Science of the Total Environment 955 (2024) 177289

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Improving the waste management system in an Italian footwear district applying MFA and LCA

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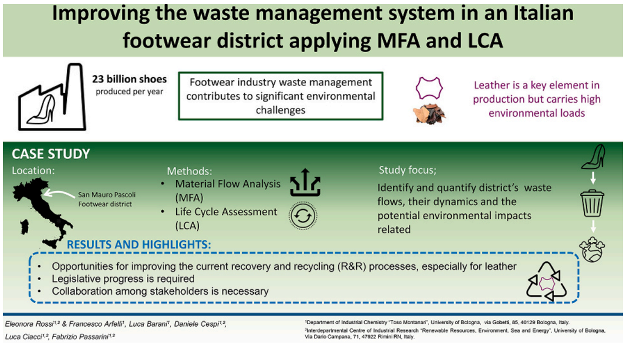
HIGHLIGHTS

- Environmental savings can be reached by optimizing the waste management of footwear;
- MFA an LCA application supports the development of waste management strategies;
- Impacts can be significantly reduced by enhancing leather recovery and recycling;
- Sustainability in the footwear sector implies legislative progress.

GRAPHICAL ABSTRACT



Improving the waste management system in an Italian footwear district applying MFA and LCA

23 billion shoes produced per year

Footwear industry waste management contributes to significant environmental challenges

Leather is a key element in production but carries high environmental loads

CASE STUDY

Location:

San Mauro Pascoli Footwear district

Methods:
- Material Flow Analysis (MFA)
- Life Cycle Assessment (LCA)

Study focus;

Identify and quantify district's waste flows, their dynamics and the potential environmental impacts related

RESULTS AND HIGHLIGHTS:
- Opportunities for improving the current recovery and recycling (R&R) processes, especially for leather
- Legislative progress is required
- Collaboration among stakeholders is necessary

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ARTICLE INFO

Editor: Antonella Petrillo

Keywords:
Italian Footwear District
Footwear waste management challenges
Life cycle assessment of footwear
Leather's environmental footprint
Environmental impact of discarded shoes
MFA of shoe production

ABSTRACT

The fashion industry presents a significant social role, employing millions of people, but it also contributes to resource depletion, ecosystem stress, and climate change. Consequently, sustainability within this sector has garnered increased attention. As part of the fashion sector, the footwear industry is also facing this challenge. With over 23.9 billion shoes produced annually, waste management in this sector presents significant environmental hurdles. In this case study, material flow analysis and life cycle assessment methodologies were adopted to identify and quantify waste flows, their dynamics, and the potential environmental impacts related to one of the main fashion footwear districts in Italy. The results identify opportunities for improving the recovery and recycling processes, especially concerning leather, a key component of shoes contributing to over 30 % of various environmental categories. It was also highlighted that the footwear industry's path to sustainability includes legislative progress, improvements in waste management, and collaboration among stakeholders.

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https://doi.org/10.1016/j.scitotenv.2024.177289
Received 12 July 2024; Received in revised form 11 October 2024; Accepted 27 October 2024

Table of acronyms

ARPAE	Agenzia Prevenzione Ambiente Energua Emilia-Romagna	L&H	Leather and Hide
CAGR	Compound Annual Growth Rate	HOFP	Ozone Formation Potential (human health)
CERCAL	Centro Ricerca e Scuola Internazionale Calzaturiera	HTPc	Human carcinogenic toxicity potential
EF	Environmental Footprint	HTPnc	Human non carcinogenic toxicity potential
EOFP	Ozone Formation Potential (ecosystem)	MEP	Marine Eutrophication Potential
EoL	End of Life	METP	Marine Ecotoxicity Potential
EPD	Environmental Product Declaration	MFA	Material Flow Analysis
EWC	European Waste Catalog	MUD	Environmental Declaration Models
FC	Forlì-Cesena	M&EE	Metals and Electrical Equipment
FEP	Freshwater Eutrophication Potential	ODP	Ozone Depletion Potential
FETP	Freshwater Ecotoxicity Potential	P&T	Paintings and toners
FFP	Fossil Resources Scarcisty Potential	PCW	Paper, Cardboard and Wood
FU	Functional Unit	R&R	Recovery and Recycling
GHG	Greenhouse Gases	SOP	Mineral Resources Scarcity
GWP	Global Warming Potential	SDGs	Sustainable Development Goals
IRP	Ionizing radiation potential	SMPd	San Mauro Pascoli District
LCA	Life Cycle Assessment	TAP	Terrestrial Acidification Potential
LCI	Life Cycle Inventory	TETP	Terrestrial Ecotoxicity Potential
LCIA	Life Cycle Impact Assessment	WCP	Water Consumption Potential
LOP	Land Use Occupation Potential	WtE	Waste-to-Energy

1. Introduction

1.1. *The fashion and footwear sector concerning circular economy and sustainable development goals*

The fashion industry stands as a towering giant in the global economy, generating over 1.3 trillion € in annual revenue in 2022 (Smith, 2023) and employs approximately 2.2 million workers (European Commission, 2024). However, the pivotal role of the fashion sector in the global economic market entails significant environmental burdens due to intensive resource demand and strain on natural ecosystems, including a significant contribution to climate change, accounting for approximately 8–10 % of annual worldwide carbon emissions (Chrobot et al., 2018; Morell-Delgado et al., 2024; Rehman et al., 2024). One of the main approaches to mainstream environmental sustainability is the application of circular economy principles and measures. Circular Economy aims to close the loop within the supply chain by replenishing materials, thereby reducing resource consumption, pollution, and waste generation at every stage of the product life cycle (Rizos et al., 2017). According to the European Commission (European Commission, 2020), circularity may be crucial for a broader industry transformation towards climate neutrality and long-term competitiveness, ultimately leading to significant material savings across value chains and production processes, creating additional value, and unlocking economic opportunities. Indeed, the transition from a linear to a circular economy is a crucial aspect of the European Green Deal (European Commission, 2020), especially in the case of the fashion sector (Shirvanimoghaddam et al., 2020).

The fashion industry, given also the significant amount of waste generated, is one of the key sectors to implement the principles of the Circular Economy. This perspective has been emphasized not only by the United Nations and the European Union (European Commission, 2022a) but also by major brands leading the relevant market and engaging in sustainability innovations. In addition, the main actors in the market are adopting strategies to promote sustainable practices such as reducing emissions and minimizing water use. These aspects are reported in the Fashion Pact, a global commitment signed by over 400 brands and aimed to address the major environmental and social challenges in the sector (Pinault and Polman, 2020). The goals of Circular Economy and sustainability broadly coincide with various United Nations Sustainable Development Goals (SDGs), notably, Circular Economy can actively contribute to advancing SDGs 8 (8.4), 12 (12.2, 12.4, 12.5, 12.6), and 13 (Garcia-Saravia Ortiz-de-Montellano et al., 2023). Examining specific targets from the 2030 Agenda, it emerges integration with the circular economy framework (Malik et al., 2021; United Nations, 2015). For instance, target 8.4 emphasizes the need to progressively enhance global resource efficiency in consumption and production by 2030, striving to disconnect economic growth from environmental degradation. Similarly, point 12.5 reflects a convergence with the circular economy, stating the aim to substantially reduce waste generation through prevention, reduction, recycling, and reuse. The importance of large companies and strategic sectors undertaking these initiatives is underscored in point 12.6, urging companies, huge and transnational ones, to adopt sustainable practices and integrate sustainability information into their reporting cycle. Because of this shared urgency, the various sectors of the fashion industry, including the footwear industry, are moving closer to sustainability.

1.2. *Sustainability of the footwear sector*

The fashion industry comprises diverse segments, among which the footwear sector distinguishes itself due to its significant economic impact and environmental consequences. Globally, the footwear industry has generated more than 290 billion € revenues in 2022 (Statista, 2023), and it is projected to reach about 410 billion € by 2027. Conversely, it also bears responsibility for substantial emissions, accounting for approximately 1.4 % of global greenhouse gases (GHGs) and significant resource consumption, including about 40,900 billion MJ of energy and 215 billion m^3 of water (Chrobot et al., 2018). In 2021, the global sustainability market related to the footwear industry was estimated to be 7 billion € and is projected to reach 12 billion € by 2030, with a Compound Annual Growth Rate (CAGR) of 5.8 % (Priya and Deshmukh, 2021). Most notably, this growth is taking place in the European context, in line with the Green Deal (European Commission, 2019): the EU footwear industry is committed to promoting sustainability and innovation in both production and recycling processes. Footwear companies, in particular, are reevaluating their business models to create innovative products, employing efficient technologies and including eco-design principles during the product's concept (European Confederation of Footwear Industry, 2024). The growth of activity in the sustainable footwear sector is also demonstrated by initiatives such as the revision of the EU Ecolabel criteria for “Footwear and leather products” (Kowalska et al., 2016), which aims to assess the sustainability of products through the life cycle perspective, and by the development of new PEFCR (Product Environmental Footprint Category Rules) (Quantis, 2021).

Despite these initiatives, the gap between global environmental goals and local waste management practices remains underexplored. This study seeks to address this gap by examining the waste management practices within the San Mauro Pascoli district (SMPd), a significant cluster within Italy's footwear production sector, to assess how waste flows align with sustainability goals. The choice of SMPd as representative district is elaborated in section 1.4.

1.3. Waste management and environmental assessment in the footwear sector

The global annual production of over 23 billion shoes (World Footwear, 2023) emphasizes the need to address the environmental impacts associated with the End-of-Life (EoL) phase related to the sector. However, while much attention has been paid to the waste generated in the post-use, there has been a lack of public information on the quantities generated during the production and manufacturing phases of the footwear (Saira and Shanthakumar, 2023; Sawalha et al., 2019; Staikos and Rahimifard, 2007; Van Rensburg et al., 2020). The miscellaneous and complex composition of the resulting waste streams and the consequent challenges observed in separating and reclaiming materials affordably are well-known (Van Rensburg et al., 2020). Indeed, fashion shoes are, in general, heterogeneous products composed of leather, thermoplastic rubbers, ethylene vinyl acetate, PVC, and several types of fabrics. Leather and suede make up a significant portion, while various polymers contribute to the overall composition (packaging excluded). Among the others, leather represents one of the extensively researched waste streams (Chrobot et al., 2018) especially due to the dominant impact of its processing phase (Gatto and Parziale, 2024; Kılıç et al., 2018) and the consistent use of chromium in the tanning process, which is known to be an element of environmental concern (Van Rensburg et al., 2020). In the Brazilian market, around 15 % of the leather inputs used in the manufacturing process are discarded as waste, either as scraps or shavings (Schreiber and Silva, 2024). Accordingly, many environmental evaluations have been performed to estimate the sustainability associated with the sector, many of them applying the Life Cycle Assessment (LCA) (Dom, 1998; Rossi et al., 2021; Van Rensburg et al., 2020). From a general perspective, some indicative results are reported by Chrobot et al. (2018): considering the whole sector, leather shoes represent more than 30 % of the impacts on climate change, human health, resources, and freshwater withdrawal, and over 80 % for ecosystems. This figure is significant because leather shoes represent a substantial portion of the market, accounting for 38 %, according to data from the World Footwear Yearbook 2024 (APICCAPS, 2024). Moreover, leather stands out as one of the fashion industry's most environmentally problematic materials (Shou and Domenech, 2022).

In this context, the disposal of leather waste deriving from the footwear production process accounts for approximately 20–30 % of the inlet leather mass flow (Senthil et al., 2015). The amount of discarded leather is mainly generated during the manufacturing phase which involves cutting the input material into pieces to create the upper pattern. Broadly, the issue is not linked to industrial inefficiencies but rather to the raw materials of animal origin, which often exhibit irregular shapes and certain surface defects (Jadhav and Jadhav, 2020). These residual materials typically evade recovery and recycling procedures, commonly finding their way to landfill disposal, a practice that is still perceived as a cost-effective alternative, posing a risk of toxic components leaching into the soil and causing groundwater contamination (Tshifularo and Maduna, 2021). Parisi et al. (2021) proposes alternative approaches for recycling leather, including leather hydrolysis and the development of polymer composites. The first, while simple and cost-effective, may face adoption barriers due to specialized requirements. The synthesis of composite materials, particularly regenerated leather, shows promise, but challenges like achieving sufficient mechanical strength persist. Overall, comprehensive strategies emphasizing sustainable alternatives are crucial to increase the efficiency of waste management and reduce the environmental impact of the footwear industry.

1.4. Italian footwear sector

The footwear sector of the fashion industry is particularly relevant for Italy since over 160 million pairs of shoes were manufactured in 2022, with an estimated value of 8.5 billion € (Assocalzaturifici, 2022). The Italian footwear industry holds global importance, more for its value than its volume. In fact, in 2017, Italy ranked as the third-largest exporter of footwear worldwide, primarily due to the high quality of its products (APICCAPS, 2024; Cocozza and Camagnolo, 2020). This makes the Italian footwear sector a key player in the market for high-quality shoes and a leader in innovations in this field. The Italian footwear sector is complex and composed of a multitude of actors such as suppliers of raw materials, components, accessories and machinery, model makers, and stylists, which led to the development of site-specific clusters of companies and specialized shoe manufacturing districts. The synergy within these districts, often facilitated by close collaboration among stakeholders in the supply chain, has been pivotal in fostering the national sector's competitiveness on a global scale. It is essential to engage these companies as they represent crucial collaborative partners, particularly in discussions on sustainable innovation, unlike larger enterprises (Kwak et al., 2023).

There is a notable absence of studies aimed at evaluating the sustainability of the footwear sector. At the national level, in Italy, the only recent existing study date back to 2012, where Tatàno et al. (2012) quantified and characterized the waste flow of a similar district in the Marche region. They estimated a total amount of waste generated during the manufacturing phase of about 13,100 t. This value include all the waste types and has been estimated by drawning on Environmental Declaration Models (*in Italian*, Modello Unico di Dichiarazione Ambientale – MUD), similarly to our case. A second study, published in 1995 (Rabellotti, 1995), compared an Italian and a Mexican footwear district and estimated a number of employes of #108,350 for the whole Italian footwear industry, in 1992. A third study was developed in the Bengali context (Mia et al., 2017), where an approximative amount of 5000 t of leather waste is estimated to be produced during the footwear manufacturing. None of these studies addressed a sustainability assessment.

To address this gap, the study focuses on a representative selection of companies from the SMPd in Italy, gathering primary qualitative and quantitative data on the annual waste flows generated in the district. The SMPd was selected due to its long-standing role as one of Italy's most active footwear production centres. Additionally, its production processes, waste composition, and associated challenges mirror those of major global footwear clusters. The district's waste streams—comprising leather, polymers, and various mixed materials—present similar difficulties in terms of waste separation, recovery, and recycling as seen worldwide (Van Rensburg et al. 2020). By analysing these waste flows, this study offers valuable insights into global sustainability challenges in the footwear industry and identifies potential strategies for improvement. Additionally, the selection was encouraged by direct contacts with the key companies within the SMPd, which shared primary information for conducting the analyses. The collaboration of the selected companies enabled to meet high-quality requirements for data collection and understand current waste management practices. Furthermore, the study's focus on an entire district is understood as an extended system. This comprehensive view strengthens the waste management system within the district itself while also providing a reference case for other systems where such information is often inferred from background processes. Starting from the preliminary model of the SMPd, data shared by "Agenzia Prevenzione Ambiente Energia Emilia-Romagna (ARPAE)" (ARPAE, 2024) allowed the extension of the evaluation from the district to the whole Forlì-Cesena (FC) province. More details related to the analytical samples are reported in section 2.1. Ultimately, this provided a quantitative basis for exploring the potential adoption of novel recycling methods to foster a participatory approach in embracing paths for sustainable development.

To achieve this objective, LCA and Material Flow Analysis (MFA) were employed to evaluate the environmental impacts associated with the management of the waste generated in 2021 and treated according to the type (i.e., paper & board, wood, hide and leather, plastic, paints, metals and liquids) of waste and different management options (i.e., reuse and recycling, landfill, Waste-to-Energy) both in the SMPd and in the FC province. Such assessment evaluates the current waste management practices in the SMPd and explore how these practices could be aligned with broader sustainability goals. Specifically, the research aims to answer the following questions:

The objective of this study is to assess

- What are the primary waste streams generated during footwear production in the SMPd, and how are they currently managed?
- What are the potential environmental impacts of these waste management practices, and where are the critical areas for improvement?
- How could alternative recycling and waste management strategies reduce the district's environmental footprint?

By addressing these questions, the study aspire to identify critical areas for improvement, to provide recommendations for improving waste management practices within the district and contribute to broader discussions on sustainability in the global footwear industry., assisting policymakers and companies in making informed decisions regarding sustainability initiatives.

2. Material and methods

This study focused on the footwear SMPd, in the province of FC, northern Italy. The term “district” refers specifically to the geographically confined area known as the “San Mauro Pascoli district,” which represents a smaller manufacturing zone, with an area of about 17 km^2, and does not encompass the entire province. In contrast, “province” refers to the full political boundary of the Forlì-Cesena (FC) province, encompassing all companies involved in footwear manufacturing throughout the entire provincial area. The following description of the SMPd is drawn from a report containing data for the year 2022 (Assocalzaturifici, 2022). The authors consider these data appropriate, even though it is not directly from the reference year selected for the LCA study (2021), since no significant differences are expected between the two years. Moreover, the information derived from the report is used solely to provide a contextual description and does not affect the results of the LCA study.

Building on this contextual foundation, the MFA was applied by utilizing data from MUDs to track mass inflows and outflows across nine waste categories specific to the SMPd. These data were integrated into Sankey diagrams to visually map these flows, highlighting inefficiencies in resource use within the district. The MFA allowed for detailed quantification of material inefficiencies, particularly in handling leather and polymer wastes, which constitute most of SMPd's output. This provided a quantitative foundation for LCA modelling, which evaluated the environmental impacts of current waste management strategies, helping identify key areas for potential improvement, such as increasing leather recovery through innovative recycling techniques. For the LCA, primary data on waste flows from the SMPd was further combined with secondary data from the ecoinvent database to quantify environmental impacts, including climate change, resource depletion, and human toxicity. This combined approach allowed for a comprehensive understanding of the environmental challenges specific to SMPd's waste management practices.

2.1. The San Mauro Pascoli footwear district

The SMPd hosts a limited number of large footwear factories, around which numerous subcontracting businesses operate. In the FC province, the manufacturing sector involved in the “Tanning and dressing of leather; manufacture of luggage, handbags, saddlery and harness; dressing and dyeing of fur" (ATECO 15.2 and NACE 15.2) is characterized by:

a) A total of 216 companies in the sector, collectively employing 3193 workers. On average, each company has a workforce of approximately 15 employees.
b) Exports of textiles, clothing, leather, and accessories in the January–September 2022 period for a total value higher than 300 M€ in the province of Forlì-Cesena (Cimatti, 2022).

This study was conducted in collaboration with the Research and International Footwear School CERCAL (*in Italian*, Centro Ricerca e Scuola Internazionale Calzaturiera) held in the regional project Territorial Laboratories for Innovation and Sustainability in the SMPd (*in Italian*, Laboratori territoriali per l'innovazione e la sostenibilità nel distretto calzaturiero di San Mauro Pascoli), funded under the “Territorial Laboratories for Innovation and Sustainability of Emilia-Romagna Enterprises-2022-2023” (Regione Emilia-Romagna, 2024). CERCAL, established in 1984 in San Mauro Pascoli, is a prestigious educational institution specializing in the art of footwear.

The analyzed sample consists of 27 companies that actively participated in the data collection campaign initiated by the research group. The sample includes 7 footwear manufacturers, 4 heel manufacturers, 6 sole manufacturers, 3 cutting manufacturers, 1 moulding manufacturer, 3 leather goods or tanning companies, and finally, 3 activities classified as other miscellaneous (since able to provide different services). The waste fraction generated by the sampled companies in 2021 amounted to approximately 728 t, with a total turnover of 398 million € calculated over an average of the last 3 years. The 27 companies employed 1919 workers in 2022.

2.2. Material and economic flow analysis

MFA is a consolidated methodology in industrial ecology applied for characterising flows and stocks of resources and supporting sustainability analysis at different geographical levels (Ciacci et al., 2022) by supporting the detailed study of the flows of input, processing and output of materials in different production systems (Xavier et al., 2023). MFA is based on the principle of mass conservation and lays the foundation for assessing the efficiency of resource utilisation and the circularity of material cycles, forming a cornerstone for environmental impact evaluations through LCA.

In collaboration with companies, we garnered primary data and formulated a comprehensive data collection document, strategically designed from the existing datasets present in the MUD. These documents serve as annual declarations by entities and businesses, outlining the quantity and types of waste generated and managed in the preceding year. This meticulous data collection process empowered stakeholders to provide primary insights into the waste flows prevalent in 2021, and enabled us to build a representative MFA model for material inflows and outflows of the SMPd.

The data collection relied on the European Waste Catalog (EWC-Stat categories) (European Commission, 2010). This catalog classifies waste types according to the guidelines of Directive 75/442/EEC (European Commission, 2000). EWC codes, comprising 6 digits, uniquely identify each waste type. The waste generated by the SMPd, in consistency with their EWC classification, has been divided into 9 macro-categories as follows: Leather; Hide; Paper, Cardboard, Wood; Metals; Electrical Equipment; Plastics; Liquids; Paintings & Toner; and Other. In Table S1 of the ESI the assignments are reported transparently. In the context of the district, the distinction between leather and hide lies not in the type of material but in the tanning method applied. Specifically, the term “hide” is used to refer to any kind of vegetable-tanned leather, while the term “leather” is used for all types of leather tanned by chrome, vegetable, alum, or synthetic materials.

The nine waste categories have been further grouped into the following subclasses: i) Leather and Hide (L&H); Paper, Cardboard, and Wood (PCW); Metals and Electronic Equipment (M&EE); Liquids, Plastics, Paints, and Toners (P&T); and “others”, with the latter including all the materials that cannot be associated with the listed categories (e.g., dirty rags, exhausted filters or any kind of material contaminated by toxic or dangerous substances). Companies were re-named from #1 to #27 for confidentiality reasons.

Sankey diagrams were employed during data processing to illustrate waste mass flows from classified sectoral categories (e.g., shoe factories, heel factories) and their respective management methods. Waste quantities were derived from company-specific MUD, leading to high-quality data associated with descriptive of the SMPd. Information about real waste management scenarios was gathered from questionnaires, covering around 97.3 % of the generated waste. Questionnaires were created ad hoc and delivered to the companies to support and enhance data collection. The subsequent analysis assumed that waste coded as R11, R12, and R13 (indicating temporary storage for subsequent recovery) undergoes recovery and recycling (R&R) and R1 undergoes Waste to Energy (WtE) plant. While this assumption aligns with the received information, further investigation would enhance result accuracy, providing more representative insights into the analyzed system. An additional parameter relevant to waste flow identification is the associated cost for EoL management. The surveys administered to the selected companies as well as the collected MUDs have enabled to quantify waste management costs. These costs can stem not only from the material type but also from economic arrangements between involved parties (e.g., the producing company and the management entity). However, recognising the burden of management, particularly if it is significant, may incentivise the producing company to investigate potential valorisation strategies aimed at mitigating disposal costs.

2.3. *System expansion: Mapping waste flows in the FC province and associated management*

The detailed collection of information from the sample companies has also allowed the modelling of waste management scenarios in larger geographical contexts, assuming that similar territories assign the same management scenarios to identical EWC codes. Accordingly, an extension of the system from the district to the FC province is proposed, since most of the investigated companies are located there. The Sankey diagrams representing the waste flows of the sample are reported in Fig. S1 (mass perspective) and Fig. S2 (economic perspective) of the ESI. The selection of representative companies from the whole province was based on ATECO codes (*in Italian*, Attività Economiche) related to activities in the footwear sector, a classification system adopted by the Italian National Institute of Statistics for national economic statistical surveys (European Union, 2006; Istat, 2008). Therefore, waste generated by activities connected to the same sector but labeled under different ATECO codes were excluded from the analysis. The selected codes for processing data are listed in Table 1.

Table 1
List of ATECO codes considered in the analysis, their respective masses, and economic management costs.

ATECO Code	Description	Waste mass generated in 2021 in FC (t)	Management cost (€)
15,201	Manufacture of footwear	491.7	€ 65,604
15,202	Manufacture of leather parts for footwear	573.8	€ 182,109
162,911	Manufacture of wooden parts for footwear	0.4	€ 431
221,901	Manufacture of rubber soles and other rubber parts for footwear	24.4	€ 6172
222,901	Manufacture of plastic parts for footwear	108.3	€ 27,991
Total		*1198.6*	*€ 282,307*

2.4. *Life cycle assessment*

According to the ISO standards 14,040–14,044 (ISO, 2006a, 2006b), LCA is a strategic technique to identify and quantify the potential environmental impacts associated with a product or a system throughout its life cycle. The common LCA framework consists of the following conceptual phases: Goal and scope definition, Life Cycle Inventory (LCI), and Life Cycle Impact Assessment (LCIA), which applies environmental mechanisms and characterization models to relate the LCI results to selected category indicators for a quantitative evaluation of environmental impacts. A fourth phase, interpretation, is transversal to the previous ones to guarantee consistency between the aims of a study and its execution and finally structured to draw recommendations. In the following paragraphs, the four phases are described with reference to the system under investigation. After mapping the SMPd and obtaining data on material waste flows and management costs, LCA was applied to perform an environmental impact assessment. LCA includes both direct and indirect (i.e., embodied) potential impacts on the environment. The standardized approach (ISO, 2006a, 2006b) guarantees transparency and results replicability. The LCA objectives include identifying and quantifying environmental loads, assessing damages, and evaluating possible mitigation options.

2.4.1. *Goal and scope definition*

This study aims to estimate the potential environmental impacts of the current waste management strategy within the SMPd to identify the most burdensome flows. For this reason, the selected functional unit (FU) was set at 1 kg of managed waste, while the environmental impacts of the whole system were calculated on an annual basis (i.e., FU = mass of waste during the manufacturing phase generated by the whole SMPd or in the province in the whole year 2021), to provide impact estimates related to the companies' annual operational period. This approach allowed for a better understanding of the significance of the impact within a broader context, and consequently, the potential benefit associated with the valorization of this waste, based on the actual waste masses generated.

The system boundaries include alternative waste treatment scenarios (namely, WtE, R&R, or landfilling), the consumption of resources and auxiliaries for the process, and the emissions and burdens associated with the treatments. Since both WtE and R&R allow for the potential recovery of valuable products, a system boundaries expansion was performed to credit electrical energy and secondary materials recovery for the avoided production of the same amount of energy and materials supplied, respectively, from the Italian electricity grid mix and virgin sources. Since the core phase of the system is the management of waste, the selected approach was identified as a *cradle-to-grave*, including all the relevant phases of the EoL management life cycle. A diagram representing the system boundaries is shown below in Fig. 1.

2.4.2. *Life cycle inventory*

2.4.2.1. Primary data. Data regarding the quantity of waste generated by the sampled companies, the cost of its management at EoL, and the associated treatment scenarios were collected directly from the interviewed companies, constituting primary data. The collection procedure consisted of gathering MUD data and transcribing it into a spreadsheet file, where data were elaborated. Information concerning the overall amount of waste generated by the entire SMPd in the FC province was sourced from ARPAE (representing the regional agency for environmental protection) databases (the whole list is reported in Table S 2, while the association between the ATECO and NACE (*in French*, Nomenclature statistique des activités économiques dans la Communauté européenne) codes is reported in Table S 3 in the ESI). The total material quantities reported in the MUD and ARPAE files were used directly in the model without any modifications. The only assumptions,

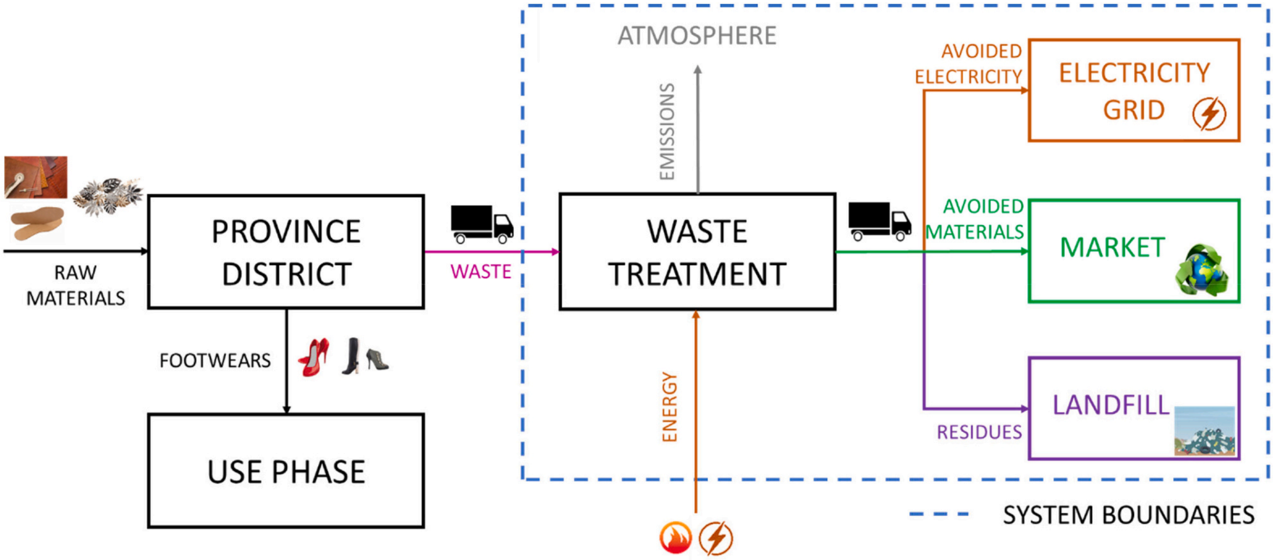

Fig. 1. Simplified system boundaries of the study.

which did not impact the LCA analysis, pertain to the management cost of waste generated by the FC province, where it was assumed that each EWC code shared the same average cost as the corresponding EWC code in the SMPd. Since, to date, waste streams generated by the SMPd do not have a market value and SMPd companies have to pay for managing their waste, a “zero burden” criterion was applied to the input waste to the treatment plant, according to previous studies (Arfelli et al., 2024b; Ware and Power, 2016).

2.4.2.2. Secondary data. Concerning the WtE scenarios, compositions, emissions occurring in the WtE, and the calorific value (MJ/kg) related to paper, plastic, and wood handled were extrapolated from the ecoinvent 3.9.1 database (Wernet et al., 2016), assuming generic mixes of packaging waste. The composition, emissions, and calorific value of L&H were estimated based on literature data (Bahillo et al., 2004). Accordingly, the recovered electricity (3.48 MJ/kg for plastic, 1.30 MJ/kg for wood, 2.17 MJ/kg for L&H and 1.74 MJ/kg for paper) was included in the model as a credit following the “avoided impact” criterion (ISO, 2006a), assuming that an equal amount does not need to be produced through the national mix, which contains about 50 % fossil-sourced electricity in Italy (IEA, 2022). A chipping process was assumed for wood recovery. An average process was taken from the ecoinvent database (Wernet et al., 2016). For the R&R scenarios, due to the absence of primary and secondary data for the L&H category, it was decided to not develop a model for its management. For all three management scenarios, an avoided product was identified and counted as a credit: “low-grade” plastic, recycled paper, and wood pellets. A list of the proxy processes that have been adapted to the context is provided in Table S 4 of the ESI. The inventories of the R&R of plastic and paper were drawn by Ferrara and De Feo (2021) and Shan et al. (2023) and accordingly modelled. The inventories of the two processes were reported in Table S 5 and Table S 6 of the ESI.

Finally, data allowing the comparison of different leather production alternatives (see section 3.3), according to their derivation (e.g., animal-based, fossil-based, bio-based leather), were drawn from different sources, such as the Environmental Footprint (EF) database (EPLCA, 2023) or Environmental Product Declaration (EPD) certificates (EPD search 2020). The significance of utilizing EPDs to promote the development of a more environmentally sustainable industry has already been addressed in the literature (Swarr et al., 2019). Further details are reported in 3.3.

2.4.3. *Life cycle impact assessment*

During the LCIA, ReCiPe 2016 (v1.08) (Huijbregts et al., 2017). was selected as the reference analysis method for evaluating the effects of inventory streams. This method was chosen because it is used in similar studies (Bianchi et al., 2022; Dahlbo et al., 2017; Moazzem et al., 2021; Shou and Domenech, 2022) and is recommended by the European Commission, especially for evaluating pollutants (European Commission, 2022).

The hierarchical perspective (H) was identified as the most representative of the context of the study. This method comprehensively addresses 18 impact categories at midpoint level, so-called problem-oriented and provides a comprehensive estimation of the interactions between the system under scrutiny and the environment. The categories are: GWP, Global warming (kg CO_2 eq); ODP, Stratospheric ozone depletion (kg CFC11 eq); IRP, Ionizing radiation (kBq Co-60 eq); HOFP, Ozone formation-human health (kg NOx eq); PMFP, Fine particulate matter formation (kg PM 2.5 eq); EOFP, Ozone formation Terrestrial ecosystems kg NOx eq); TAP, Terrestrial acidification (kg SO_2 eq); FEP, Freshwater eutrophic. (kg P eq); MEP, Marine eutrophic. (kg N eq); TETP, Terrestrial ecotoxicity (kg 1,4-DCB eq); FETP, Freshwater ecotoxicity (kg 1,4-DCB eq); METP, Marine ecotoxicity (kg 1,4-DCB eq); HTPc, Human carcinogenic toxicity (kg 1,4-DCB eq); HTPnc, Human non-carcinogenic toxicity (kg 1,4-DCB eq); LOP, Land use occupation (m^2a crop eq); SOP, Mineral resource scarcity (kg Cu eq); FFP, Fossil resource scarcity (kg oil eq); WCP, Water consumption (m^3).

2.4.4. *Sensitivity and uncertainty analysis*

Sensitivity analysis is performed to test the robustness of the model created and enable identification and quantification of the influence of the main exogenous parameters on the environmental impact of the entire system (Goedkoop et al., 2016).

Uncertainty evaluation was performed at the midpoint level by taking the pedigree matrix as a reference for data quality (Weidema and Wesnæs, 1996). In general, as discussed above, the LCA model for waste generated by the sample and sent to EoL treatments was created with primary data provided by the companies within the sample (extrapolated from MUDs) or provided by ARPAE in the case of the whole FC province. As such, these data can be considered very reliable and fulfil the highest scores for data quality criteria commonly applied in LCA such as, for instance, geographical, temporal, and technological representativeness. The obtained results ensure the reproducibility of this study, but they are specific to the reference year. Applying the model to subsequent or previous years would not necessarily yield the same results. If there is interest in obtaining specific information for different years, it is recommended to recalculate the results based on a model with the same structure, but using data from temporal contexts consistent with the period of interest. More severe uncertainty factors were assigned to the flows in the EoL phase since they have been modelled according to the sample or literature information since primary data were not available. More details on the pedigree matrix factors were reported in Table S 7 of the ESI. Finally, a Monte Carlo analysis was performed assuming a lognormal distribution with a confidence interval of 95 % and an iteration of 10,000 runs.

2.4.5. Software and database

The LCA modelling was conducted using SimaPro software (v.9.5) (PRè, 2023) in conjunction with the ecoinvent database (v.3.9.1) (Wernet et al., 2016). SimaPro empowers the modelling of products and systems through a life cycle lens, while the ecoinvent database furnishes vital information for a comprehensive LCI.

3. Results and discussion

3.1. Mass and cost analysis of the waste generated in the SMPd and FC province

Concerning the SMPd, the highest quantities of treated waste fall into the categories L&H (approximately 42 %) and PCW (around 25 %), followed by M&EE, for which WtE is considered a non-applicable treatment (12 %), plastics (10 %), other (6 %), P&T (4 %), and finally liquid waste (2 %). Regarding the waste management scenarios, 31 % of the flows are currently subject to thermal treatment (code R1), resulting in the production of electricity (i.e. WtE); 59 % is allocated to R&R (which includes material recycling), while 10 % undergoes traditional landfill disposal (category D, i.e., “landfill disposal”) or has an unknown fate. Such information is summarized in Fig. S 1 and Table S 1 of the ESI. The most significant waste streams occurring in the FC province in terms of mass (Fig. 2 and Table S 2) are still those related to PCW (approximately 40 %) and L&H (23 %), followed by M&EE (10 %), plastic (7 %), liquids (7 %), P&T (7 %), and other (6 %) (Fig. 2). Comparing the flows of the SMPd and the FC province, it is notable that the percentages of waste sent to the three management scenarios are similar. Specifically, 31 % of the waste from SMPd and 30 % of the waste from the FC province are conveyed to WtE; 59 % of the waste from SMPd and 54 % of the waste from the FC province are sent to R&R; and 10 % of the waste from SMPd and 16 % of the waste from the FC province are sent to landfill.

By understanding the current FC province management scenario, it is possible to identify those fractions that could benefit from enhanced R&R processes. For example, only 1%*w*/w of L&H is currently valorized by recycling, while the remaining 99 % is sent to the WtE plant. Therefore, an in-depth investigation at the SMPd level into potential R&R alternatives for this fraction could lead to material circularity benefits within the fashion SMPd. Conversely, it is estimated that, despite the high amount of material, 93 % of the PCW fraction is already subjected to R&R processes, suggesting the existence of virtuous management. The same applies to the M&EE and plastic categories, both of which are recovered at around 98 %. Regarding the last three categories, respectively: liquids, P&T, and Other, 86.2 %, 95.4 %, and 76.5 % of the amounts are all sent to landfill, mainly due to their complex composition and, in some cases, the content of hazardous substances, which could hinder the possibility of alternative management options.

According to the assumptions reported in the previous paragraph, the waste management costs in the context of the FC province are currently predominantly attributed to the WtE scenario (around 51 % of the total), which receives 30 % of the overall output flow from the sample investigated. At the same time, the R&R scenario contributes only 30 % to the costs, while landfill management accounts for 19 % (Fig. 3). In line with the considerations of the previous paragraph, the PCW category, despite the substantial quantities to be disposed of, presents significantly reduced management costs (approximately 4 %). The L&H category, which alone represents about 48 % of the SMPd sample and 31 % of the FC province costs in terms of waste, once again proves to be of particular interest to the stakeholder in terms of new circularity strategies to be implemented. Specifically, the visualization of the economic flows graph (Fig. 3) indicates that by valorizing the L&H stream a potential environmental benefit can be associated with a subsequent economic advantage. The significance of the “other” category's contribution is noteworthy, despite accounting for only 6 % of the total waste mass, as it imposes an economic burden close to 19 % of the overall total.

A comparison of mass contributions and management costs for the

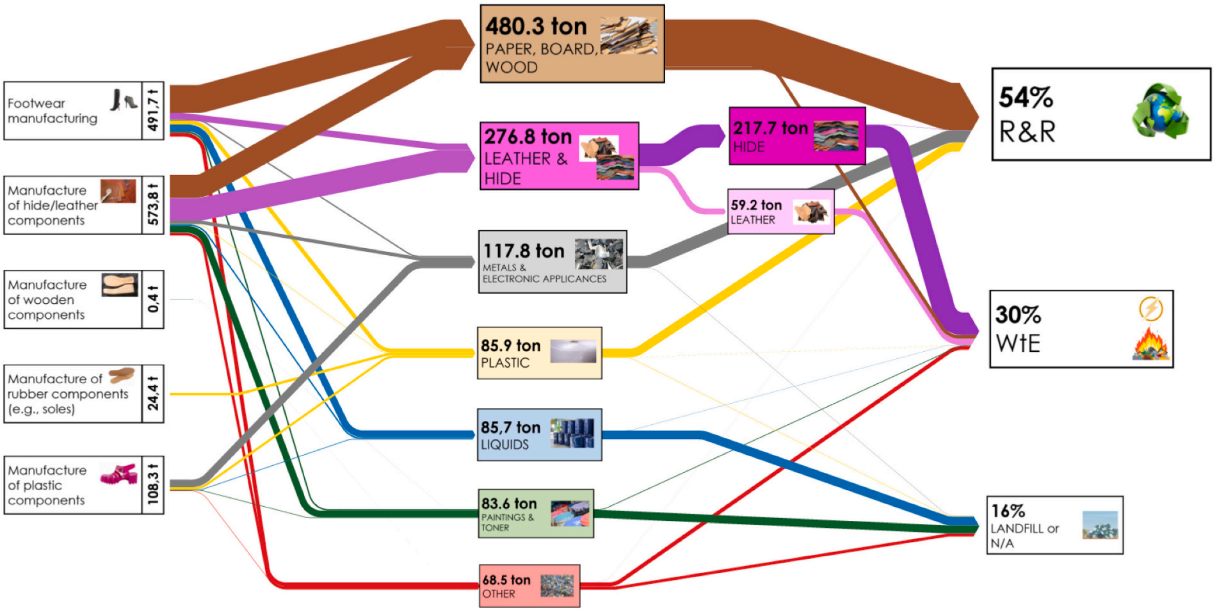

Fig. 2. Graphical representation of the annual waste mass flows generated in the province of FC related to ATECO codes 15,201, 15,202, 162,911, and 221,901, and their EoL management scenarios.

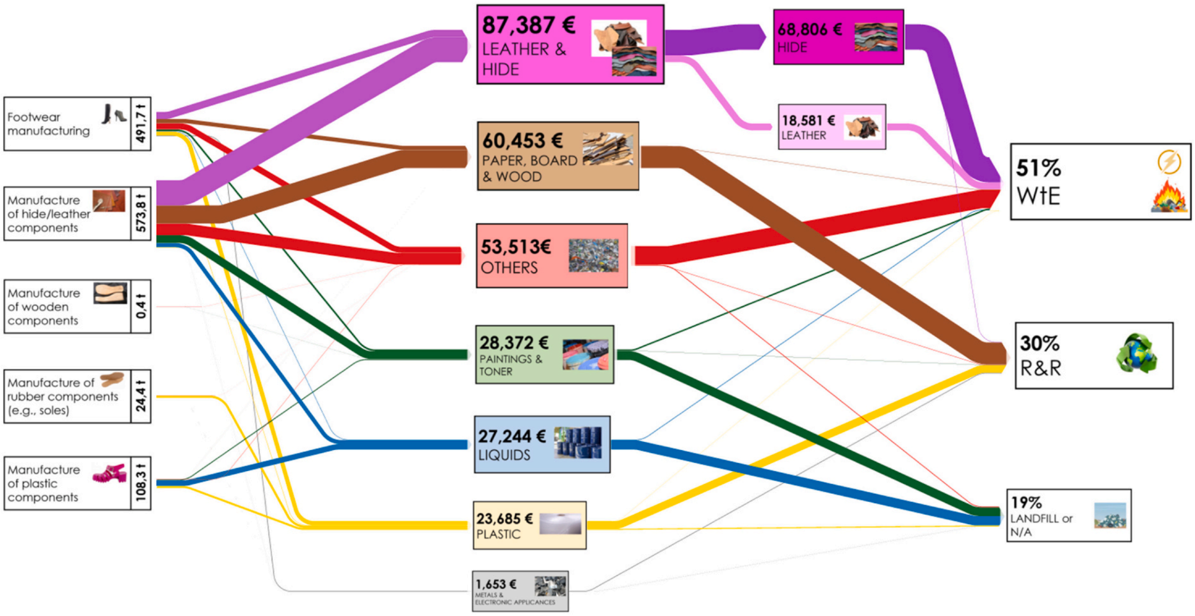

Fig. 3. Graphical representation of the annual flows related to estimated economic costs for the management of waste generated in the province of FC, referring to ATECO codes 15,201, 15,202, 162,911, and 221,901.

FC context has been proposed in Fig. 4. This visualization also allows to observe the uncertainty associated with the obtained values, which were calculated using the estimated standard deviation of the sample. The information used to generate Fig. 4 is reported in Table S 8 of the ESI. The high cost associated with the retirement and management of the "other" fraction, as well as the high standard deviation associated with the average value estimated for the waste category, may be justified by the heterogeneous composition which, on one hand, makes it complex to hypothesize a different management scenario, but it also implies a consistent difference in the retirement and management cost (see Table S 2 in the ESI), depending on the materials composing the fraction. These costs may also depend on the amount of waste retired and managed, on the third company responsible for the retirement and management and on existing agreements between the producer and the third company.

3.2. *Life cycle impact assessment of the current waste management scenario*

In this section, the environmental impacts associated with the management of the most relevant waste streams (both in mass and monetary terms) within the FC province context have been estimated. These include the categories L&H, PCW, and plastic. Among the 18 environmental categories analyzed, GWP was selected for a more detailed analysis, given the high level of interest in the literature (Giaccherini et al., 2017) and the higher availability of data on GWP allowed the further discussion reported in section 3.3. The choice was made based on the potential for improvement in their management. However, to be compliant with ISO 14044 (ISO, 2006b) and consistent with what is described in section 2.4.3, the results will be provided for all the environmental categories proposed by ReCiPe 2016. Furthermore, for those excluded (especially referring to the categories other, P&T, and liquids), the heterogeneous composition of the flow did not allow further accurate processing. Specifically, for the LCIA stage, the waste type and the assumed management scenario were considered.

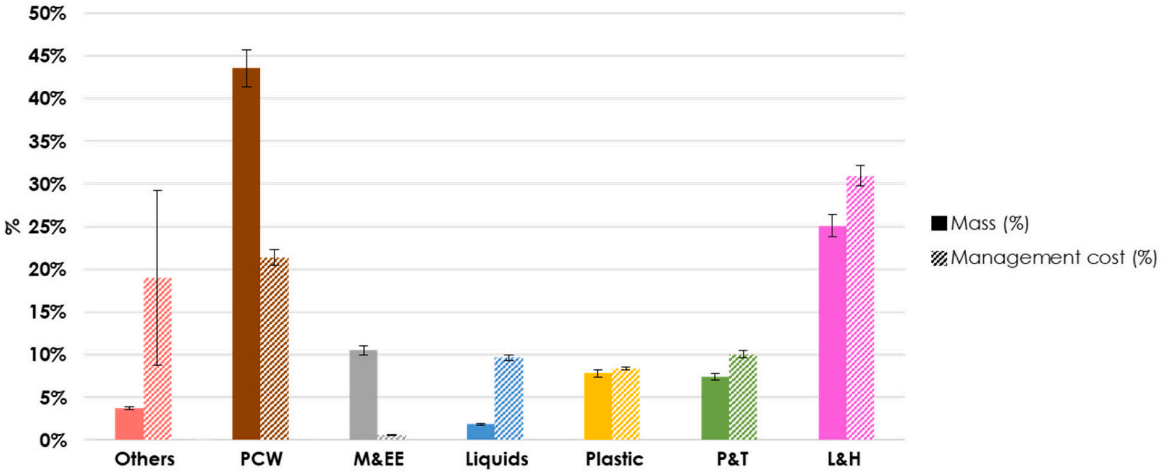

Fig. 4. Comparison between the annual mass percentage contribution and the economic percentage contribution of each waste group on the total mass and total economic burden (province). PCW: Paper, cardboard and wood; M&EE: Metal and Electronic Equipment; P&T: Paintings and Toner; L&H: Leather and Hide.

Fig. 5a depicts the potential environmental impact estimated per kilogram of waste, associated with different management scenarios, generated by the sector in the province: recycling of paper and cardboard (R&R paper, cardboard), WtE of wood (WtE wood), recovery of wood R&R (wood), WtE of L&H (WtE leather), WtE of plastic (WtE plastic), and recycling of plastic (R&R plastic). The results indicate that the credit for the avoided production of electricity and that for the avoided extraction of virgin materials, allowed by the incineration or the R&R of the five waste types, determines net-negative values for the majority of environmental categories. Such an outcome suggests that the avoided impact associated with feeding energy into the grid offsets, in most cases, the impacts caused by waste processing, particularly the emissions of substances into the environment. It is reiterated that in the proposed model, no environmental impacts are attributed to the incoming waste (zero burden criterion, see section 2.4.2.1). At the same time, all emissions, both short- and long-term, are calculated as if released at the beginning of the assessment (Wernet et al., 2016), as also recommended by ISO 14067:2018 when GHG emissions are measured (ISO, 2018). This approach ensures that even emissions from material degradation occurring after 20–30 years are accounted for in the analysis. Specifically, R&R of wood always resulted in negative impacts, WtE of wood in 5/18 categories (HOFP, EOFP, FEP, MEP and HTPc), WtE of L&H in 4/18 categories (GWP, FETP, METP and HTPnc), WtE of plastic in 7/18 categories (GWP, FEP, MEP, FETP, METP, HTPc and HTPnc) and R&R of plastic in 3/18 categories (ODP, TETP and WCP). According to the climate change category, the estimated impact for 1 kg of material indicates a net gain for the three R&R scenarios, specifically 0.33 $kgCO_2$ eq/kg of paper and cardboard, 0.08 $kgCO_2$ eq/kg of wood, and 0.11 $kgCO_2$ eq/kg of plastic. A potential credit result also in the wood WtE scenario, identified as 0.13 $kgCO_2$ eq/kg. Regarding plastic, the minor in terms of mass among the three materials (8 % of the total in the province), there is a clear preference for an R&R (−0.11 $kgCO_2$ eq/kg) scenario rather than WtE (1.95 $kgCO_2$ eq/kg). Results are also reported in Table S 9 (Fig. 5a) and S 10 (Fig. 5b) of the ESI.

Fig. 5b represents the impacts associated with the management of all waste types, divided into three categories: PCW, L&H, and plastic. Thus, following again the categorization: "R&R of paper and cardboard", "R&R of wood", and "WtE of wood" are incorporated into a single category, while "plastic WtE" and "plastic R&R" are incorporated into another single category. These findings align with Fig. 5a, since the environmental credits for the avoided burdens determine net-negative impact values for 17/18 categories in PCW (the exception is the FETP category), 14/18 categories in L&H (GWP, FETP, METP and HTPnc make an exception, because of the CO_2 and cadmium emissions occurring in the incineration phase) and 10/18 categories for plastic management, respectively (ODP, FEP, MEP, TETP, FETP, METP, HTPnc, WCP). However, it is again specified that the observed impacts derive from inventories generated with the support of secondary sources, also. The direct impacts are primarily caused by emissions into the environment that occur during waste treatments, while the indirect ones by the associated energy consumption. However, the influence of the credit associated with avoided electricity, or more generally, avoided products, is highly dependent on the assumptions used in the reference databases. In the case of electricity, the savings reflect the national energy mix (around 50 % of fossil-sourced electricity) and could be increased or reduced by balancing the presence of high-carbon or low-carbon electricity sources (Arfelli et al., 2023). Because of both the higher unit impact associated with the material and, particularly, the quantities produced, the estimated potential impact on climate change for the L&H group constitutes the most significant burden for waste management treatment in the FC province (484.2 tCO_2 eq/kg). The management of PCW, on the other hand, indicates a negative value of −122.4 tCO_2 eq/kg, as regardless of the scenario identified for this group, a net environmental gain is always hypothesized. The estimated value for plastic is also negative, despite Fig. 5b revealing that the WtE of plastic entails a significant disadvantage in terms of GHG emissions. This is due to the greater amount of plastic waste being recovered or recycled compared to the quantity that is incinerated (section 3.2.1).

According to ISO 14044:2006 (ISO, 2006b), the environmental impact assessment shall be carried out by referring to more than one

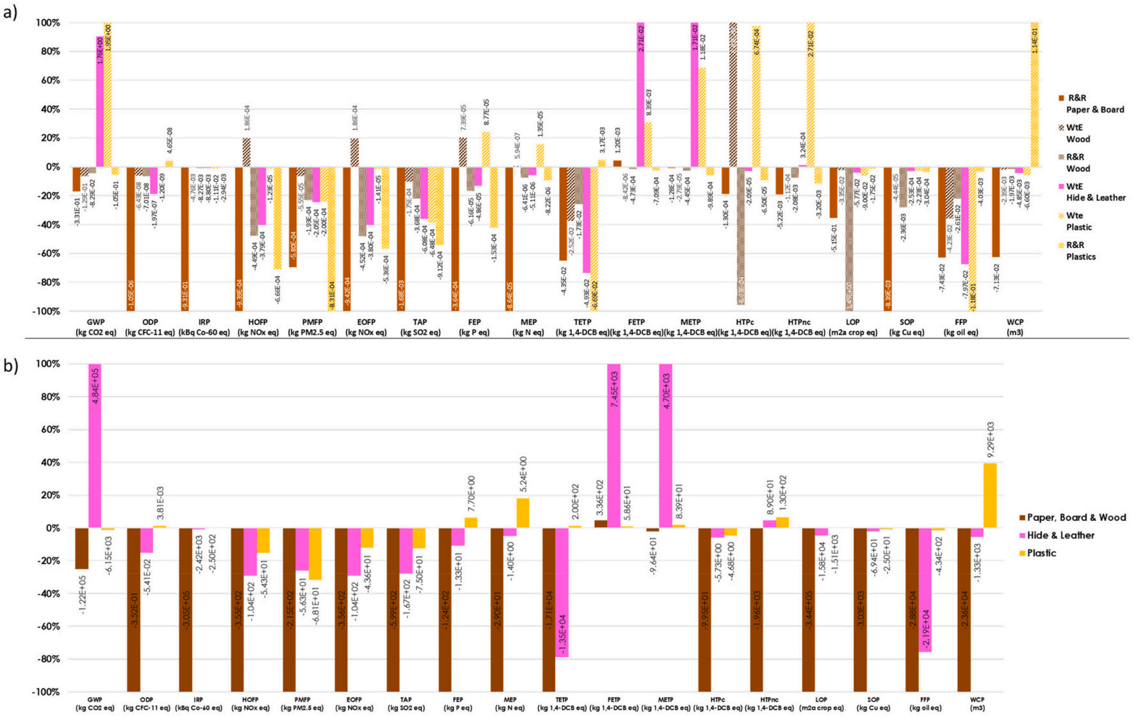

Fig. 5. (a) Comparison between the environmental impacts of the management of 1 kg of i) Reuse and Recycling (R&R) of Paper & Board; ii) Waste-to-Energy (WtE) of Wood; iii) Reuse and Recycling (R&R) of Wood; iv) WtE hide and leather; v) Waste-to-Energy (WtE) of plastic; iv) Reuse and Recycling (R&R) of Plastic; and (b) Environmental impacts assessment of the current waste management scenario.

LCIA method in order to verify that the results obtained by the selected one are not affected by the methodological choice. To this aim, the LCIA calculation was also conducted using the CML-baseline (v. 3.09). Results are reported in Table S11 of the ESI. One of the limits of such comparison is the possible difference in scenario ranking among the environmental categories considered in the two selected methods and, sometimes, also the differences in the characterization factors associated with the same categories but belonging to the two methods. The provided comparison allowed to state that, for the common or similar categories, such as the ones evaluating GWP, ozone depletion, acidification eutrophication and abiotic resources depletion the relative preferences were generally confirmed. More significant differences are observed in the categories related to the toxicity, being it related to human health aspects, or freshwater and marine water. However, such differences may be justified by the intrinsic uncertainty associated with the toxicity evaluation in the LCIA methods (Hauschild et al., 2018). In addition, especially regarding plastic waste, the toxicity-related categories resulted in values associated with high uncertainty, which could the same affect the trends and preferences observed.

3.3. Sensitivity analysis

As already described in section 2.4.2, part of the employed inventory data derives from secondary sources, such as information related to waste R&R. Other data, such as the electricity mix, are drawn from sources updated annually but, despite being highly time-specific, these data are subject to significant temporal variability. Based on this, three sensitivity scenarios have been developed, in which the process models used to calculate the avoided impacts were adjusted. Specifically, in the first sensitivity scenario (scenario 1), a fully fossil-sourced electricity mix was assumed to estimate the avoided impact of the electricity produced during the WtE phase of L&H. This choice is intended to assess the influence of the energy mix on the final result and is inspired by the suggestion made by Hauschild et al. (2018), which states that ideally, the electricity displaced by alternative sources should be fossil-based. Accordingly, the decision to retain the Italian electricity mix (with around 50 % of renewable energy) in the Baseline model reflects a conservative approach. The second and third scenarios, aimed at investigating the influence of the recycling processes for plastics (scenario 2) and paper (scenario 3), by assuming a reduced recycling efficiency of 50 %. The outcomes of the sensitivity analysis are reported in Table S12. In general, in scenario 1 8/18 categories, among which GWP, benefit from the shifting to a dirtier electricity mix. The GWP result confirms the paradox observed in Arfelli et al. (2023), where it was noted that increasing the renewable fraction of energy mixes reduces the avoided impact associated with the displaced electricity production. The results obtained after assuming a reduction in recycling efficiencies to 50 % highlight the significant role of the R&R process in the environmental impacts, particularly in the case of plastics, across all impact categories studied. This outcome underscores the need for future work on site- and technology-specific inventories for the R&R process in question.

3.4. Environmental impacts of virgin material and the state-of-the-art technology for impact reduction

Fig. 6 compares the greenhouse gas (GHG) performance of various alternatives to chrome-tanned animal leather, considered to be more sustainable: vegetable-tanned leather and two types of synthetic leather (one with fossil-based components and one without). Since the emission values quantified per kilogram of the product (blue columns, right axis) are highly dependent on the density and thickness of the material used, values per square meter of the product (orange columns, left axis) have also been reported. The discussion centres on GWP for two primary

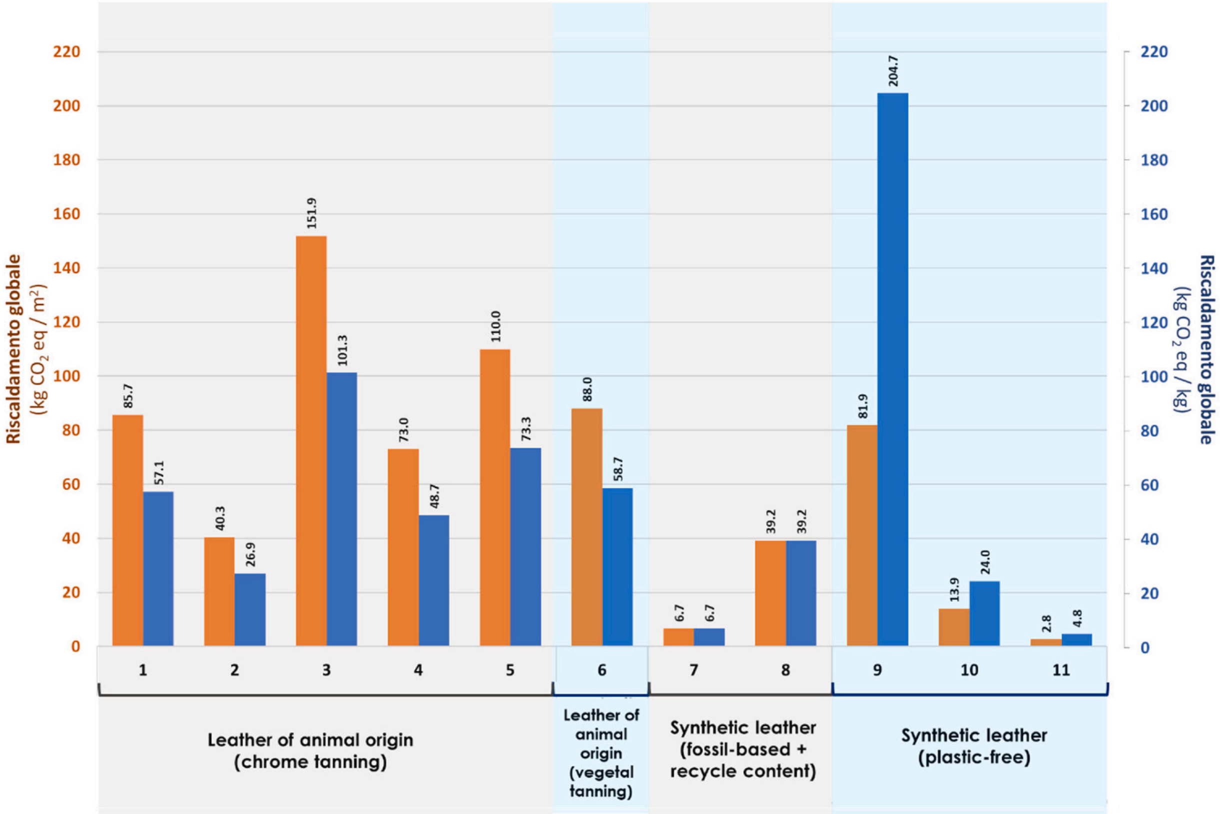

Fig. 6. The carbon footprint of different leather materials, based on alternative raw materials and manufacturing processes. Orange bars represent value per square meter of product, while blue bars represent scores per kilogram of product. Numeric values and references are reported in Table S13 of the ESI.

reasons. First, it is one of the most commonly evaluated categories in the literature. Second, the data used for comparison came from different sources (Table S13 of the ESI), such as the EF database (EPLCA, 2023) or EPDs (EPD search 2020), which rely on varying LCIA calculation methods. Since both ReCiPe 2016 (Huijbregts et al., 2017b) and EPD are based on the IPCC method, GWP was selected as the sole category for comparison.

The wide range between the values found in The Environmental Footprint 3.1 database (European Commission, 2023) reports values of 57.1 $kgCO_2$ eq/kg (85.7 $kgCO_2$ eq/m^2) for chrome-tanned natural leather, 58.7 $kgCO_2$ eq/kg (88.0 $kgCO_2$ eq/m^2) for vegetable-tanned natural leather, and 39.2 $kgCO_2$ eq/kg (39.2 $kgCO_2$ eq/m^2) for synthetic leather, indicating a preference, in terms of GHGs, for synthetic leather over natural alternatives and a slight preference for chrome tanning over vegetable tanning. However, chrome is more likely to affect other environmental categories, such as toxicity, for which GWP may not be the optimal indicator to discuss these two alternatives. Conversely, it is interesting to observe that synthetic leather made from both fossil-based materials and recycled content shows lower GWP values. These values depend on the allocations assigned during the impact calculation phase of animal-derived materials, which represent only a portion of the apparel market of the components exploitable from livestock. At the same time, Environmental Product Declarations (EPDs) published by leather-based materials manufacturers report values of 26.86 $kgCO_2$ eq/kg (40.3 $kgCO_2$ eq/m^2) for bovine leather (Dani SPA, 2021) and only 6.71 $kgCO_2$ eq/kg (6.71 $kgCO_2$ eq/ m^2) for synthetic leather (Miko SPA, 2021). The relatively low value can be partially justified by the presence of 19 % recycled material in the finished product. Various literature sources have quantified the carbon footprint of chrome-tanned leather within a range of 48.7 to 101.3 $kgCO_2$ eq/kg (73.0–151.9 $kgCO_2$ eq/m^2), with an average value, considering also the EPD, resulting in 62.86 $kgCO_2$ eq/kg (91.2 $kgCO_2$ eq/m^2).

According to Kim et al. (2021), one of the most promising options available to reduce waste generation and the related environmental impact can be the use of plant-based leather (plastic-free) instead of petroleum-based leather produced following eco-design principles. Regarding the values obtained for naturally sourced leather, the study “Leather Carbon Footprint - Review of the European Standard” promoted by the United Nations Industrial Development Organization (UNIDO), which estimates a carbon footprint of 73.0 $kgCO_2$ eq/kg, reports that about 85 % of the value is connected to cattle breeding activities, while the remaining 15 % is due to tanning activities and other product treatment operations (UNIDO, 2017). Plastic-free leather presents itself as a promising alternative already available on the market, as its production process does not involve the use of fossil-based products but it is produced using waste derived from various types of plants. Its carbon footprint varies between 0.8 and 8.8 $kgCO_2$ eq/m^2 of leather (Lewandowski and Ullrich, 2023). However, as for other versions of synthetic leather, produced in these cases from organic materials such as hemp or a mixture of organic and textile waste (in the second case using dedicated fungi), a GWP of approximately 81.9 $kgCO_2$ eq/kg (204.65 $kgCO_2$ eq/m^2) has been calculated for the hemp-derived version and a value between 4.8 and 24.0 $kgCO_2$ eq/kg (or 2.8–13.9 $kgCO_2$ eq/m^2) for the version derived from a mixture of waste and recycled (Hultkrantz, 2018). The outcomes revealed that in some of the cases, the plastic-free alternatives result in higher values compared to the synthetic leather discussed above, especially when GHG emissions per square meter of fabric are compared. The wide range of values encourages stakeholders to conduct a thorough LCA analysis before choosing one alternative over another. This ensures that the decision is not solely based on the benefit of reducing overall fossil-based material usage but also includes a broader spectrum of environmental information in the evaluation.

The graph demonstrates a considerable uncertainty linked with average values, posing challenges in accurately estimating the impacts. Consequently, during the LCA application phase, it is unwise to utilize this information and attribute an avoided impact to products obtained from R&R sources, unless an accurate sensitivity analysis is applied to support the outcomes.

In Fig. 6 the comparison il limited to the GWP impacts. However, as previously mentioned, the presented comparison is not intended to provide definitive impact values but to highlight that the choice of different “avoided products” plays a significant role in the modelling process. Current available EPDs provide impact values related to eutrophication, acidification, resource availability, ozone formation, and water scarcity. Impact values related to toxicity are not required by the EPD standard, despite, as previously noted, the presence of chromium in the waste being of significant interest in the scientific studies available in the literature. Concerning the toxicity aspects, especially in the case of the chromium content of leather waste, Peng et al. (2022) investigated the environmental impact by identifying hazardous substances involved in the manufacturing phase. In the findings, they reported that chromium, formaldehyde, and anionic polyelectrolyte may significantly affect the toxicity impacts, especially if during the waste management phase episodes of leaching are verified. However, the study evaluated the impact without following a life cycle approach, but referring to assessments based on Effective Concentration (EC_{50}) or Lethal Concentration (LC_{50}). Similar outcomes have been obtained by (Sivaram and Barik, 2019), who identified that both the manufacturing waste and the solid waste derived by EoL a potentially responsible for the increasing toxicity impacts, especially in the case of involvement of heavy metals and chromium, in particular.

3.5. *Legislative aspects related to waste management*

Despite the existence of several promising initiatives aimed at recovering the high amount of waste generated during various stages of shoe production, there are currently some legislative constraints in the Italian and European contexts that could limit their diffusion. The main constraints relate to the distinction set by Article 184-bis of Legislative Decree 152/06 (*in Italian*, Testo Unico Ambientale or TUA) (Repubblica Italiana, 2006), between waste and by-products. In particular, for a by-product to be classified as such, it must meet certain specified requirements. Failure to meet these requirements leads the material to be considered as a waste. The fine distinction between the two materials from a terminological standpoint plays a significant legal role, as waste requires specific authorizations and procedures for collection or treatment. Such requirements entail costs and often complex structures for companies to meet, thereby effectively limiting the proliferation of small initiatives such as startups proposing innovative recycling and recovery processes.

Another important step forward is Italy's Legislative Decree 116/2020 (Repubblica Italiana, 2020), which links to the Directive 2008/98/EC (European Commission, 2008). This directive seeks to establish a legal framework for waste treatment, a unified waste hierarchy across EU member states, and the safeguarding of the environment and human health through the implementation of proper waste management practices. The decree introduces the concept of Extended Producer Responsibility which obligates producers to finance and organize the separate collection, preparation for reuse, recycling, and recovery of textile by-products and waste. Noteworthy provisions include the mandatory separate collection of all textile products, the requirement for labelling providing disposal information, and the setting of recycling targets by individual EU member states. To comply with Extended Producer Responsibility principles, companies are encouraged to adopt proactive measures such as incorporating more sustainable materials, designing products for durability and recyclability, and actively promoting reuse and recycling initiatives. These actions not only align with the objectives of Extended Producer Responsibility but also position companies favourably to contribute to EU-wide sustainability goals while potentially mitigating the environmental impact of the textile sector.

3.6. Limits of the study

As mentioned in Section 2.1, the information related to the amount and type of produced waste, as well as the waste management technology at EoL (i.e. R&R, landfilling or WtE) was provided directly by the companies located in the SMPd. R&R was assumed to be the fate of the waste generated associated with intermediate codes (i.e., R11, R12, and R13). This assumption represents the first limitation of the study. A second limitation derived from the assumption that data provided by ARPAE were modelled according to the same scenario identified for EWC codes in the sample. This aspect could be resolved in future studies by enhancing communication with the companies involved in waste management, as they could provide primary information related to the actual fate.

A third limitation arises from the absence of site-specific data related to the waste management process. Since no primary data concerning waste treatment technology were available, the related information was drawn from secondary sources to allow the completion of the model. We are aware that such limitations might increase the model uncertainty, as it has been widely demonstrated that having information consistent with the waste management system allows for more accurate results (Arfelli et al., 2024a; Dangi et al., 2023; Schneider et al., 2023). However, although the use of secondary data may represent a limitation for an LCA study, as it affects the uncertainty associated with the results, it is reiterated that the purpose of the study is not solely to quantify the environmental impact, but to identify the waste flows that represent environmental hotspots and on which efforts should be focused when developing policies aimed at improving the sustainability of the system. Such purposes motivated also the decision to perform a sensitivity analysis on the electricity mix used in the WtE processes and on the R&R technologies. In the first case, the selected mix (Italian) was deemed highly consistent with the territory of analysis, and we believe that focusing on different energy mixes to model future conditions or different geographical contexts would highlight the effect of the avoided electricity on the results. In the second case, the sensitivity analysis results confirm the importance of adopting site and technological-specific inventories to model the recycling processes. Rather, it is encouraged the assessment of new promising recycling technologies in future studies. Accordingly, further studies should prioritize the collection of site-specific information related to the actual destination of the waste generated in the FC province as well as site and material-specific information related to the waste treatment plants.

3.7. Broader implications for sustainable waste management in the footwear industry

The findings from this study provide insights into waste management practices within the SMPd, offering broader lessons for the global footwear industry. By identifying key waste streams, assessing their environmental impacts, and exploring recovery strategies, the study highlights opportunities to align with EU directives and global sustainability goals. These insights are important for improving waste management both within the district and in other major footwear production hubs worldwide. The study identifies leather and hide (L&H) waste and post-consumer waste (PCW) as the primary waste streams in the SMPd, reflecting challenges found globally. While PCW has a high recycling rate, L&H is a major issue, with most of it primarily incinerated through waste-to-energy (WtE) processes. This reliance on WtE highlights a critical need for innovation in L&H recycling, a challenge that extends beyond the district to the entire global footwear industry. Scaling technologies like leather hydrolysis could provide a more sustainable approach to leather waste management, helping to reduce the sector's environmental footprint.

The study's findings are timely, aligning with the European Union's circular economy initiatives, which emphasize waste reduction and recycling over incineration. In the SMPd, WtE processes handle only one third of the waste by mass yet account for half of waste management costs, indicating a clear opportunity to reduce both environmental impacts and economic burdens by advancing recycling and recovery (R&R) strategies. Globally, the footwear industry faces increasing pressure to meet international sustainability standards, such as the UN SDGs. By addressing inefficiencies in waste management, particularly in recycling L&H, the industry can better align with these goals, especially SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

The SMPd's high PCW recycling rate serves as a model that could be replicated in other footwear production regions. Meanwhile, the challenges with L&H waste highlight the need for collaborative innovation in recycling technologies. Cross-border cooperation between research institutions, industries, and policymakers can drive the development of alternative recycling methods and create a more sustainable global footwear sector.

The study emphasizes the need for collaborative working groups that bring together suppliers, waste managers, public authorities, and local communities to foster open communication and innovation. This approach, already recommended for the SMPd, is equally applicable on a global scale. Stakeholder collaboration is essential for driving forward new recycling technologies, improving waste monitoring, and developing regulatory frameworks that support sustainability.

4. Conclusion

Sustainability transversely involves the whole footwear sector and related industries, influencing the market and encouraging the intervention of political and legislative bodies in the drafting and implementation of laws and specific initiatives. In this study, MFA and LCA methodologies were applied to identify the environmental hotspots of the management practices of the waste generated by the companies involved in the sector, in the context of SMPd and FC province. Our study revealed that, concerning the provincial context, PCW and L&H are the largest waste streams by mass. However, while PCW achieves a relatively high recycling rate of 93 %, L&H is recycled at just 1 % as it is mainly processed by means of WtE, highlighting a significant opportunity for improved R&R strategies for L&H. Additionally, WtE processes, which handle only 31 % of the waste by mass, account for about 51 % of the waste management costs, making R&R promising also to reduce the economic burdens related to the management. A further perspective for improvement lies in gaining a more in-depth understanding of the actual composition of the waste (in this study, assumed consistent with the declared EWC code) and its fate, which has been largely hypothesized by referring to temporary storage codes (e.g., R11, R12, R13), representing a generic unspecified recovery operation. Once the current R&R process is identified, the LCA methodology can be applied to obtain specific impact estimation from both a process and application site perspective.

In this view, LCA is crucial to assess the environmental profile of new technologies and to guide and support their implementation, accordingly. Furthermore, evaluations should extend beyond GHG emissions to include complementary impacts, such as atmospheric particulate emissions, substances causing potential eutrophication, release of toxic substances, and depletion of mineral and fossil resources, as recommended by ISO 14044. Wherever possible, a proper application of LCA should be accompanied by a review of the legislative aspects discussed in section 3.4, which may hinder the development of more virtuous management practices.

All these perspectives could benefit from establishing company and SMPd working groups that collaboratively involve all stakeholders, such as suppliers, public authorities, clients, waste manager actors, universities, policymakers, and representatives from the local community. This approach aims to enhance communication, identify the specific needs of each stakeholder, and assess the feasibility of various management, design, and technical solutions, with the ultimate goal of effectively promoting the stakeholder engagement process.

CRediT authorship contribution statement

Eleonora Rossi: Writing – original draft, Visualization, Resources, Investigation, Formal analysis, Data curation. **Francesco Arfelli:** Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Luca Barani:** Resources, Data curation. **Daniele Cespi:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Luca Ciacci:** Writing – review & editing, Validation, Supervision, Project administration, Methodology. **Fabrizio Passarini:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Fabrizio Passarini reports financial support was provided by Emilia-Romagna Region, Italy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge the "*Centro Ricerca e Scuola Internazionale Calzaturiera*" (CERCAL), the working group of the initiative: "*Laboratori Territoriali Per l'Innovazione e la Sostenibilità nel Distretto Calzaturiero di San Mauro Pascoli*" and in particular Serena Musolesi and Serena Tagliente for the constant support during the study. In addition, the authors acknowledge the companies of the SMPd who have been available to share primary data: Angelini srl, Bianco Accessori, Calzaturificio Casadei spa, Calzaturificio Catia di Talacci e c. snc, Calzaturificio Twenty Five srl, Cbr tacstile, D.D.S. design srl, Formificio romagnolo spa, Giglioli production s.r.l., Giovagnoli s.r.l., Giuseppe Zanotti spa, Greymer, Italsform spa, Maxisuola srl, Pazzaglia srl, Pollini spa, Ramones srl, Sergio Rossi spa, Smart leather s.a.s. di Alessandri Primo & c., Soledan srl, S.i.l.c.e.a. srl, Tacchificio Zanzani s.r.l., Tranceria Gobbi, Tranceria Modigliani di Casadei Paola, Trancificio Romagnolo, Viva Pelle srl, Vissani Macchine srl, Il Solco Cooperativa Sociale, Team s.r.l., La Cart s.r.l., Esa Servizi Ambientali. Finally, the authors acknowledge ARPAE (https://www.arpae.it/it) for their availability to share information related to the provincial waste flows.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177289.

Data availability

No data was used for the research described in the article.

References

APICCAPS, 2024. The World Footwear Yearbook 2024.

Arfelli, F., Cespi, D., Ciacci, L., Passarini, F., 2023. Application of life cycle assessment to high-soil conditioner production from biowaste. Waste Manag. 172, 216–225. https://doi.org/10.1016/j.wasman.2023.10.033.

Arfelli, F., Roguszewska, M., Torta, G., Iurlo, M., Cespi, D., Ciacci, L., Passarini, F., 2024a. Environmental impacts of food packaging: is it all a matter of raw materials? Sustain Prod Consum 49, 318–328. https://doi.org/10.1016/j.spc.2024.06.032.

Arfelli, F., Tosi, C., Ciacci, L., Passarini, F., 2024b. Life cycle assessment of a wood biomass gasification plant and implications for syngas and biochar utilization. Energies (Basel) 17, 2599. https://doi.org/10.3390/en17112599.

ARPAE, 2024. Agenzia Prevenzione Ambiente Energia Emilia-Romagna.

Assocalzaturifici, 2022. Tutti i passi dell'industria calzaturiera italiana. https://www.assocalzaturifici.it/wp-content/uploads/2024/07/INFOGRAFICA-2023-ASSOCALZATURIFICI.pdf.

Bahillo, A., Armesto, L., Cabanillas, A., Otero, J., 2004. Thermal valorization of footwear leather wastes in bubbling fluidized bed combustion. Waste Manag. 24, 935–944. https://doi.org/10.1016/J.WASMAN.2004.07.006.

Bianchi, I., Forcellese, A., Simoncini, M., Vita, A., Castorani, V., 2022. Comparative life cycle assessment of safety shoes toe caps manufacturing processes. Int. J. Adv. Manuf. Technol. 7363–7374. https://doi.org/10.1007/s00170-022-09240-x.

Chrobot, P., Faist, M., Gustavus, L., Martin, A., Stamm, A., Zah, R., Zollinger, M., 2018. Measuring fashion: Environmental impact of the global apparel and footwear industries study.

Ciacci, L., de Matos, C.T., Reck, B.K., Wittmer, D., Bernardi, E., Mathieux, F., Passarini, F., 2022. Material system analysis: characterization of flows, stocks, and performance indicators of manganese, nickel, and natural graphite in the EU, 2012–2016. J. Ind. Ecol. 26, 1247–1260. https://doi.org/10.1111/jiec.13226.

Cimatti, C., 2022. Camera di commercio della Romagna – Forlì-Cesena e Rimini (Rapporto sull'Economia 2021 e prospettive).

Cocozza, S.K., Camagnolo, D., 2020. Il Calzaturiero di San Mauro Pascoli. Università degli Studi di Padova, Stile, Qualità e Lusso Made In Italy tra Tradizione e Innovazione.

Dahlbo, H., Aalto, K., Eskelinen, H., Salmenperä, H., 2017. Increasing textile circulation — consequences and requirements. Sustain Prod Consum 9, 44–57. https://doi.org/10.1016/j.spc.2016.06.005.

Dangi, M.B., Malla, O.B., Cohen, R.R.H., Khatiwada, N.R., Budhathoki, S., 2023. Life cycle assessment of municipal solid waste management in Kathmandu city, Nepal – an impact of an incomplete data set. Habitat Int. 139. https://doi.org/10.1016/j.habitatint.2023.102895.

Dani SPA, 2021. EPD - Leather for furniture, footwear and leather goods.

Dom, X., 1998. LCA Case Studies Application of Life Cycle Assessment to Footwear 3, 203–208.

EPD search, 2020. The International EPD® System [WWW Document]. URL https://www.environdec.com/EPD-Search/ (accessed 4.14.20).

EPLCA, 2023. European Platform on LCA | EPLCA.

European Commission, 2000. European list of wastes. Official Journal of the European Commission L 226, 3–24.

European Commission, 2008. Directive 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing certain directives. Off. J. Eur. Union L312, 1–59.

European Commission, 2010. Guidance on classification of waste according to EWC-stat categories. Eurostat 2150 (2002), 82.

European Commission, 2019. The European Green Deal sets out how to make Europe the first climate- neutral continent by 2050, boosting the economy, improving people's health and quality of life, caring for nature, and leaving no one behind, European Commission - Press re.

European Commission, 2020. Circular economy action plan – for a cleaner and more competitive Europe. European Commission. https://doi.org/10.2779/05068.

European Commission, 2022a. EU Strategy for Sustainable and Circular Textiles, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

European Commission, 2022b. COMMISSION RECOMMENDATION (EU) 2022/2510 of 8 December 2022 establishing a European assessment framework for "safe and sustainable by design" chemicals and materials. Off. J. Eur. Union. https://doi.org/10.2760/879069.

European Commission, 2023. European platform on LCA | EPLCA [WWW document]. Environmental Footprint reference packages. https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.

European Commission, 2024. Textiles Ecosystem – TCLF (Textiles, Clothing, Leather and Footwear) Industries [WWW Document]. Internal Market, Industry, Entrepreneurship and SMEs. https://single-market-economy.ec.europa.eu/Sectors/Textiles-Ecosystem_En.

European Confederation of Footwear Industry, 2024. Environmental Policy [WWW Document].

European Union, 2006. Regulation (EC) no 1893/2006 of the European Parliament and of the Council of 20 December 2006 Establishing the Statistical Classification of Economic Activities NACE (Revision 2 and amending Council Regulation (EEC) No 3037/90 as well as certain EC Regula, Official Journal of the European Union).

Ferrara, C., De Feo, G., 2021. Environmental assessment of the recycled paper production: the effects of energy supply source. Sustainability (Switzerland) 13. https://doi.org/10.3390/su13094841.

Garcia-Saravia Ortiz-de-Montellano, C., Samani, P., van der Meer, Y., 2023. How can the circular economy support the advancement of the sustainable development goals (SDGs)? A comprehensive analysis. Sustain Prod Consum 40, 352–362. https://doi.org/10.1016/j.spc.2023.07.003.

Gatto, A., Parziale, A., 2024. Towards a green and just industry? Insights from traditional leather districts in southern Italy. Sci. Total Environ. 942. https://doi.org/10.1016/j.scitotenv.2024.171552.

Giaccherini, F., Munz, G., Dockhorn, T., Lubello, C., Rosso, D., 2017. Carbon and energy footprint analysis of tannery wastewater treatment: a global overview. Water Resour Ind 17, 43–52. https://doi.org/10.1016/j.wri.2017.03.001.

Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, E., 2016. Introduction to LCA with SimaPro. Introduction to LCA with SimaPro.

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Assessment.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Hultkrantz, M., 2018. An overview on the environmental impacts of synthetic leather made of hemp fiber with preliminary life cycle assessment.

IEA, 2022. Electricity Generation by Source, Italy 2020.

ISO, 2006a. 14040/Amd 1:2020: Environmental management - Life cycle assessment - Requirements and guidelines.

ISO, 2006b. 14044/Amd 1:2017+Amd 2:2020: Environmental management - Life cycle assessment - Requirements and guidelines.

ISO, 2018. ISO 14067:2018 - Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification.

Istat, 2008. ATECO (Classification of Economic Activity) 2007.

Jadhav, N.C., Jadhav, A.C., 2020. Waste and 3R's in footwear and leather sectors. Springer Singapore. https://doi.org/10.1007/978-981-15-6296-9_10.

Kılıç, E., Puig, R., Zengin, G., Zengin, C.A., Fullana-i-Palmer, P., 2018. Corporate carbon footprint for country climate change mitigation: a case study of a tannery in Turkey. Sci. Total Environ. 635, 60–69. https://doi.org/10.1016/j.scitotenv.2018.04.111.

Kim, H., Song, J.E., Kim, H.R., 2021. Comparative study on the physical entrapment of soy and mushroom proteins on the durability of bacterial cellulose bio-leather. Cellulose 28, 3183–3200. https://doi.org/10.1007/s10570-021-03705-0.

Kowalska, M., Kaps, R., Wolf, O., 2016. EU Ecolabel criteria for Footwear Final Technical Report.

Kwak, K., Kim, D., Heo, C., 2023. Sustainable innovation in a low- and medium-tech sector: evidence from an SME in the footwear industry. J. Clean. Prod. 397, 136399. https://doi.org/10.1016/j.jclepro.2023.136399.

Lewandowski, S., Ullrich, A., 2023. Measures to reduce corporate GHG emissions: a review-based taxonomy and survey-based cluster analysis of their application and perceived effectiveness. J. Environ. Manag. 325. https://doi.org/10.1016/j.jenvman.2022.116437.

Malik, A., Lafortune, G., Carter, S., Li, M., Lenzen, M., Kroll, C., 2021. International spillover effects in the EU's textile supply chains: a global SDG assessment. J. Environ. Manag. 295. https://doi.org/10.1016/j.jenvman.2021.113037.

Mia, Md.A.S., Nur-E-Alam, Md., Murad, A.B.M.W., Ahmad, F., Uddin, M.K., 2017. Waste Management & Quality Assessment of Footwear Manufacturing Industry in Bangladesh: An Innovative Approach.

Miko SPA, 2021. EPD - Microfibre for Internal Coverings for the Automotive Sector.

Moazzem, S., Wang, L., Daver, F., Crossin, E., 2021. Resources , Conservation & Recycling Environmental impact of discarded apparel landfilling and recycling. Resour. Conserv. Recycl. 166, 105338. doi:https://doi.org/10.1016/j.resconrec.2020.105338.

Morell-Delgado, G., Talens Peiró, L., Toboso-Chavero, S., 2024. Revealing the management of municipal textile waste and citizen practices: the case of Catalonia. Sci. Total Environ. 907. https://doi.org/10.1016/j.scitotenv.2023.168093.

Parisi, M., Nanni, A., Colonna, M., 2021. Recycling of chrome-tanned leather and its utilization as polymeric materials and in polymer-based composites: a review. Polymers (Basel) 13, 1–23. https://doi.org/10.3390/polym13030429.

Peng, L., Long, W., Zhang, W., Shi, B., 2022. Leaching toxicity and ecotoxicity of tanned leather waste during production phase. Process. Saf. Environ. Prot. 161, 201–209. https://doi.org/10.1016/j.psep.2022.02.001.

Pinault, F.-H., Polman, P., 2020. Fashion Pact - First Steps to Transform Our Industry Signatories 15, 21–31.

PRè, 2023. https://simapro.com/ Accessed 15 January 2024.

Priya & Roshan Deshmukh, 2021. SUSTAINABLE FOOTWEAR MARKET: Global Opportunity Analysis and Industry Forecast, 2021–2030.

Quantis, 2021. Draft Product Environmental Footprint Category Rules: Apparel and Footwear 176.

Rabellotti, R., 1995. Is there an "Industrial District model"? Footwear districts in Italy and Mexico compared. World Dev. 23, 29–41. https://doi.org/10.1016/0305-750X(94)00103-6.

Regione Emilia-Romagna, 2024. Sviluppo sostenibile e Agenda 2030 - Innovazione e sostenibilità nel distretto calzaturiero [WWW Document]. https://imprese.regione.emilia-romagna.it/rsi/doc/laboratori-territoriali/progetti-laboratori-2023/distretto-calzaturiero.

Rehman, M., Petrillo, A., Ortiz Barrios, M.A., Forcina, A., Baffo, I., De Felice, F., 2024. Sustainable fashion: mapping waste streams and life cycle management. J. Clean. Prod. 444, 141279. https://doi.org/10.1016/j.jclepro.2024.141279.

Repubblica Italiana, 2006. DECRETO LEGISLATIVO 3 aprile 2006, n. 152.

Repubblica Italiana, 2020. DECRETO LEGISLATIVO 3 settembre 2020, n. 116.

Rizos, V., Tuokko, K., Behrens, A., 2017. The Circular Economy, a Review of Definitions, Processes and Impacts, Centre for European Policy Studies. Belgium, Brussels.

Rossi, M., Papetti, A., Marconi, M., Germani, M., 2021. Life cycle assessment of a leather shoe supply chain. Int. J. Sustain. Eng. 14, 686–703. https://doi.org/10.1080/19397038.2021.1920643.

Saira, G.C., Shanthakumar, S., 2023. Zero Waste Discharge in Tannery Industries – An Achievable Reality? J Environ Manage, A recent review. https://doi.org/10.1016/j.jenvman.2023.117508.

Sawalha, H., Alsharabaty, R., Sarsour, S., Al-Jabari, M., 2019. Wastewater from leather tanning and processing in Palestine: characterization and management aspects. J. Environ. Manag. 251. https://doi.org/10.1016/j.jenvman.2019.109596.

Schneider, F., Parsons, S., Clift, S., Stolte, A., Krüger, M., McManus, M., 2023. Life cycle assessment (LCA) on waste management options for derelict fishing gear. Int. J. Life Cycle Assess. 28, 274–290. https://doi.org/10.1007/s11367-022-02132-y.

Schreiber, D., Silva, D.A. da, 2024. Analysis of solid waste treatment practices in footwear factories. Environmental Management and Sustainable Development 13, 1. https://doi.org/10.5296/emsd.v13i2.21817.

Senthil, R., Hemalatha, T., Kumar, B.S., Uma, T.S., Das, B.N., Sastry, T.P., 2015. Recycling of finished leather wastes: a novel approach. Clean Techn. Environ. Policy 17, 187–197. https://doi.org/10.1007/s10098-014-0776-x.

Shan, C., Pandyaswargo, A.H., Onoda, H., 2023. Environmental impact of plastic recycling in terms of energy consumption: a comparison of Japan's mechanical and chemical recycling technologies. Energies (Basel) 16. https://doi.org/10.3390/en16052199.

Shirvanimoghaddam, K., Motamed, B., Ramakrishna, S., Naebe, M., 2020. Death by waste: fashion and textile circular economy case. Sci. Total Environ. 718. https://doi.org/10.1016/j.scitotenv.2020.137317.

Shou, M., Domenech, T., 2022. Integrating LCA and blockchain technology to promote circular fashion – a case study of leather handbags. J. Clean. Prod. 373, 133557. https://doi.org/10.1016/j.jclepro.2022.133557.

Sivaram, N.M., Barik, D., 2019. Chapter 5 - toxic waste from leather industries. In: Barik, D. (Ed.), Energy from Toxic Organic Waste for Heat and Power Generation, Woodhead Publishing Series in Energy. Woodhead Publishing, pp. 55–67. https://doi.org/10.1016/B978-0-08-102528-4.00005-5.

Smith, P., 2023. Revenue of the Global Apparel Market 2014–2027. Statista.

Staikos, J.T., Rahimifard, S., 2007. Post-consumer waste management issues in the footwear industry. Proc. Inst. Mech. Eng. B J. Eng. Manuf. 221, 363–368. https://doi.org/10.1243/09544054JEM732SC.

Statista, 2023. Footwear market revenue worldwide from 2017 to 2027 [WWW Document].

Swarr, T.E., Cucciniello, R., Cespi, D., 2019. Environmental certifications and programs roadmap for a sustainable chemical industry. Green Chem. https://doi.org/10.1039/c8gc03164a.

Tatàno, F., Acerbi, N., Monterubbiano, C., Pretelli, S., Tombari, L., Mangani, F., 2012. Shoe manufacturing wastes: characterisation of properties and recovery options. Resour. Conserv. Recycl. 66, 66–75. https://doi.org/10.1016/j.resconrec.2012.06.007.

Tshifularo, C.A., Maduna, L., 2021. Management of Textile Leather Waste, Waste Management in the Fashion and Textile Industries. Elsevier Ltd. https://doi.org/10.1016/B978-0-12-818758-6.00013-2

UNIDO, 2017. Leather carbon footprint &. Review of the European Standard EN 16887, 2017.

United Nations, 2015. Transforming our world: the 2030 agenda for sustainable development. United Nations. https://doi.org/10.1201/b20466-7.

Van Rensburg, M.L., Nkomo, S.L., Mkhize, N.M., 2020. Life cycle and end-of-life management options in the footwear industry: a review. Waste Manag. Res. https://doi.org/10.1177/0734242X20908938.

Ware, A., Power, N., 2016. Biogas from cattle slaughterhouse waste : energy recovery towards an energy self-sufficient industry in Ireland. Renew. Energy 97, 541–549. https://doi.org/10.1016/j.renene.2016.05.068.

Weidema, B.P., Wesnæs, M.S., 1996. Data quality management for life cycle inventories- an example of using data quality indicators. J. Clean. Prod. 4, 167–174. https://doi.org/10.1016/S0959-6526(96)00043-1.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and mWernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. International journal of life cycle ass. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

World Footwear, 2023. The World Footwear 2023 Yearbook.

Xavier, L.H., Ottoni, M., Abreu, L.P.P., 2023. A comprehensive review of urban mining and the value recovery from e-waste materials. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2022.106840.