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Original Research

Trash or treasure? A circular business model of recycling plasmix

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ABSTRACT

The production of plastic materials in the mid-20th century brought about transformative changes in consumer goods manufacturing and societal norms. However, this advancement paralleled an alarming surge in plastic pollution, driven by unrestrained consumption. This study focuses on the non-homogeneous and non-recyclable plastic waste (also known as plasmix in the Italian waste management), a residual blend resulting from plastic recycling processes. The main goals are to conduct an in-depth study of the plasmix landscape, to identify integration challenges, and to create a sustainable business model for broader adoption. Additionally, we aim to use life cycle assessment to examine the environmental effects of semi-finished plasmix-based materials that can be used to produce different products. This integrated approach ensures a holistic understanding of plasmix recycling, promoting both economic and environmental sustainability. The study contributes to sustainable waste management practices by offering a strategic approach to transform a challenging waste stream into economic opportunities. By addressing the market viability of plasmix-based products through an empirically supported business model, the research underscores the significance of recycling in mitigating plastic pollution and advancing a circular economy.

1. Introduction

Global plastic production has reached 390.7 million tons in 2021 and it is expected to double within the next two decades (Plastics Europe, 2022). Plastic polymers are the most widely used materials in the world, and this popularity comes from their versatility and strength. Moreover, they are easy to produce industrially and come at a low production cost. These polymers find applications across diverse sectors, including packaging, automotive, and electronics. However, in a world increasingly dependent on plastic, plastic waste and end-of-life disposal has become a critical concern. Therefore, the need for sustainable management strategies of plastic waste is more crucial than ever.

In Europe, Italy ranks as the second-largest plastic consumer, with 5.9 million tons of fossil polymers consumed in 2020 alone (Novati & Leonardi, 2022). While over 1 million tons of plastic wastes were treated in the same year, only half was effectively recycled. According to the National Consortium for the Collection, Recycling, and Recovery of Plastic Packaging (COREPLA), the total amount of packaging put into circulation for the past year was estimated at 2198 kilotonnes, showing a decrease of about 5% compared to 2019. Contrary to this trend, the separate collection of plastic packaging increased even in 2020. The collected and sorted amount, including that managed by autonomous systems, amounted to 1,433,203 tonnes, marking a 4% increase compared to 2019. This new record in terms of waste amount processed brings Italy to an average per capita of 23.7 kg annually (COREPLA, 2020). Topping the chart in Italy are Aosta Valley, Umbria, and Sardinia, with over 32 kg per inhabitant. It is worth noting how the results of separate collection in individual regions are increasingly approaching the national average figure, surpassing the significant disparities that characterized the Italian situation up to three years ago (COREPLA, 2020).

PHOENIX (push for a second valuable life to plasmix) is an Italian multidisciplinary project, led by the Università degli Studi di Milano, Politecnico di Torino, and Università del Piemonte Orientale, with a primary focus on tackling the challenges of plastic waste management. Specifically, the project targets the treatment of mixed plastic waste, known as plasmix, within the framework of a circular economy (CE). Notably, a notable fraction of plastic waste remains non-recyclable, as highlighted by the 518,388 tonnes of plasmix packaging reported in Italy (Fiore & Tamborrini, 2024).

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Therefore, the project efforts to develop innovative strategies for efficiently reusing various types of plasmix waste through mechanical recycling. Additionally, it involves the creation of laboratory samples using these modified materials to assess their chemical and structural characteristics compared to native plasmix waste. PHOENIX aims at identifying potential markets and suitable business models for the utilization of plasmix-based materials. Furthermore, it applies systemic design approaches to create a diverse range of products using these novel materials. Ultimately, the project seeks to disseminate its findings widely in accessible formats, aiming to raise awareness and encourage the adoption of proper disposal and recovery practices for plastic waste, thereby contributing to the broader goals of transitioning towards a CE.

In this study, we primarily focus on the work package that investigates the economic and environmental sustainability of the entire recycling process. This is achieved through the application of life cycle assessment (LCA) and a sustainable business model canvas. The objective is to provide a comprehensive framework for both academics and managers.

The LCA, adopting a cradle-to-gate approach, analysed five semi-finished materials, each containing different proportions of plasmix, to evaluate their distinct environmental impacts. Following this, we explored additional environmental impacts and benefits of plasmix by incorporating an environmental layer into our analysis. This component of the sustainable business model allows us to refer and assess the environmental impacts across the supply chain, encompassing distribution channels, the usage phase, and the disposal or recycling of finished products made with plasmix.

2. Theoretical backgrounds

2.1. Circular business models and life cycle thinking

The concept of a CE, originating in the late 1970s with the pioneering work of Stahel and Reday (1981), imagines an economic model that reduces waste, promotes employment, and optimizes natural resource utilization. The Ellen MacArthur Foundation (EMF) provides comprehensive definitions of a CE, emphasizing an industrial approach that prioritizes renewable energy, reduces toxic chemical usage, and promotes waste reduction through thoughtful design (EMF, 2013). This economic model, based on the '3-R principles' of replace, reduce, and refine, along with responsible valuation of products and resources, holds significant potential for sustainable development across economic, environmental, and social domains (EMF, 2015a; 2015b). Moreover, the CE aims to be restorative, relying on renewable energy, while minimizing and eliminating the use of toxic chemicals through careful design (EMF, 2013). This economic model fosters multiple value-creation mechanisms decoupled from finite resource consumption, driving growth from within existing economic structures, products, and materials (EMF, 2015a; 2015b).

Moving away from the traditional linear economy's focus on maximizing profit through high volume sales (Pigosso et al., 2010), the shift towards a CE emphasizes the importance of considering the life cycle aspects of products. This approach aims to optimize product value and benefits from engineering to disassembly in a sustainable closed loop (Chiappetta Jabbour et al., 2020), with objectives to reduce environmental losses and adhere to life cycle restrictions (Westkämper, 2003).

Therefore, life cycle thinking (LCT) evaluates the environmental impact of products or services across all stages of their life, from design to disposal, promoting sustainability (UNEP, 2005). Recognized as crucial for analysing potential impacts (EC, 2003), LCT underscores the need for a systemic view of resource life cycles (Ghisellini et al., 2016; Iacovidou et al., 2017; Reike et al., 2018), particularly in high-impact sectors like the plastics industry. Here, LCT involves a comprehensive assessment of a product's environmental impact throughout its lifespan (ISO 14040, 2006; Lieder & Rashid, 2016).

This approach forms the basis for LCA methodologies, moving businesses towards resource efficiency and sustainable practices (Lieder & Rashid, 2016). It prompts a meticulous assessment of a product's environmental impact throughout its life cycle, uncovering opportunities for waste reduction and improved recycling. Moreover, it facilitates innovative strategies for material substitution and product redesign, instrumental in reducing the ecological footprint of plastic products (Bocken et al., 2016).

Embracing LCT within the plastics industry offers multiple benefits, including cost savings, enhanced brand reputation, regulatory compliance, and fostering innovation and customer loyalty (Korhonen et al., 2018). However, transitioning to LCT presents challenges such as data collection and analysis, technical constraints, and requires a paradigm shift in traditional business operations (Seidel-Sterzik et al., 2018).

A tangible example of LCT within the plastics industry is the adoption of cradle-to-cradle design principles. This design philosophy revolves around creating products that can be cyclically reintegrated into the system, aligning seamlessly with LCT's principles, and promoting resource efficiency (Braungart et al., 2007).

LCT is essential in driving the transition towards circular business models. It not only emphasizes environmental stewardship but also strategically positions firms in a competitive marketplace (Nuβholz, 2017).

Business models (BMs) are tools used for analysing business behaviour, tracking goals, and visualizing overall structure. They outline how a company transforms core competencies into commercial benefit, encompassing organizational and financial planning, along with assumptions about clientele, requirements, revenue, and expenses (Morris et al., 2005). Moreover, BM provides a cognitive aid in understanding how a company executes its business operations, enabling performance comparison, monitoring, evaluation, strategic communication, and innovation (Wiśniewska-Paluszak et al., 2023). In addition, it is recognized as a critical asset that influences firm performance (Mason & Chakrabarti, 2017; Zott & Amit, 2010).

According to Pigneur and Osterwalder (2010), a business model is defined as 'the rationale of how an organisation creates, delivers, and captures value'. They developed the 'business model canvas' (BMC) that is the most widely used architecture tool for planning a business model (Zilia et al., 2023). It helps define strategies to deliver products to target customers, establish profitable businesses through product innovation and efficient processes, and reduce the risk of failure (Fahim et al., 2021).

To implement the sustainable value creation, Joyce and Paquin (2016) proposed the 'triple layered business model canvas' (TLBMC), which integrate economic, social, and environmental aspects. The environmental layer utilizes the business model canvas and life cycle perspective to analyse each component's environmental impact, while the Social Layer focuses on stakeholder management, expanding the definition of stakeholders to include non-human entities, such as natural ecosystems, to ensure the interests of all parties are balanced. By linking the economic, environmental, and social layers, an integrated business model can be developed from a sustainability perspective (Kwak et al., 2021; Teece, 2010).

2.2. Tools for assessing environmental impacts

In the current global economy, international value chains that span production, use, and disposal of goods are responsible for widespread environmental impacts (Diggle & Walker, 2022). The practice of LCA is oriented to monitoring and evaluating these effects aiming to pinpoint enhancement strategies that prevent the shifting of environmental burdens across different sectors. Identifying and implementing the most effective improvement strategies necessitates a thorough consideration of impacts throughout the entire value chain, including supply chain operations, product use, and disposal phases. LCA is described as the systematic evaluation of inputs, outputs, and potential environmental impacts of a product system across its lifespan (Hellweg and Milà i Canals, 2014), typically unfolding in four stages as standardized by ISO 14044 (2006): goal and scope definition, inventory analysis, lifecycle impact assessment, and results interpretation (Curran, 2013).

LCA seeks to measure the environmental impacts of products and processes from their raw materials to their end ('cradle-to-grave') (Moretti et al., 2021), serving as a crucial decision-support tool for firms looking to enhance their environmental performance, as well as for policy makers crafting sustainable consumption and production regulations (Jegen, 2024).

On one hand, LCA provides invaluable support for decision-making, notably in waste management as highlighted by the European Waste Framework Directive (European Parliament and Council, 2008), which advocates for LCA's use to identify alternative approach from the traditional waste hierarchy (i.e., prevention, reuse, recycling, recovery, and disposal). Moreover, models and software tools for assessing environmental impacts of recycling (Riber et al., 2008) and disposal strategies are widely applied across different scenarios to enhance the eco-friendliness of waste management practices (Christensen et al., 2009). On the other hand, LCA's focus remains only on environmental impacts, overlooking the economic and social pillars of sustainability (Goffetti et al., 2022) and failing to account the real human behavior (Gutowski, 2018). As such, this approach should be complemented with a broader analysis that includes sustainable business models capable of assessing environmental, economic, and social aspects.

In recent years, the number of articles in the literature dealing with LCA applied to plastic and its waste management has been steadily increasing (Alhazmi et al., 2021; Davidson et al., 2021; Vlasopoulos et al., 2023). In the specific case of plasmix, Cossu et al. (2017) examined six different management scenarios for this material, comparing them based on their potential environmental impacts and restricting the analysis to the material's treatment, omitting the production phase. The results showed that among all management alternatives, from an environmental perspective, the most sustainable choices included replacing coke with thickened plasmix in a blast furnace and landfill disposal of waste after a washing process (Cossu et al., 2017). However, almost all the contributions that use LCA applied to plastic provide an analysis of environmental impacts only on a certain phase of the product's treatment or disposal process, as in the case of the analysis of environmental impacts of waste end-of-life in Singapore conducted by Yap et al. (2023).

Our aim is to perform a LCA on semi-finished products containing different proportions of plasmix and to develop a sustainable business model for the application in plasmix-based products to fully assess all environmental impacts.

To the best of our knowledge, this represents the initial effort to carry out a LCA for plasmix within the 'cradle-to-gate' system boundaries, focusing on the environmental impacts related to the production of semi-finished products made from plasmix. We tested the LCA on five types of tiles, each of 1 kg and containing different amounts of plasmix and evaluated their environmental impacts across 16 different categories. Furthermore, to consider also the possible environmental impacts during the distribution channels, usage phase and at the end-of-life of plasmix-based products comprehensively, we incorporated a specific environmental layer into our analysis (refer to Section 4.2). This approach allowed us to thoroughly assess the environmental impacts associated with the plasmix supply chain and to determine whether products made from plasmix result in a lower environmental impact during their use and disposal phases compared to analogous products not based on plasmix.

3. Methodology

3.1. Research setting

Plastic consumption is on the rise globally and most evidently in the packaging industry. Plastic packaging, especially in the food industry, offers numerous benefits, such as extending the shelf life of food products, preserving their quality until consumption, and effectively safeguarding them during storage and transportation (Kan & Miller, 2022). Indeed, it is widely recognized that the separate collection of plastic materials plays a key role in sustainable waste management (Rigamonti et al., 2014). This is a topic of growing environmental as well as social relevancy, as large quantities of plastics are used daily in industrial and domestic settings to transport, distribute, preserve, and store consumer goods. Recycling is crucial to reduce the dependency on non-renewable fossil resources needed to produce new plastics. In alignment with this, the European Union has established that by 2030 all plastic packaging placed on the European market must be reusable or effectively recyclable in terms of cost, and at least half must be recycled (Hudson et al., 2023).

3.1.1. Plasmix: an end and a new beginning

As Fig. 1 displays, the story of plasmix begins when the supply chain of plastic products reaches the end of lifecycle. The recycling of plastics has indeed improved in the last decades, but it is far from being 100% effective. Nowadays still 50% of the waste remains unrecycled because existing sorting systems often fall short in isolating all types of polymers (Hopewell et al., 2009). Moreover, packaging is identified as the largest contributor to global waste, with production reaching 146 million tons in 2015. Out of this, 141 million tons were not recycled (Rosenboom et al., 2022). Going backwards, it all starts with the manufacturing of monomers and additives, which serve as main components for plastics. These chemicals are synthesized in chemical plants and then distributed to plastic manufacturing facilities. Manufacturers and producers are the backbone of this industry, responsible for creating 350 million tonnes of plastic products per year through processes of polymerization, compounding and moulding (Wiesinger et al., 2021). These plastic products are used in plenty of industries, and as they reach the end of their lifecycle, they enter the disposal phase.

In Italy, disposal options include recycling, incineration, and landfill, with recycling playing a crucial role in reducing the environmental impact of plastic waste. Then, the products and materials that the actual technologies do not manage to recycle collectively contribute to the increasing amount of plasmix. Once collected, these plastics are sorted and separated to ensure they meet the necessary quality and purity standards. The subsequent steps involve cleaning and shredding the plastic materials to prepare them for processing. Then, these shredded plastics are transported to recycling facilities, where they undergo various processes such as extrusion, moulding, or compounding to create recycled plastic pellets. These pellets play a vital role in manufacturing a diverse array of products, thus fostering the principles of the CE and advancing sustainability within the plastics industry. Moreover, environmental organizations and activists are fervent advocates for

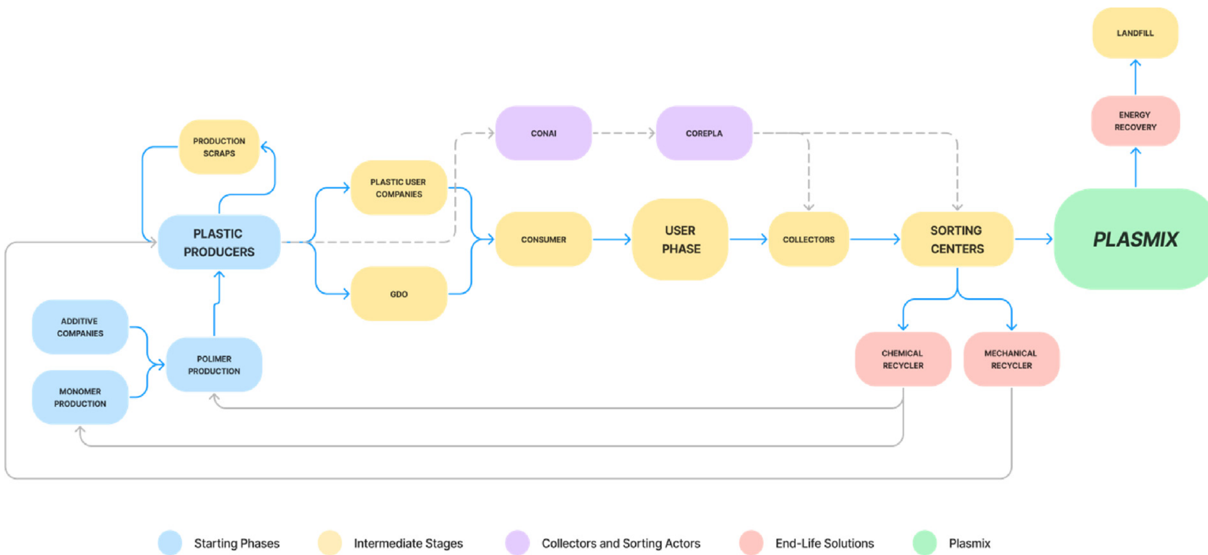

Fig. 1. Plastic supply chain.

sustainability, diligently raising awareness about the environmental impact of plastic and emerging as influential stakeholders.

3.1.2. Plasmix: production, characteristics, and final product

As already explained, plasmix is a complex material consisting not only of polyolefins, such as polypropylene (PP) and polyethylene (PE), but also a varied assortment of other plastics. Being it a 'discard-of-discards' its composition fluctuates based on factors such as the specific batch, timing, and location of collection. Moreover, certain polymers within plasmix lack market value as secondary materials. Consequently, recycling facilities do not deliberately separate these polymers because they would remain unsold, nullifying the efforts made during the selection process. The polymers contained in the plasmix include, in addition to the polyolefin mixtures, other polymers such as polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), ethylene-vinyl acetate (EVA), polystyrene (PS), which are present in varying quantities depending on the geographic area and collection period (Gazzotti et al., 2022). Residues from the selection process, such as wood, iron, and other non-plastic materials, can also be found. COREPLA defines two main categories: *i)* the 'plasmix line term', which is collected at the end of the selection operations, includes the polyolefin mix and the polyethylene terephthalate mix, and *ii)* 'the fine plasmix', which is collected in the first phase of the process, where small packaging composed of the remaining polymers, excluding polyolefins and processing residues, are present (COREPLA, 2015). According to COREPLA, the main processes applied for plasmix are incineration (57%), burning as a substitute for coal (27%), and landfill (16%) (Cossu et al., 2017).

Surely, preliminary LCA studies have presented a silver lining, suggesting that when executed efficiently, these methods offer the least environmental impact among available alternatives (Cossu et al., 2017). Nevertheless, the diverse composition of plasmix, with its myriad of plastic materials, positions it as a potential goldmine for raw materials in the production of innovative and sustainable products. To utilize it in recycling, it is essential to determine its properties suitable for processing into new products, including its polymeric composition, the presence of additives or low molecular weight compounds, and the extent of degradation. Plasmix is well-suited for raw materials in extrusion and moulding processes, necessitating a deeper understanding of its viscoelastic and mechanical properties. This involves identifying appropriate treatment phases, such as the use of suitable chemical additives or the incorporation of virgin plastics into the mix. Furthermore, the resulting materials should be thermoplastic, with plasmix melting characteristics falling within the injection moulding range for PE and PP plastics (Fig. 2).

3.2. Life cycle assessment of plasmix

The goal of this LCA study is to compare different semi-finished products derived from the recovery and processing of plasmix. These products were processed during the PHOENIX project to evaluate their physical and ecotoxicological characteristics with the goal of testing their potential to be reintroduced into the market as secondary raw materials. However, it should be noted that during the project, these tests were carried out using test specimens ('laboratory samples') resulting from the injection moulding of different plasmix mixes and other virgin polymers solely for laboratory analysis, and therefore not intended for commercial use.

The use of plasmix as starting material to produce new products with higher added values has not been previously investigated in detail from an environmental point of view. Different plasmix management pathways were evaluated by LCA (Cossu et al., 2017) but there is a lack of information about plasmix processing and use as raw material. In this regard, the results of our LCA are useful because they provide a preliminary overview of the environmental performances of different materials made by a different composition between plasmix and other components. These results can be used as starting point for the LCA application to high added valued products made also with plasmix as raw material.

3.2.1. Functional unit and system boundary definition

From an LCA perspective, the functional unit (FU) of 1 kg of printed material was used rather than individual printed objects. The printed materials studied in this contribution are a total of 5 and can be divided into two main categories:

1. Products printed from extruded predominantly plasmix, including:
   - 100% plasmix;
   - 96% plasmix and 4% acrylonitrile butadiene styrene (ABS);
   - 96% plasmix, 3.6% polypropylene, and 0.6% peroxide.

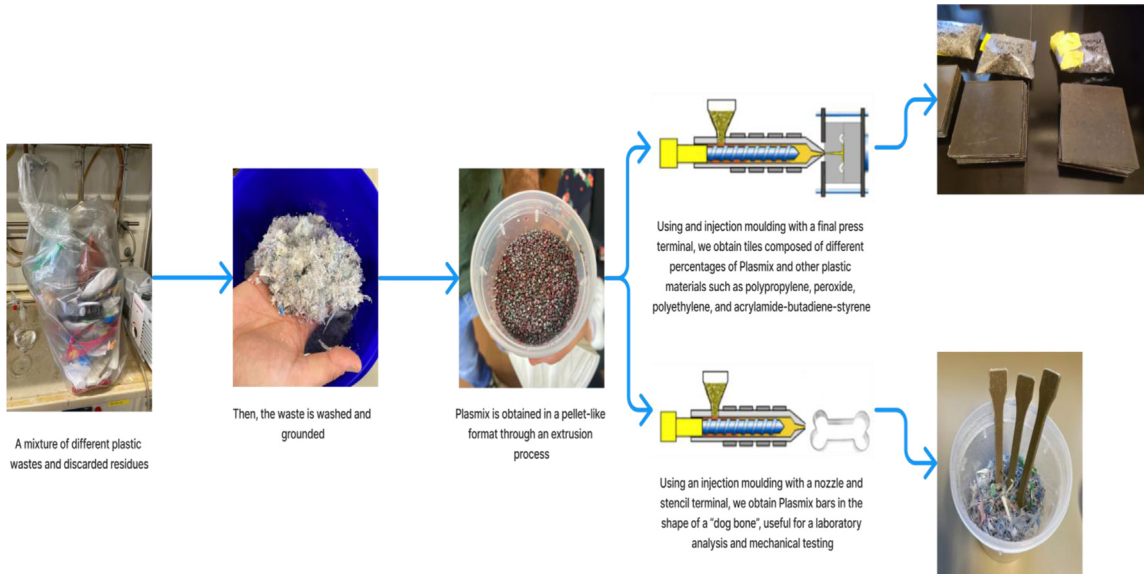

Fig. 2. Schematically illustrates all the process stages employed to obtain the plasmix-based product.

2. Products printed from extruded different combinations of plasmix and virgin plastic, including:
   - 60% plasmix and 40% polyethylene;
   - 10% plasmix and 90% polyethylene.

The processing method, schematically shown below in Fig. 3, is divided into the following stages: washing, intensive shredding, extrusion (one or two, depending on the different final product), and finally moulding. The system boundaries, of the cradle-to-gate type, follow the scheme shown, including for each process the associated energy and material consumption as well as generated waste. For example, water consumption and wastewater disposal are included for the washing stage.

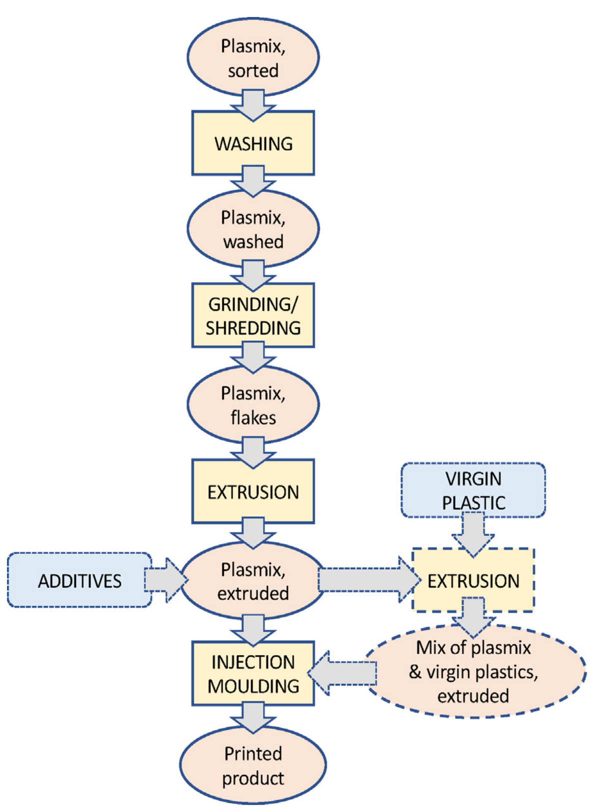

Fig. 3. Schematic representation of system boundaries (Notes: dashed lines indicate all the products and processes that are involved in the production cycle of only certain finished prints among those analysed).

For the extruded products made from different combinations of plasmix and virgin plastic, two extrusions in series were required: the first for the plasmix only, and the second one to create the two different combinations with polyethylene.

The previous stages of the supply chain, including waste collection and transportation and the separation process, were excluded. This approach is known as 'burden-free': since plasmix is currently a waste product with zero economic value, its production is considered to have zero impact because all energy and material consumption, as well as emissions, of the collection and separation processes aimed at recycling are allocated to the primary raw materials obtained from them.

3.2.2. *Life cycle inventory*

The plasmix processing and recovery steps were internally designed by researchers at the Università degli Studi di Milano (Table 1). Although it was performed on a laboratory scale, the researchers used tools that are widely applied on a commercial scale in industrial recycling facilities. Since the process does not require dedicated equipment, it was simulated for implementation

Table 1
Processes used by the Ecoinvent® database and their respective notes.

Process	Reference dataset	Note
Washing	N.A.	Modelled considering energy consumption by Rigamonti et al. (2014). For washing, water consumption and consequent generation of wastewater were considered by Cossu et al. (2012).
Shredding	Plastic flake production, for recycling, by grinding/shredding, formal sector {IN}	Modified considering energy sources representative for RER geography
Extrusion	Extrusion, plastic film {RER}	–
Moulding	Injection moulding {RER}	–

in an existing plastic material recovery and recycling plant, with the following assumptions:

- Excluding the transportation of plasmix from the site where it is generated to the site where it is processed for recovery and valorisation.
- Assuming energy and material consumption like those of machinery installed and in operation in commercial plants, as retrieved from literature and reference databases, particularly Ecoinvent® v 3.8 using the Allocation at the point of substitution (APOS) modelling approach. Table 1 reports the main Ecoinvent® datasets used.

3.2.3. *Life cycle impact assessment*

To address the complex challenges of environmental pressures and resource scarcity comprehensively, our study leveraged the Environmental Footprint 3.0 Method (adapted) V1.00/EF 3.0 normalization and weighting set (Fazio et al., 2018), to convert inventory data into nuanced environmental indicators. This method was proposed and developed by the European Commission as a common way of measuring environmental performance (EC, 2021). It is the standardized method recommended for use within Product Environmental Footprint Category Rules (PEFCRs), Organisation Environmental Footprint Sector Rules (OEFSRs), and in the analysis of Product Environmental Footprints (PEF) and Organisation Environmental Footprints (OEF) (Knigawka & Ganczewski, 2023).

This choice was motivated by the method's robust characterization factors, tailored to accurately reflect a broad spectrum of environmental impacts, thereby ensuring a detailed understanding of the assessed activities' environmental and resource implications.

In details, all the 16 impact categories considered: Climate change, Ozone depletion, Ionising radiation, Photochemical ozone formation, Particulate matter, Human toxicity, non-cancer, Human toxicity, cancer, Acidification, Eutrophication, freshwater, Eutrophication, marine, Eutrophication, terrestrial, Ecotoxicity, freshwater, Land use, Water use, Resource use, fossils, Resource use, minerals and metals.

4. Results and discussion

4.1. *Environmental results from LCA*

Table 2 presents the results of the impact analysis. As expected, the product with the lowest environmental footprint is the one derived entirely from plasmix for all impact categories, even though it has the worst chemical-physical and mechanical characteristics, and it is particularly unsuitable for market standards. However, this semi-finished product is interesting because it serves as a reference point. The results will be used in an eco-design perspective to find the best compromise between increased impacts due to the introduction of virgin material into the system and the technological characteristics of the resulting products. The relative comparison among the different solutions is reported in Fig. 4.

Comparing the two semi-finished products composed of 96% plasmix and 4% other material, the product with peroxide has a lower impact for 11 out of 16 categories (ranging from −0.1% to −0.7%), including climate change, and the product with ABS has a lower impact for the remaining categories.

The extruded products made of different combinations of plasmix, and virgin plastic have significantly higher impacts, but they cannot be directly compared with the other products as they underwent two extrusions and involved much larger quantities of virgin raw materials. It should be noted that, from the perspective of introducing plasmix-based products into the market, it is plausible that a second extrusion would be carried out in any case (usually this process involves adding colorants to plastic materials, for example) and thus does not represent an additional step solely due to the current need to combine extruded plasmix with other polymers to achieve satisfactory technological characteristics of the final product.

Moreover, Table 3 provides an in-depth analysis of climate change, with a breakdown of contributions to weigh the different phases of the process and their inputs compared to the kilogram of printed product. The results in the table confirm that the process becomes more impactful as more external virgin chemical materials are added in combination with plasmix, as shown particularly by the role of polyethylene in those products in which it was used.

4.2. *The environmental layer*

As shown in Fig. 5, the key point of the environmental layer resides in the *functional value* of the product. This aspect encompasses the tangible output of a company's production processes, denoting what a product or service provides in terms of physical quantity (Joyce & Paquin, 2016; Zilia et al., 2021). As extensively elaborated in Section *3.2, life cycle assessment* of plasmix, a LCA was performed on tiles of material printed with varying percentage of plasmix content, with each unit carrying a functional unit of 1 kg of printed product. These analyses were undertaken to discern the

Table 2
Results expressed in reference to 1 kg of printed product.

Impact category	Unit	Plasmix 100%	Plasmix 96% (with ABS)	Plasmix 96% (with peroxide)	Plasmix 60% - PE 40%	Plasmix 10% - PE 90%
Climate change	kg CO_2 eq	1.452E+00	1.637E+00	1.539E+00	2.593E+00	3.529E+00
Ozone depletion	kg CFC11 eq	1.632E−07	1.661E−07	1.648E−07	1.998E−07	2.101E−07
Ionising radiation	kBq U-235 eq	5.577E−01	5.579E−01	5.595E−01	6.917E−01	6.290E−01
Photochemical ozone formation	kg NMVOC eq	3.644E−03	4.127E−03	3.922E−03	7.336E−03	1.080E−02
Particulate matter	Disease inc.	3.766E−08	4.668E−08	4.121E−08	8.057E−08	1.198E−07
Human toxicity, non-cancer	CTUh	1.335E−08	1.385E−08	1.395E−08	2.181E−08	2.749E−08
Human toxicity, cancer	CTUh	9.096E−10	9.414E−10	9.407E−10	1.346E−09	1.468E−09
Acidification	mol H+ eq	6.886E−03	7.493E−03	7.230E−03	1.164E−02	1.523E−02
Eutrophication, freshwater	kg P eq	9.473E−04	9.563E−04	9.609E−04	1.258E−03	1.296E−03
Eutrophication, marine	kg N eq	1.340E−03	1.444E−03	1.401E−03	2.226E−03	2.875E−03
Eutrophication, terrestrial	mol N eq	1.148E−02	1.253E−02	1.217E−02	2.090E−02	2.862E−02
Ecotoxicity, freshwater	CTUe	2.129E+01	2.306E+01	2.236E+01	3.326E+01	4.124E+01
Land use	Pt	1.450E+01	1.455E+01	1.462E+01	1.986E+01	1.816E+01
Water use	m^3 depriv.	1.421E+00	1.515E+00	1.464E+00	2.342E+00	2.400E+00
Resource use, fossils	MJ	3.138E+01	3.487E+01	3.404E+01	6.404E+01	9.548E+01
Resource use, minerals, and metals	kg Sb eq	5.833E−06	5.910E−06	6.336E−06	1.222E−05	1.756E−05

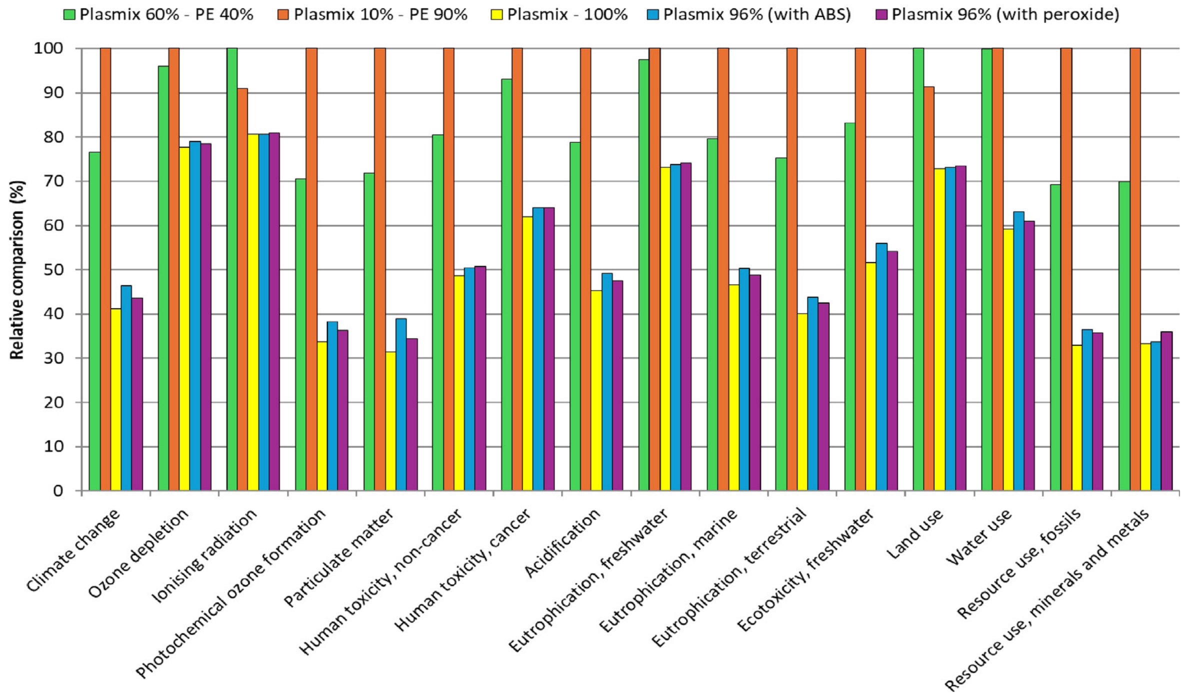

Fig. 4. Relative comparison among the different solutions.

Table 3
Relative contribution of different processing stages and inputs to climate change (CO_2 eq. emissions) per kg of printed product.

Relative contribution	Plasmix 100%	Plasmix 96% (with ABS)	Plasmix 96% (with peroxide)	Plasmix 60%—PE 40%	Plasmix 10%—PE 90%
Washing (only plasmix)	1.1%	0.9%	1.0%	0.4%	0.0%
Shredding (only plasmix)	8.3%	7.1%	7.5%	2.8%	0.3%
Additives for the 1st extrusion	–	11.6%	6.0%	–	–
1st extrusion	27.0%	23.9%	25.5%	9.1%	1.1%
Polyethylene	–	–	–	37.0%	61.2%
2nd extrusion	–	–	–	15.1%	11.1%
Moulding	63.6%	56.5%	60.1%	35.6%	26.2%

optimal utilization of the five tiles with different plasmix content for crafting prospective end-products.

Regarding the *end-of-life* phase for plasmix-based products, it is crucial to underscore that this material is entirely recyclable, thereby holding the potential for multiple reuse cycles, aligned with the principles of a CE.

In the realm of *production*, the processes exerting the most substantial environmental impact in the pursuit of pure plasmix are the stages of plastic washing and cleaning, gridding into smaller components, extrusion, and finally, moulding. These practices necessitate the consumption of electric energy, heat, and water, consequently engendering environmental issues. The *environmental impact* encompasses the quantification of the ecological costs inherent in the company's operational activities (Joyce & Paquin, 2016). In our case study, aside from the energy and water consumption during production processes, there might be additional challenges if plasmix-based products are not properly disposed of and instead become dispersed within the environment. This issue parallels the ongoing predicament associated with plastics in general, frequently mismanaged and causing significant harm to ecosystems.

A market oriented toward a CE, distinguished by sustainable products forged from waste-derived materials, undoubtedly brings forth *environmental benefits*. Commercial utilization of plasmix would not only drastically curtail the accumulation of solid plastic waste but also yield broader advantages, including the reduction of CO_2 emissions. Moreover, as discerned from the LCA conducted on the plasmix laboratory sample, products composed entirely of plasmix exhibit lesser environmental impacts than comparable items with lower plasmix proportions across all 16 analysed impact categories. While a market exclusively producing products entirely made of plasmix might currently pose challenges due to mechanical aspects of the material, its distinctive characteristics render it a compelling subject for further research.

Lastly, the *distribution* process encompasses both the transportation of plasmix from sorting centres to recycling facilities and the conveyance of the final product to consumers (Fig. 5). In Italy, road transportation predominates as the primary choice given the localized nature of the business.

4.3. Plasmix applications: pioneering sustainable innovations

At the heart of the Phoenix project's mission lays the vision of a future where plasmix's transformative capabilities are utilised to create a range of environmentally conscious products.

Through teamwork, our semi-finished material was entrusted to eco-designers. They adopted a systemic approach to create everyday sustainable products made with plasmix, such as cinerary

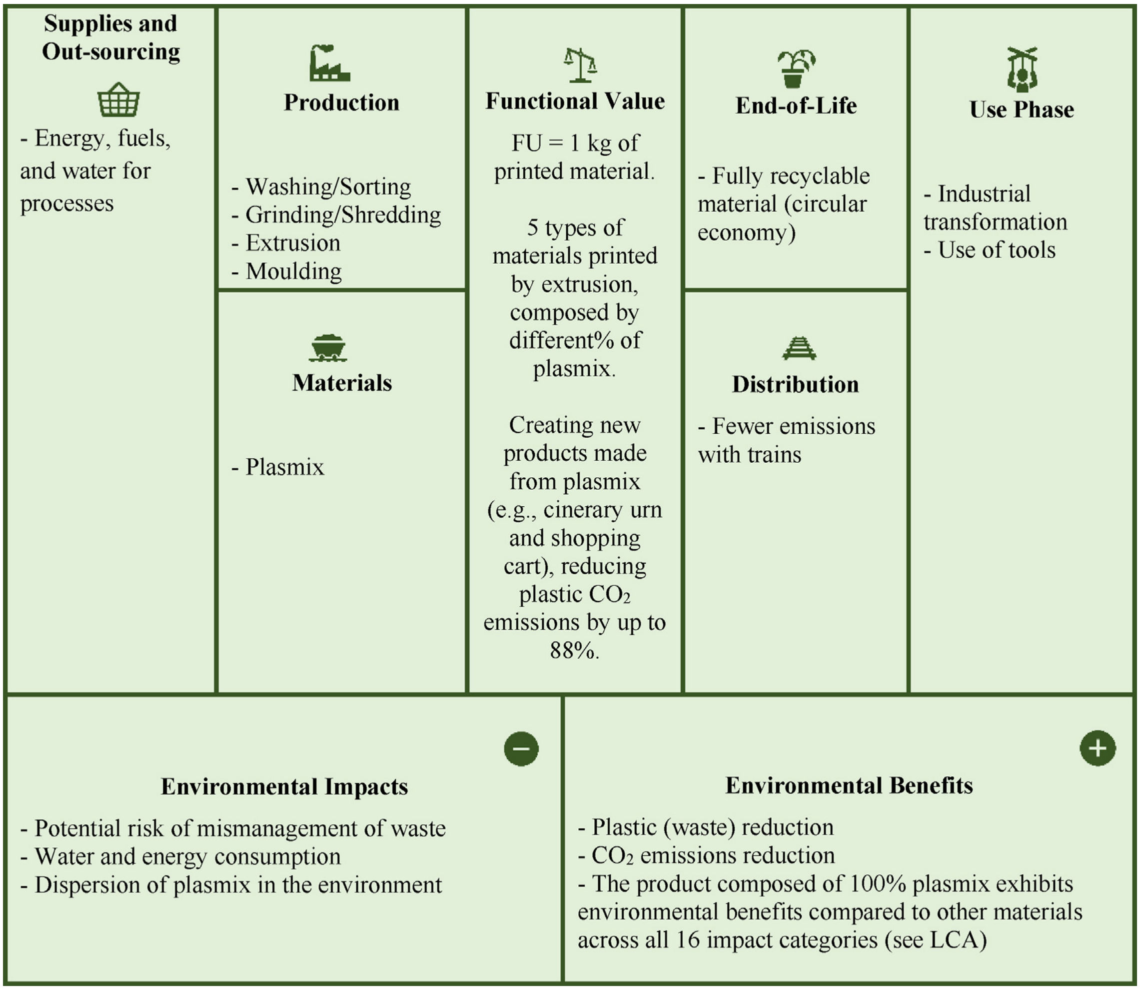

Fig. 5. The environmental layer for plasmix products (Joyce & Paquin, 2016).

urns, dog waste bag holders, sunglasses, urban furniture, and shopping carts.

Among these innovations, the concept of a cinerary urn is particularly notable. Still in its experimental phase, this urn embodies a fusion of aesthetic sophistication and environmental stewardship, reimagining a traditionally solemn item into a symbol of rebirth and continuity.

Moving beyond urns, the plasmix material holds immense potential for a diverse array of products. Concepts have been put forth for items such as waste bag holders for dogs, sunglasses, urban furniture, and even a shopping cart. While these ideas are in their early stages, they exemplify the versatility of plasmix to integrate into various aspects of daily life. From essential household items to personal accessories, the adaptability of plasmix as a material offers a distinctive avenue for sustainable design. As we delve into these possibilities, it is crucial to bear in mind that plasmix originates from what is presently slated for incineration or landfilling. Its composition, a blend of recycled plastic waste and non-plastic materials, presents both challenges and opportunities.

Basically, this research is a ground-breaking effort to deal with the complexities of plastic use and waste. By repurposing plasmix into innovative, sustainable products, we not only mitigate environmental impact but also usher in a new era of eco-conscious design. This undertaking underscores the transformative potential of collaborative research and the boundless possibilities of recycled materials in moulding a more sustainable future.

4.4. Managerial and policy implications

Based on the comprehensive analysis of the plasmix project, there are several noteworthy managerial and policy implications. Firstly, given the potential for plasmix to serve as a foundational material for various eco-sustainable products, it is crucial for businesses to invest in research and development aimed at optimizing its properties. This involves ongoing efforts to enhance the mechanical characteristics and stability of plasmix-based products, ensuring they meet market standards. Additionally, companies should focus on innovative techniques in production, including refining the extrusion and moulding processes, to maximize the material's potential.

In addition, in March 2018, the Italian Chamber of Deputies introduced Legislative Proposal C.59 during the XVIII Legislature, aimed at regulating and incentivizing the acquisition of products and furnishings made from plasmix and non-hazardous waste derived from industrial production processes and the sorting and recovery of municipal solid waste. This proposal, which progressed to the Senate as Act No. 635 in December 2018, sought to facilitate a 50% tax credit for all purchases of such products. It aimed to extend benefits to energy-intensive companies (in Article 39, Legislative Decree 83/2012, as amended by Law 134/2012), those involved in the selection and recycling of plastic packaging, companies processing plasmix materials, and facilities managing end-of-life vehicles (L'Abbate et al., 2018).

The provision of subsidies to newcomers in the plasmix-based product market was intended to significantly reduce entry barriers in this sector, characterized by high management and production costs. Such financial incentives were expected not only to ease the entry of new competitors but also to encourage innovation and foster a competitive environment in a sector demanding substantial initial and ongoing investment. By alleviating the economic challenges faced by these entities, the subsidies aimed to promote wider adoption of sustainable waste management and recycling practices, contributing to more eco-friendly production approaches and advancing the CE concept (Mishra et al., 2023).

Moreover, the legislative proposal included measures to ensure the appropriate allocation of funds, such as the mandatory acquisition of a 'second-life plastic' certification by companies seeking environmental subsidies and financing. It also proposed the creation of a €300 million annual fund managed by the Ministry of the Environment from 2018 onwards. This fund was designated for public entities and private organizations to enhance urban green spaces, public park furnishings, traffic products, and plasmix-based waste collection containers. Although the bill has not been ratified and published in the Official Gazette (in Italian *Gazzetta Ufficiale*), several Italian companies have been active in the mixed-plastic recycling sector for years, producing recycled mixed-plastic granules. Among them, Revet Recycling specializes in processing this material into a raw material for manufacturing packaging, construction components like roof tiles and garden tiles, as well as outdoor furniture and urban area fittings (Fiore & Tamborrini, 2024).

The strategic collaboration with key stakeholders within the plastic waste management ecosystem, including recycling facilities and government agencies, is crucial for ensuring a stable and dependable plasmix supply.

As the project aligns with the principles of a CE, businesses need to adopt a forward-thinking approach to their product life cycles. This entails designing products with end-of-life considerations in mind, facilitating their recyclability and reusability. Implementing effective take-back schemes and reverse logistics will be crucial for efficiently managing the return of plasmix-based products to the production cycle.

Additionally, companies should prioritize eco-design practices, exploring opportunities for customization and personalization to meet diverse customer preferences. Indeed, prioritizing eco-design leads to a stronger environmental commitment, consequently becoming a crucial practice in green supply chain management (Ahmad et al., 2022). From an operational standpoint, investing in state-of-the-art recycling machinery and technologies will be paramount in ensuring the efficient processing of plasmix. This includes advanced sorting, washing, and cleaning equipment, as well as extrusion and moulding technologies that can handle the specific characteristics of plasmix. Moreover, businesses should explore opportunities for energy recovery from plasmix processing, contributing to both environmental sustainability and cost efficiency.

Finally, in terms of market positioning, companies venturing into the plasmix-based product industry should actively engage in consumer education and awareness campaigns. This will serve to highlight the environmental benefits of plasmix products and foster a consumer base that values sustainability. Additionally, transparent communication regarding the eco-friendly attributes of plasmix-based items will be instrumental in building trust and brand loyalty. Overall, the successful integration of plasmix into business models necessitates a holistic and forward-looking approach that encompasses research, production, operations, and marketing strategies. This approach not only positions businesses at the forefront of sustainable innovation but also contributes positively to the broader goals of environmental conservation and resource optimization.

5. Conclusions

This study offers a comprehensive analysis of semi-finished plasmix-based products and future possible goods, highlighting their potential as secondary raw materials in the market. Plasmix, a unique composition of plastic waste mixed with non-plastic materials like wood, metals, and cardboard, presents a distinctive opportunity for recycling and reusing waste. The research underscores the significance of considering the life cycle aspects of partially processed products made from plasmix, emphasizing their value and benefits through various stages, including engineering, assembly, service, maintenance, and disassembly.

Plasmix exhibits a range of properties, and its applications are diverse. One of the most promising uses involves the manufacture of plastic pellets, which maintain identical composition, appearance, and properties to pellets produced from virgin raw materials. This not only addresses the issue of waste but also allows for seamless integration into existing manufacturing processes. Furthermore, this recycling approach aligns closely with the concept of reusing materials, making it an environmentally friendly option.

The study also identifies business opportunities in the waste management sector, where companies can profit from disposing of plasmix. This contrasts with the environmental and spatial sustainability issues associated with landfilling, which poses risks of pollution and exhausts finite land resources.

Considering the comprehensive nature of this study, certain limitations must be acknowledged. First, the analysis of plasmix would benefit from further research to assess its mechanical properties, material stability, and resistance. This would provide a more robust foundation for its widespread application.

Moreover, some prototypes like sunglasses made from a combination of metal and plasmix, may face challenges in a competitive market and their prolonged contact with the skin. Health-related implications remain a consideration. Additionally, prolonged exposure to atmospheric agents could potentially affect the quality and characteristics of the product.

Second, the LCA covers only a specific segment of the material's supply chain. Indeed, it was conducted solely on semi-finished materials with varying contents of plasmix. Future analyses should encompass the entire life cycle of the end-product, from production to disposal, to provide a comprehensive assessment of its environmental impact.

Third, data availability at an industrial level was also found to be limited, with key industry actors often challenging to identify or contact. This dearth of accessible information poses a hurdle to comprehensive research and development efforts.

In recent years, as future directions, through collaborations among institutions, research entities, and the market, there has been an increase in the number of projects and initiatives aimed at experimenting with new technologies to produce syngas and methanol from mixed plastic waste that is otherwise non-recyclable, such as plasmix. The availability of mechanical recycling facilities and the development of new technologies to complement mechanical recycling are crucial for maximizing the recycling of plastic packaging materials that are not yet recoverable as matter. Consequently, significant focus is placed on the development of chemical recycling aimed at converting plastic waste back into plastic, known as feedstock recycling.

This strategic approach to waste management aligns with the growing emphasis on sustainable practices and the circular economy, where the goal is to keep resources in use for as long as possible, extract the maximum value from them while in use, and recover and regenerate products and materials at the end of their service life.

By leveraging collaborations across various sectors, the development and implementation of these cutting-edge technologies for the recycling of mixed plastic waste not only tackle environmental issues but also lay the foundation for more efficient resource use and waste reduction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ahmad, A., Ikram, A., Rehan, M. F., & Ahmad, A. (2022). Going green: Impact of green supply chain management practices on sustainability performance. *Frontiers in Psychology, 13*, Article 973676.
Alhazmi, H., Almansour, F. H., & Aldhafeeri, Z. (2021). Plastic waste management: A review of existing life cycle assessment studies. *Sustainability, 13*, 5340.
Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering, 33*, 308–320.
Braungart, M., McDonough, W., & Bollinger, A. (2007). Cradle-to-cradle design: Creating healthy emissions–A strategy for eco-effective product and system design. *Journal of Cleaner Production, 15*, 1337–1348.
Chiappetta Jabbour, C. J., Seuring, S., Lopes de Sousa Jabbour, A. B., Jugend, D., De Camargo Fiorini, P., Latan, H., & Izeppi, W. C. (2020). Stakeholders, innovative business models for the circular economy and sustainable performance of firms in an emerging economy facing institutional voids. *Journal of Environmental Management, 264*, Article 110416.
Christensen, T. H., Simion, F., Tonini, D., & Møller, J. (2009). Global warming factors modelled for 40 generic municipal waste management scenarios. *Waste Management & Research: The Journal for a Sustainable Circular Economy, 27*, 871–884.
COREPLA. (2015). *COREPLA - Consorzio Nazionale per la raccolta, il recupero e il riciclaggio dei rifiuti di imballaggi in plastica*. Available at: https://www.corepla.it/prodotti (in Italy).
COREPLA. (2020). Consorzio Nazionale per la raccolta, il riciclo e il recupero degli imballaggi in plastica. *Rapporto di Sostenibilità*. Available at: https://www.corepla.it (in Italy).
Cossu, R., Garbo, F., Girotto, F., Simion, F., & Pivato, A. (2017). PLASMIX management: LCA of six possible scenarios. *Waste Management, 69*, 567–576.
Cossu, R., Lai, T., & Pivnenko, K. (2012). Waste washing pre-treatment of municipal and special waste. *Journal of Hazardous Materials, 207–208*, 65–72.
Curran, M. A. (2013). Life cycle assessment: A review of the methodology and its application to sustainability. *Current Opinion in Chemical Engineering, 2*, 273–277.
Davidson, M. G., Furlong, R. A., & McManus, M. C. (2021). Developments in the life cycle assessment of chemical recycling of plastic waste–A review. *Journal of Cleaner Production, 293*, Article 126163.
Diggle, A., & Walker, T. R. (2022). Environmental and economic impacts of mismanaged plastics and measures for mitigation. *Environments, 9*, 15.
EC. (2003). *Communication from the Commission to the Council and the European Parliament - integrated product policy - building on environmental life-cycle thinking*. Brussels: European Commission (EC). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52003DC0302.
EC. (2021). Commission Recommendation (EU) 2021o/2279 of 15 December 2021o on the use of the environmental footprint methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021H2279#document1.
EMF. (2013). *Towards the circular economy - economic and business rationale for an accelerated transition*. Available at: https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an.
EMF. (2015a). *Delivering the circular economy a toolkit for policymakers*. Available at: https://www.ellenmacarthurfoundation.org/a-toolkit-for-policymakers.
EMF. (2015b). *Growth within: A circular economy vision for a competitive Europe*. Available at: https://www.ellenmacarthurfoundation.org/growth-within-a-circular-economy-vision-for-a-competitive-europe.
European Parliament and Council. (2008). *Directive 2008/98/EC of the European parliament and of the council of 19 november 2008 on waste and repealing certain directives*. Available at: http://data.europa.eu/eli/dir/2008/98/2018-07-05.
Fahim, I., Mohsen, O., & ElKayaly, D. (2021). Production of fuel from plastic waste: A feasible business. *Polymers, 13*, 915.
Fazio, S., Castellani, V., Sala, S., Schau, E. M., Secchi, M., & Zampori, L. (2018). *Supporting information to the characterisation factors of recommended EF life cycle impact assessment methods, version 2, from ILCD to EF 3.0, EUR 29600 EN*. European Commission. https://doi.org/10.2760/002447. Ispra ISBN 978–92–79–98584–3.
Fiore, E., & Tamborrini, P. (2024). Phoenix: Towards a circular economy of plasmix waste—a systemic design approach. *Circular Economy, 3*, Article 100075.
Gazzotti, S., De Felice, B., Ortenzi, M. A., & Parolini, M. (2022). Approaches for management and valorization of non-homogeneous, non-recyclable plastic waste. *International Journal of Environmental Research and Public Health, 19*, Article 10088.
Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production, 114*, 11–32.
Goffetti, G., Böckin, D., Baumann, H., Tillman, A. M., & Zobel, T. (2022). Towards sustainable business models with a novel life cycle assessment method. *Business Strategy and the Environment, 31*, 2019–2035.
Gutowski, T. G. (2018). A critique of life cycle assessment; where are the people? *Procedia CIRP, 69*, 11–15.
Hellweg, S., & Milà i Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science, 344*, 1109–1113.
Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: Challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*, 2115–2126.
Hudson, G., Brzezicka, P., Verbeek, A., & Samoylov, R. (2023). *Cutting plastics pollution – financial measures for a more circular value chain*. Luxembourg: European Investment Bank.
Iacovidou, E., Velis, C. A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., Millward-Hopkins, J., & Williams, P. T. (2017). Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review. *Journal of Cleaner Production, 166*, 910–938.
ISO 14040. (2006). *Environmental management - life cycle assessment - principles and framework*. Geneva: International Organization for Standardization.
ISO 14044. (2006). *Environmental management - life cycle assessment - requirements and guidelines*. Geneva: International Organization for Standardization.
Jegen, M. (2024). Life cycle assessment: From industry to policy to politics. *International Journal of Life Cycle Assessment, 29*, 597–606.
Joyce, A., & Paquin, R. L. (2016). The triple layered business model canvas: A tool to design more sustainable business models. *Journal of Cleaner Production, 135*, 1474–1486.
Kan, M., & Miller, S. A. (2022). Environmental impacts of plastic packaging of food products. *Resources, Conservation and Recycling, 180*, Article 106156.
Knigawka, P. A., & Ganczewski, G. J. (2023). Environmental assessment of hard coal char as a carbon reductant for silicon alloys production. *International Journal of Life Cycle Assessment, 28*, 1640–1657.
Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: The concept and its limitations. *Ecological Economics, 143*, 37–46.
Kwak, H. Y., Kim, M. H., Lee, S. T., & Gim, G. Y. (2021). The triple layered business model canvas for sustainability in mobile messenger service. In H. Kim, & R. Lee (Eds.), *Studies in computational intelligenceSoftware engineering in IoT, big data, cloud and mobile computing*. Cham: Springer.
L'Abbate, P., Moronese, V., Quarto, R., La Mura, V., Mantero, M., De Falco, G., Nugnes, P., Anastasi, C., Croatti, M., Coltorti, M., Dessi, E., Ferrara, G., Turco, M., Mininno, C., Gallicchio, A., Garruti, V., Grassi, U., & Dell'Olio, G. (2018). Incentivi per favorire la diffusione dei prodotti derivanti da materiale post-consumo a base di plastica (plasmix e scarti non pericolosi dei processi di selezione e di recupero), nonché disposizioni concernenti la realizzazione dei veicoli. *Senato della Repubblica*. Available at: https://www.senato.it/leg/18/BGT/Schede/Ddliter/50156.htm (in Italy).
Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production, 115*, 36–51.
Mason, K., & Chakrabarti, R. (2017). The role of proximity in business model design: Making business models work for those at the bottom of the pyramid. *Industrial Marketing Management, 61*, 67–80.
Mishra, B., Mohanta, Y. K., Reddy, C. N., Reddy, S. D. M., Mandal, S. K., Yadavalli, R., & Sarma, H. (2023). Valorization of agro-industrial biowaste to biomaterials: An innovative circular bioeconomy approach. *Circular Economy, 2*, Article 100050.
Moretti, C., Hamelin, L., Jakobsen, L. G., Junginger, M. H., Steingrimsdottir, M. M., Høibye, L., & Shen, L. (2021). Cradle-to-grave life cycle assessment of single-use cups made from PLA, PP and PET. *Resources, Conservation and Recycling, 169*, Article 105508.
Morris, M., Schindehutte, M., & Allen, J. (2005). The entrepreneur's business model: Toward a unified perspective. *Journal of Business Research, 58*, 726–735.
Novati, G., & Leonardi, M. (2022). Plastics in Italy: A vice or a virtue? Technical report. In *The Italian climate change think tank*. Milan: ECCO. Available at: https://eccoclimate.org/wp-content/uploads/2022/04/Plastics-in-Italy.pdf.

Nußholz, J. (2017). Circular business models: Defining a concept and framing an emerging research field. *Sustainability, 9*, 1810.
Pigneur, Y., & Osterwalder, A. (2010). Business model generation: A handbook for visionaries. *Game changers, and challengers*. John Wiley & Sons.
Pigosso, D. C. A., Zanette, E. T., Filho, A. G., Ometto, A. R., & Rozenfeld, H. (2010). Ecodesign methods focused on remanufacturing. *Journal of Cleaner Production, 18*, 21–31.
Plastics Europe. (2022). *Plastics – the facts 2022*. Available at: https://plasticseurope.org/knowledge-hub/plastics-the-facts-2022/.
Reike, D., Vermeulen, W. J., & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? —exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling, 135*, 246–264.
Riber, C., Bhander, G. S., & Christensen, T. H. (2008). Environmental assessment of waste incineration in a life-cycle-perspective (EASEWASTE). *Waste Management & Research: The Journal for a Sustainable Circular Economy, 26*, 96–103.
Rigamonti, L., Grosso, M., Møller, J., Martinez Sanchez, V., Magnani, S., & Christensen, T. H. (2014). Environmental evaluation of plastic waste management scenarios. *Resources, Conservation and Recycling, 85*, 42–53.
Rosenboom, J. G., Langer, R., & Traverso, G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials, 7*, 117–137.
Seidel-Sterzik, H., McLaren, S., & Garnevska, E. (2018). Effective life cycle management in SMEs: Use of a sector-based approach to overcome barriers. *Sustainability, 10*, 359.
Stahel, W. R., & Reday, G. (1981). *Jobs for tomorrow: The potential for substituting manpower for energy*. New York: Vantage Press.
Teece, D. J. (2010). Business models, business strategy and innovation. *Long Range Planning, 43*, 172–194.
UNEP. (2005). *Life Cycle Approaches- the road from analysis to practice*. United Nations Environment Programme (UNEP). Available at: file:///C:/Users/Administrator/Downloads/2005%20-%20LCA.pdf.
Vlasopoulos, A., Malinauskaite, J., Żabnieńska-Góra, A., & Jouhara, H. (2023). Life cycle assessment of plastic waste and energy recovery. *Energy, 277*, Article 127576.
Westkämper, E. (2003). Assembly and disassembly processes in product life cycle perspectives. *CIRP Annals, 52*, 579–588.
Wiśniewska-Paluszak, J., Paluszak, G., Fiore, M., Coticchio, A., Galati, A., & Lira, J. (2023). Urban agriculture business models and value propositions: Mixed methods approach based on evidence from Polish and Italian case studies. *Land Use Policy, 127*, Article 106562.
Wiesinger, H., Wang, Z., & Hellweg, S. (2021). Deep dive into plastic monomers, additives, and processing aids. *Environmental Science & Technology, 55*, 9339–9351.
Yap, K. S., Leow, Y. J., Chung, S. Y., Loke, C. P. H., Tan, D. Z. L., Yeo, Z., & Low, J. S. C. (2023). Life cycle assessment of plastic waste end-of-life treatments in Singapore. *Procedia CIRP, 116*, 522–527.
Zilia, F., Bacenetti, J., Sugni, M., Matarazzo, A., & Orsi, L. (2021). From waste to product: Circular economy applications from sea urchin. *Sustainability, 13*, 5427.
Zilia, F., Orsi, L., Costantini, M., Tedesco, D. E. A., & Sugni, M. (2023). Case study of Life Cycle Assessment and sustainable business model for sea urchin waste. *Cleaner Environmental Systems, 8*, Article 100108.
Zott, C., & Amit, R. (2010). Business model design: An activity system perspective. *Long Range Planning, 43*, 216–226.