting a system-level engineering perspective, integrating laboratory evidence, LCA outcomes, and policy frameworks.

This discussion examines the interdependencies among material properties, industrial operations, environmental impacts, and governance structures, with the objective of evaluating the effective feasibility of circular economy projects based on the reuse of specific industrial waste categories.

11.1 Laboratory Feasibility: Strengths and Limitations

The analyses conducted in this research considered the reuse of selected industrial by-products such as ceramic residues, textile waste and polycarbonate sheets. The results revealed that:

- ceramic by-products can be integrated into several ceramic mixtures without compromising product quality;
- textile waste streams can be classified and processed to support reuse pathways;
- recycled polycarbonate maintains adequate mechanical and thermal properties for secondary applications.

Also, the laboratory experiments and environmental assessments performed on polycarbonate by-products demonstrated that the specific blends of virgin and recycled polycarbonate can achieve functional equivalence with raw materials while significantly reducing environmental impacts.

These findings highlight the importance of material characterization, quality control, and process adaptability. Laboratory feasibility thus represents the first validation layer, enabling the identification of reuse scenarios that are compatible with industrial requirements and safety standards. The results confirm that circular solutions are most effective when embedded within a holistic system design, where material selection, process optimization, and environmental performance are considered simultaneously. This systemic integration reduces inefficiencies and enhances the resilience of industrial systems to resource scarcity and regulatory pressure.

The transition toward circularity involves the interaction of multiple subsystems, including supply chains, manufacturing processes, logistics networks, and end-of-life management. The case studies analyzed demonstrate that successful circular economy implementation depends on:

- cross-sector collaboration among material suppliers, manufacturers, and waste managers;
- industrial symbiosis, enabling by-products from one process to become resources for another;

- organizational readiness and technological capability to manage secondary raw materials.

These findings reinforce the concept that circular economy projects must be designed as system-wide interventions, rather than isolated process improvements.

11.2 Sustainability and Feasibility of Reuse

The integration of circular economy projects into industrial systems allows the mitigation of ecosystem degradation and resource depletion by reducing material extraction, energy consumption, and waste generation. However, the reuse of industrial by-products reveals potential trade-offs, as:

- additional processing requirements for material stabilization and quality control;
- regulatory uncertainty related to waste classification and end-of-waste criteria;
- potential increases in logistical complexity;
- variability in by-product quality and availability.

Economic feasibility depends on scale, supply chain coordination, and regulatory incentives, confirming that circular economy implementation must be embedded within broader industrial strategies rather than isolated pilot projects.

LCA plays a central role in evaluating technically feasible reuse solutions that are also environmentally justified. The comparative LCA analyses conducted on virgin and recycled polycarbonate demonstrated that circular scenarios achieve lower cumulative energy demand, reduced greenhouse gas emissions, and improved resource efficiency.

LCA represents a decision-support tool that provides feasibility evaluating quantitative confirmation of environmental benefits, identification of potential trade-offs (e.g., additional processing energy), guidance for optimizing reuse strategies at system level. Nevertheless, LCA results are influenced by:

- system boundary definitions;
- data availability and quality;
- assumptions regarding end-of-life scenarios.

The alignment between laboratory performance and LCA outcomes confirms that the investigated circular solutions are not only technically viable but also environmentally advantageous, reinforcing their ecological credibility.

11.3 Regulatory Frameworks: Enablers and Constraints

Laboratory validation and LCA evidence are necessary to support regulatory compliance, but they are not always sufficient to overcome administrative barriers. A critical implication is that technical innovation must be accompanied by regulatory innovation, ensuring that legal frameworks evolve alongside industrial practices. While European and national policies increasingly promote reuse and

recycling, regulatory ambiguity, especially concerning by-product classification and end-of-waste criteria, can hinder industrial adoption. This tension reinforces the role of engineering research in grounding sustainability ambitions in technical and quantitative evidence, supporting realistic and actionable pathways toward sustainable development.

11.4 Scientific Contribution and Limitations

The interpretation of the circular economy as a design paradigm for complex industrial systems, rather than a set of isolated recycling practices represents the basis of this research. The case studies analysed among these three years reveal that circular solutions are most effective when embedded within reconfigured supply chains, industrial symbiosis networks and organizational learning processes.

The aim of this research consists in developing a methodological approach to exploring complex industrial systems supporting circular economy projects. Successful implementation requires:

- integration of material science, process engineering, and environmental assessment;
- coordination across industrial actors and value chains;
- alignment between industrial practices and policy objectives.

Despite the robustness of the results, certain limitations remain. These include:

- uncertainties associated with scaling laboratory results to industrial levels;
- scaling assumptions in environmental and economic analyses;
- the dynamic evolution of regulatory frameworks.

These limitations do not undermine the validity of the results but define their applicability domain, offering transparency and scientific rigor and also underlining the importance of continuous data collection and system monitoring.

The successful implementation of circular economy strategies requires a system-level approach that integrates technical feasibility, environmental performance, economic viability, and regulatory compliance. Circularity is not an automatic outcome of recycling, but the result of deliberate system design, evidence-based decision-making, and policy alignment. By integrating these dimensions within a system-level framework, the research confirms that industrial by-product reuse can serve as a robust pathway toward sustainable, circular, and resilient industrial systems.

Future research will focus on:

- scaling laboratory-proven solutions to industrial and regional systems;
- integrating digital technologies for material traceability and performance monitoring;
- refining regulatory instruments to support innovation in secondary raw materials;

- developing dynamic and scenario-based LCA models.

These directions would further enhance the feasibility and effectiveness of circular economy strategies in complex industrial systems.

12. Conclusions

This doctoral research addressed the challenge of implementing circular economy strategies within complex industrial systems, with a specific focus on the reuse of selected industrial waste and by-product categories. The main objective was to develop and validate an integrated engineering-based approach capable of supporting decision-making in circular economy projects by combining material experimentation, environmental assessment, economic evaluation, and system-level analysis.

By structuring the research around laboratory experimentation, LCA, economic evaluation, and system-level interpretation, the thesis contributes to bridging the gap between conceptual circular economy principles and their operational implementation in industrial contexts.

The results of this research demonstrate that industrial by-products, specifically polycarbonate sheets, ceramic residues, and textile waste streams, can be effectively reintroduced into production systems when supported by structured technical, environmental, and systemic evaluations.

From a technical perspective, laboratory testing confirmed that recycled materials can achieve performance levels compatible with secondary industrial applications, provided that adequate characterization and quality control measures are adopted.

LCA analyses showed that circular scenarios consistently outperform linear production models in terms of energy consumption reduction, greenhouse gas emission mitigation, and resource efficiency. The development of an integrated assessment framework combining laboratory experimentation, LCA, and system analysis for evaluating circular economy feasibility in industrial contexts allows the transition from the linear business model to the circular and sustainable one across different sectors ensuring that environmental benefits were not assumed, but measured and critically evaluated. Through experimental validation and environmental assessment, the thesis demonstrates that reuse-based circular strategies can significantly reduce:

- energy consumption across industrial life cycles;
- greenhouse gas emissions, particularly CO₂;
- dependency on raw materials.

Specifically, LCA represents a decision-support instrument guiding material selection, process configuration, and system optimization.

From an economic perspective, cost–benefit evaluations highlighted that circular economy strategies can offer competitive advantages, particularly over medium and long-term horizons, while reducing exposure to raw material price volatility and waste management costs.

The findings of this research have direct implications for industrial stakeholders, policymakers, and sustainability practitioners. The proposed approach supports industries in:

- identifying technically and environmentally viable reuse strategies,
- integrating circular economy principles into product and process design,
- improving compliance with evolving environmental regulations.

Also, the research contributes to the transition toward more sustainable production systems, aligning industrial practices with broader environmental and climate objectives.

By translating global sustainability goals into measurable industrial outcomes, the thesis bridges the gap between policy aspirations and practical implementation. Considering UN 2030 Agenda, the research contributes to:

- SDG 9 (Industry, Innovation and Infrastructure) through technological innovation and system optimization;
- SDG 12 (Responsible Consumption and Production) by promoting resource efficiency and waste reduction;
- SDG 13 (Climate Action) through quantified reductions in energy consumption and greenhouse gas emissions.

While the research provides robust evidence supporting circular economy implementation, certain limitations remain. These include:

- uncertainties associated with scaling laboratory results to industrial levels;
- scaling assumptions in environmental and economic analyses;
- the dynamic evolution of regulatory frameworks.

These limitations define the applicability domain of the findings and highlight the need for adaptive and context-specific implementation strategies underlining the importance of continuous data collection and system monitoring.

Future research could expand this work by:

- extending the integrated framework to additional industrial sectors;
- integrating digital technologies for material traceability and process monitoring;
- developing dynamic and scenario-based LCA models;
- exploring organizational and social dimensions of circular economy adoption.

In conclusion, this doctoral thesis demonstrates that circular economy implementation within complex industrial systems is feasible, measurable, and strategically advantageous when supported by rigorous engineering analysis, environmental assessment, and regulatory alignment. The research contributes both to scientific knowledge and industrial practice, offering a replicable framework for advancing sustainability and circularity in industrial contexts.

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This research was conducted within an industrial PhD framework that gives me the opportunity to carry out applied research in close contact with industrial realities and the access to real case studies, materials, and production processes, allowing the research to address concrete challenges related to circular economy implementation.

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