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Case Report

Organizational life cycle assessment: A case study in the fashion industry small and medium enterprises

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ABSTRACT

Organizations are increasingly committed to reducing their environmental footprints, a process fraught with the complex challenge of identifying and mitigating unique environmental impacts and hotspots without merely shifting burdens elsewhere. This study applies Organizational Life Cycle Assessment (OLCA) methodology using ISO 14040/14044 and ISO/TS 14072 guidance, mapped gate-to-gate flows for the firm's entire 2023 output. Inputs and emissions were compiled on-site and modelled in SimaPro 9.1.1 with the Ecoinvent 3.3 "allocation, cut-off" database, applying ReCiPe 2016 Midpoint (H) across 18 impact categories. The results show that electricity use is the main environmental hotspot, contributing 43.5 % to total climate impacts, while cotton fibre accounts for 87.3 % of freshwater eutrophication and 37.8 % of water consumption; combined measures on renewable electricity and recycled fibres could reduce the organisation's overall climate footprint by up to 34.6 %. To address these impacts, the adoption of renewable energy sources like solar energy systems to reduce electricity consumption is recommended. This analysis pinpoints concise improvements: transition to renewable electricity, favour green suppliers of water-efficient cotton and recycled polyester and replace brass with different materials. The analysis conducted aims to be transferable to peer fashion companies in Italy and beyond, favouring the spread of Life Cycle based methodologies.

1. Introduction

The fashion industry is a major contributor to the world economy, generating approximately $3 trillion and accounting for 2 % of the global GDP [1], while at the same time having significant environmental responsibility, estimated as 9 % of emissions and 20 % of water pollution worldwide [2].

These externalities are magnified by fast-fashion business models, which accelerate product turnover and complicate end-of-life management, as well as by obstacles encountered in the implementation of life cycle-oriented approaches, particularly among micro, small, and medium enterprises. As societal scrutiny is increasing, with nearly six in ten EU citizens willing to pay more for sustainably produced and repairable products [3], new EU regulations are shifting environmental accountability from isolated products to full organisational footprints, Starting from January 2025, Member State are mandated to separately collect post-consumer textiles under the amended Waste Framework Directive, with Extended Producer Responsibility fees for apparel projected for 2026/27 [4]. Moreover, a provisional agreement reached by EU co-legislator last February requires Member States to establish harmonised, eco-modulated EPR schemes for textiles [5]. Meanwhile, with the entry into force of the Corporate Sustainability Reporting Directive (CSRD), phased reporting started in 2025, obliging even listed SMEs to disclose sustainability impacts. This measure is in line with the new European Sustainability Reporting Standards which, under a separate "Omnibus" package agreed last March, made digital product passports compulsory for textiles sold on the EU market [6]. To assess environmental performances of fashion firms, as well as to understand

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where and how to intervene, methodologies such as Organizational Life Cycle Assessment (OLCA) emerge as key strategic instruments.

While organisational interest in evaluating environmental impacts is increasing, a persistent lack in comprehensive data across companies' activities hinders informed value chain decision-making, as emerged in Ahmed S. et al. [7].

Furthermore, a forensic review found that only one third of 2020 voluntary targets had credible evidence of progress by the end of 2024, global clothing production has roughly doubled since 2000, and average use per garment has fallen about 40 %, with some fast-fashion items discarded after only 7–10 wears [8]. Despite demands from investors and global platforms [9] for cradle-to-gate figures, a recent scoping review [10] found that few fashion life-cycle studies applied OLCA, and that none was centred on a real fashion SME, as evidenced in Ahmed S. et al. [7].

There is limited empirical work showing how organisational hotspots can be identified, quantified, and acted upon at SME level. This study addresses this gap by providing a concrete OLCA application to a real Italian apparel SME, linking methodological adaptation to actionable environmental and managerial insights.

To address the urgent need for sector specific evidence, OLCA standardised in the ISO/TS 14072 becomes strategically indispensable, as underlined in the UNEP-SETAC-Life Cycle Initiative Guidance, developed to support companies in its interpretation [11]. In fact, OLCA adopts a life cycle viewpoint to analyse the inputs, outputs, and potential environmental impacts of all the organization's activities, to enable fashion firms, especially SMEs to monitor environmental performance and make informed management decisions accordingly.

Notwithstanding the absence of a functional unit, which prevents direct comparisons of organizations, its application remains beneficial for year-by-year self-comparison, as underlined in Ahmed S. et al. [7]. Italy's fashion ecosystem, dominated by networks of subcontracting SMEs, illustrates the industry's environmental footprint. Using SimaPro and the Ecoinvent database, this case study presents an OLCA of an Italian clothing manufacturer in order to achieve three main objectives: (i) individuate the main contributors in terms of activities within fashion SMEs that drive most environmental impacts, (ii) understand how OLCA effectively identifies and quantifies these impacts, and (iii) demonstrate that the adoption of OLCA can deliver managerial and strategic value. The study expands OLCA research highlighting hybrid inventory and activity-based reporting methods aligned with UNEP-SETAC-LCI guidance despite limited data. It also provides actionable recommendations on renewable energy, fibre sourcing, and supplier engagement applicable to similar European firms.

1.1. Literature review

Over the past decade the OLCA has matured methodologically [12, 13], yet its empirical base in scientific literature remains narrow, particularly for fashion SMEs as emerged in Ref. [7], with 12 case studies carried out by UNEP-SETAC-LCI [14], and few more present in the literature [15,16].

In recent times, scholars have broadened OLCA in three directions that bear directly on the present study. First, hybrid inventory schemes now accommodate indirect activities where primary data are weak, while decision tools marry OLCA outputs with circular-economy prioritisation [17] and business-process dashboards intelligible to non-experts. Complementary modules have been grafted on for organisational water footprints [18] and for pesticide emission modelling in agrifood chains [19], demonstrating the method's versatility [20]. applied principal-component analysis to a suite of ReCiPe midpoint indicators and showed that GWP, eutrophication and resource-depletion frequently co-varied, indicating that a streamlined subset of uncorrelated metrics can capture the bulk of environmental variation in LCAs.

Second, robust OLCAs now exist for steel production [21], packaging lines [22], higher-education institutions [23] (Doğruparmak et al. [24], hospitals [25], as well as urban and public transports (Villalba-Pastrana et al. [26](Kunert et al. [27], and diversified agri-food groups [28], illustrating that organisation-level hotspots often trespass on conventional product LCA typically in energy management, procurement, or logistics.

Third, emerging SO-LCA stream gauges supply-chain labour conditions [29] and even individual life cycles [30], while Industry 4.0 pilots feed real-time data into OLCA dashboards [31,32] credit the UNEP/-SETAC "Guidance on OLCA" with accelerating global uptake, yet surveys reveal that analytical goals still eclipse managerial or stakeholder-communication goals. Scholars consistently flag challenges in defining reporting organizations, categorizing activities and collecting reliable primary data [33]. Compiling primary information across geographically dispersed sites is resource-intensive, and reliance on secondary databases introduces uncertainty. Although several authors propose data-quality scoring matrices, no universally accepted protocol has emerged, leaving results vulnerable to inconsistency.

Proposals to tackle these issues range from hybrid inventory protocols [34] to business-process modelling that embeds OLCA metrics in day-to-day operations (Wafa W. et al. [35] (Ahmed S. et al. [36] and management dashboards designed for non-experts.

Data scarcity, multi-tier subcontracting, and rapid style turnover pose formidable barriers, but emerging policy drivers are removing any excuse for inertia (ESPR, expected late 2025) (Parliament, 2024). Simultaneously, micro-plastic release is joining climate, water and toxicity as a priority impact pathway [37].

LCA and OLCA are key tools for assessing environmental impacts from products, processes, or entire organizations, particularly for MSMEs. Combining the two helps companies make strategic and technological decisions that strengthen their position in global value chains and meet growing sustainability demands [7]. Yet implementation is often limited by technical and resource barriers, with many organizations unfamiliar with ISO standards, making interpretation and communication of results difficult.

ISO/TS 14072 also has structural limits, as OLCA results cannot be directly compared across organizations due to the absence of a common functional unit. Analysts must also decide how to manage downstream activities, multi-site operations, and data gaps, while service organizations struggle to measure intangible processes.

This study applies a UNEP/SETAC-compliant OLCA to an Italian apparel SME to address these gaps. It documents lean-data adaptations, hybrid activity mapping, proxy allocation, and iterative stakeholder interviews, that make OLCA viable under limited resources, and shows how findings can guide strategy on energy, fibre choice, and subcontracting. By extending OLCA to fashion SMEs, the methodology complements product LCAs and provides practical insights for meeting upcoming EU sustainability requirements, which is the aim of the study.

2. Methods

OLCA is applicable to a wide range of entities, defined as any individual or group with distinct functions aimed at achieving specific objectives, including companies, partnerships, and institutions, regardless of their incorporation status or sector. This case study employed a step-by-step approach and adhered to the ISO 14040/14044 and ISO/TS 14072.

As for product LCA, it starts with the goal and scope phase, which establishes the study's motivation, intended application, audience, and defines the system boundaries of the organization under study. The inventory phase involves detailed data collection, categorizing inputs and outputs along the organization's value chain into direct, indirect upstream, and indirect downstream activities. In the impact assessment phase, these inputs and outputs are linked to potential environmental impacts, estimating their magnitude across various impact categories. The process concludes with the interpretation phase, where significant issues are identified, limitations are highlighted, and conclusions and recommendations are drawn.

2.1. *Goal and scope definition*

The company under exam, of which the name, due to data protection reasons, will be withheld, was identified as in line with the scope of the research, meaning the applicability of OLCA to SMEs in the fashion sector. The company is situated in Marche Region, Italy, has a turnover of 5 million euros as per 2023, year of reference for this study, and it deals with the assembly and finishing of clothes, especially jeans, for big brands. Analysis took place between February and September 2024.

It is specialised in the production of high-quality apparel, with expertise in prototyping models - when requested -, manufacturing and finishing fashion items, especially for top brands in the industry. Table 1 provide the quantification of all the company outputs in terms of production as per the year 2023.

The production process starts with market research and product development, where raw material samples are assessed. Approved concepts move to prototyping, and once validated, samples are produced for sales campaigns. Orders then trigger material sourcing and quality checks. Production involves modelling, cutting, and sewing, followed by packaging and quality control. Smaller batches are finished in-house, while larger ones may be outsourced. Final products are delivered to customers, though no deliveries occurred in 2023.

As outlined in the OLCA Guidance [11], the reporting flow is based on the total annual product sales in kilograms to assess organizational output and environmental impact. It covers all impacts within the production phase over a one-year period.

The reporting flow defines the organization's outputs and links value chain segments to its product portfolio. This study focuses only on direct activities due to limited data on indirect ones, consistent with ISO/TS 14072 Clause 5.2.2 and UNEP-SETAC-LCI Guidance. Fig. 1 illustrates the direct and indirect activities within the system boundaries.

Fig. 1 shows the activities classified into direct and indirect activities, visualising the system boundaries of this analysis.

2.2. *Life cycle inventory*

The Life Cycle Inventory (LCI) analysis, defined by ISO 14040 and ISO 14044, compiles and quantifies the inputs and outputs of a product's life cycle. It gathers data on materials, energy, logistics, and outputs such as emissions and waste, all within defined system boundaries.

Primary data from direct measurements provide the most accurate results but are often hard to obtain, especially for small companies with limited environmental tracking. Secondary data from databases like Ecoinvent are more accessible but less detailed. In this case study, all data came from secondary sources, highlighting the need for digital tools to improve direct environmental measurements. Although this reliance was a limitation, it was necessary given the company's low digitalisation and lack of prior analysis.

Table 1
Number of products produced in the fiscal year analysed (2023). Own elaboration.

Item	Quantity (Pieces/Pairs)	Weight (kg)
Men's Pants	14,636	8049.80
Women's Pants	7736	3403.84
Children's Pants	16,551	3310.20
Adult Skirts	4332	1299.60
Adult Jackets	3410	2046.00
Adult Shirts	1713	513.90
Adult Dresses	2619	1309.50
Children's Jackets	2080	416.00
Children's Shirts	35	3.50
Children's Dresses	58	17.40
Bags	2900	1450.00
Belts	943	188.60
Boots	5450	5450.00
Total	**62,463**	**27,458.34**

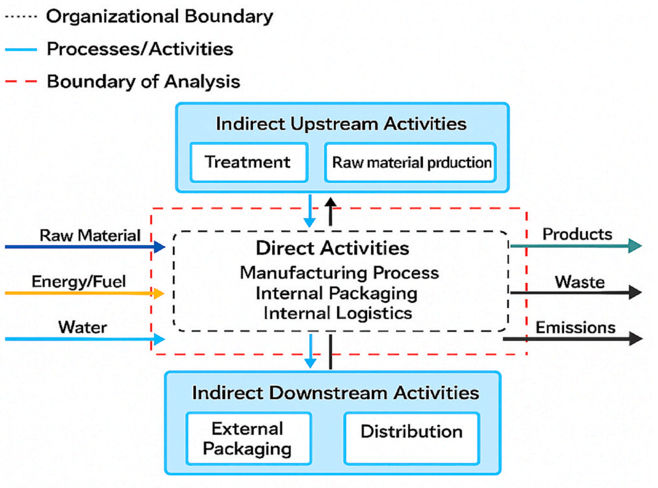

Fig. 1. Illustration of the organisation system boundaries. Own elaboration.

A site visit, employee interviews, and a company-specific questionnaire were used to map the organization's structure and processes. Relevant activities were identified based on guidance and refined through interviews, classifying them as relevant or not applicable. This process clarified the organization's operations and helped identify all direct, upstream, and downstream activities affecting the environment.

Despite efforts to conduct a comprehensive data collection, certain information gaps persisted due to limitations in the data provided by the reporting organization. To address these gaps, several assumptions informed by market research and literature review were necessary to complete the inventory analysis, ensuring the analysis remained accurate and comprehensive [38].

The fibres and tissues were assumed to consist only of polyester and cotton based on their prevalence in the provided compositions, with other materials like Elastane, which constituted a mere 0.07 % of the total cotton fibre used, deemed negligible and thus classified under cotton. This simplification aligns with literature indicating that polyester and cotton are commonly used in such products. Similarly, for components such as buckles, eyelet rivets, and buttons, brass was assumed to be the primary material, as the organization did not specify the types of metals used for a minor portion of these accessories, necessitating this assumption. The detailed data are provided in Table 2.

2.3. *Life cycle impact assessment (LCIA)*

The Impact Assessment focuses on selecting impact categories to evaluate environmental burdens within a defined system boundary. In this analysis, the ReCiPe 2016 Midpoint H method was applied [39] using the Ecoinvent 3 - allocation, cut-off by classification - system database. This method assesses midpoint indicators, capturing environmental impacts at intermediate stages. ReCiPe 2016 Midpoint is the most frequently used midpoint method in apparel LCAs published since 2020 [40,41], enhancing comparability. Midpoint indicators also avoid the value-laden weighting steps inherent in endpoint or single-score approaches while still allowing clear hotspot ranking.

For this study, SimaPro software version 9.1.1 was employed, with Ecoinvent 3.3 database, particularly the "allocation, cut-off by classification – system" version. Ecoinvent is recognized for providing comprehensive and consistent life cycle inventory data that is critical for precise environmental impact assessments. The selected library version ensures accurate allocation of environmental impacts according to system cut-off criteria, thereby enhancing the reliability of the results [42, 43].

Table 2
Illustration of inputs and outputs of the system. Own elaboration.

Outputs to Technosphere: Products and Co-products	
Item	Amount in kg
Clothes	27,458.34
Inputs from Technosphere: Materials/Fuels	
Item	Amount
Fibre, cotton, organic (GLO)| market for fibre, cotton, organic | Cut-off, S	35,214.68
Fibre, polyester (GLO)| market for fibre, polyester | Cut-off, S	979.76
Brass (GLO)| market for | Cut-off, S	267.15
Carton board box production, with offset printing (GLO)| market for | Cut-off, S	1691.76
Yarn, cotton (GLO)| market for yarn, cotton | Cut-off, S	388.65
Textile, non-woven polyester (GLO)| market for textile, non-woven polyester | Cut-off, S	388.65
Printed paper (GLO)| market for | Cut-off, S	20.05
Polyester resin, unsaturated (RER)| market for polyester resin, unsaturated | Cut-off, S	8472.00
Textile, woven cotton (GLO)| market for textile, woven cotton | Cut-off, S	50.21
Polyethylene low linear density granulate (PE-LLD), production mix, at plant RER	606.4
Polystyrene, general purpose (GLO)| market for | Cut-off, S	354.50
Natural gas, high pressure (IT)| market for | Cut-off, S	18,198.00
Water, deionised (Europe without Switzerland) | market for water, deionised | Cut-off, S	372,000.00
Diesel (Europe without Switzerland) | market for | Cut-off, S	16,527.00
Trichloroethylene (RER)| trichloroethylene production | Cut-off, S	120.00
Polyethylene, low density granulates (RER)| production | Cut-off, S	1578.00
Packaging film, low density polyethylene (GLO)| market for | Cut-off, S	841.00
Corrugated board box (RoW)| production | Cut-off, S	2014.00
Kraft paper, unbleached (GLO)| market for | Cut-off, S	36.90
Inputs from Technosphere: Electricity/Heat	
Item	Amount kWh
Electricity, low voltage (IT) | market for | cut-off, S	238,206.00

3. Results and discussion

The Results and Discussion section begins by translating the life-cycle-inventory data into environmental significance. A crucial aspect of this phase is the characterization process, which converts inventory data into potential environmental impacts, aiding in impact reduction efforts. The normalization process further identifies the most significant impact categories, helping prioritise areas for environmental improvement. This phase is essential for translating inventory data into actionable sustainability insights. Table 3 provide the environmental impacts associated with the production of a unit of final product across all the categories considered.

Fig. 2 illustrates how, through the characterization phase of LCIA, the results of LCI contribute to the analysed environmental impact categories. The results show that environmental impact of polyester resin and electricity contribute significantly to global warming potential. This mirrors recent cradle-to-gate studies on knitwear and fleece, where polyester–electricity combinations accounted for 55–70 % of total GWP because of the heat-intensive PET-spinning route and the still-fossil European power mix [44]. Recent studies back up polyester's climate profile [41]. pooled 39 cradle-to-grave garment LCAs and found polyester has the highest average footprint 40.28 kg CO_2-eq kg^{-1} textile outstripping cotton and wool by a clear margin. These published ranges confirming that the model's polyester hotspot is conservative yet fully in line with the wider literature. This impact is attributed to the energy-intensive processes involved in synthetic fibre production and the reliance on fossil fuels for the energy mix for electricity. Additionally, cotton fibre has a notable effect on global warming due to emissions generated during its cultivation and processing. This is more an indirect effect but still accounted as OLCA allow to cover for indirect activities impacts. The utilisation of certain materials is a choice of the company, therefore the impact can be included in the analysis.

Table 3
Impact assessment results by characterization. Own elaboration.

Impact category	Value	Unit of measure
Global warming	8.46	kg CO_2-eq
Stratospheric ozone depletion	$5.06x10^{-05}$	kg CFC11 eq
Ionizing radiation	0.57	kBq Co-60 eq
Ozone formation, Human health	0.02	kg NOX eq
Fine particulate matter formation	0.01	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	0.02	kg NOX eq
Terrestrial acidification	0.05	kg SO2 eq
Freshwater eutrophication	0.02	kg P eq
Marine eutrophication	0.03	kg N eq
Terrestrial ecotoxicity	33.74	kg 1.4-DCB
Freshwater ecotoxicity	0.67	kg 1.4-DCB
Marine ecotoxicity	0.87	kg 1.4-DCB
Human carcinogenic toxicity	0.22	kg 1.4-DCB
Human non-carcinogenic toxicity	9.32	kg 1.4-DCB
Land use	18.09	m^2 crop eq
Mineral resource scarcity	0.02	kg Cu eq
Fossil resource scarcity	3.52	kg oil eq
Water consumption	0.20	m^3

Polyester resin is the main factor influencing stratospheric ozone depletion, with electricity and cotton yarn also playing a considerable role. For stratospheric-ozone depletion (ODP) is led by trace CFC/HCFC emissions in virgin polyester, virgin polyester dominates (about 45 %), with electricity (about 25 %) and cotton yarn (about 10 %) trailing. Similar shares were reported for cotton–polyester sweaters by Ref. [41]. The production of polyester involves chemical processes that release ozone-depleting substances, while energy-intensive manufacturing further contributes to this impact. Ionizing radiation effects are linked to electricity, especially in areas where nuclear power is a key energy source, with polyester resin and brass also contributing through their production processes.

Regarding ozone formation, which affects both human health and ecosystems, electricity and polyester resin are among the contributors due to emissions that facilitate ground-level ozone formation, such as VOCs and Nox [45]. Cotton fibre also contributes, largely because of the nitrogen-based fertilizers used in agriculture. Similarly, particulate matter formation posing respiratory health risks is driven by electricity production, with polyester resin and cotton yarn also adding to the burden.

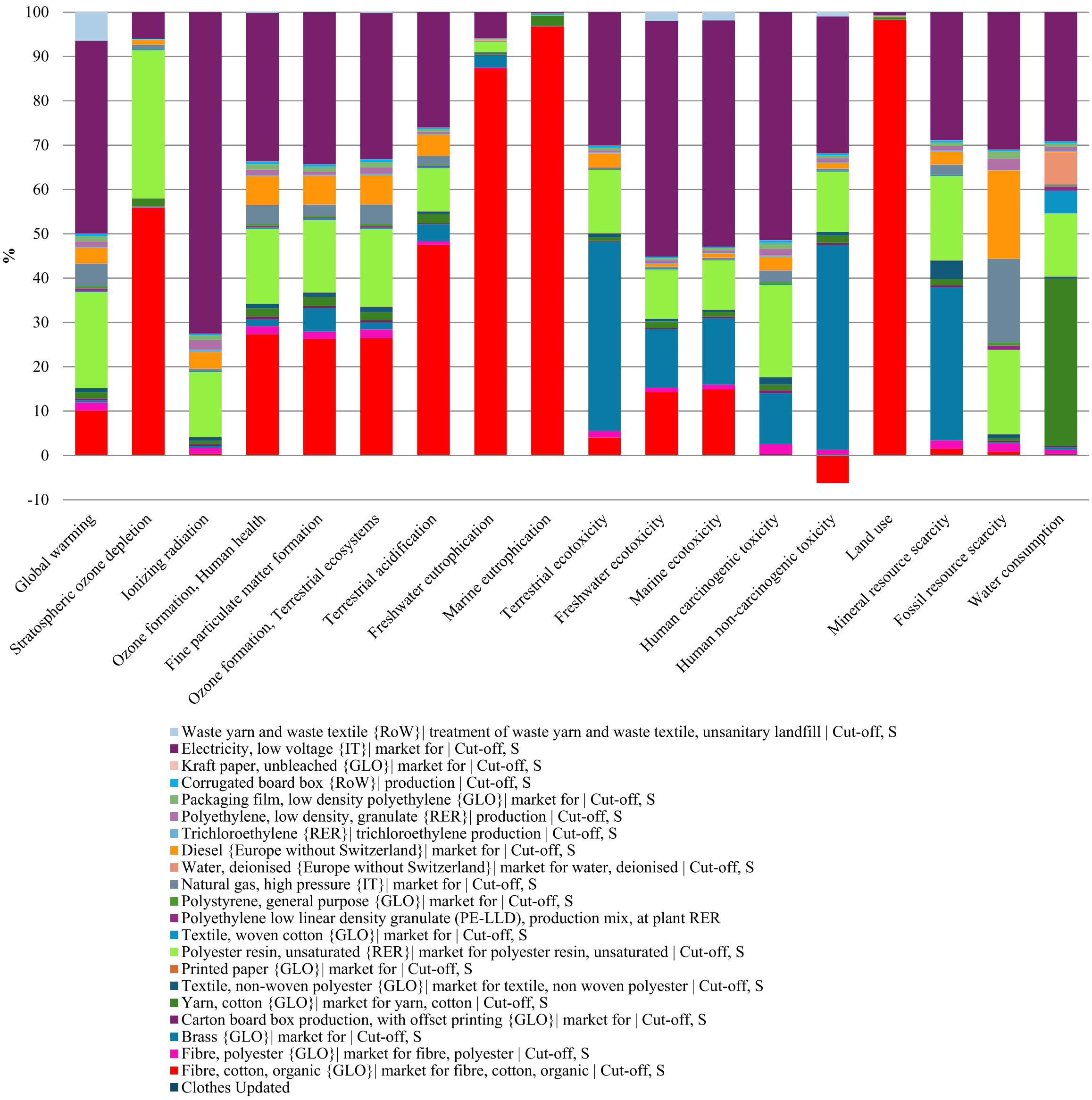

Fig. 2. Impact assessment results after characterisation. Own elaboration from the modelling phase in SimaPro-Ecoinvent.

Terrestrial acidification is caused by emissions from electricity generation and polyester resin production, driven by sulphur and nitrogen oxides. Cotton fibre also contributes, reflecting the impact of agricultural inputs used in its cultivation. Freshwater eutrophication, on the other hand, is driven by cotton fibre primarily due to upstream agricultural practices associated with fertiliser use and irrigation, which are fully captured when impacts are aggregated at organisational level through OLCA., while polyester resin contributes to a lesser extent.

Polyester resin and brass are the leading contributors to freshwater and marine ecotoxicity, as the production of synthetic fibres and metal processing release harmful substances into aquatic environments. Electricity and cotton fibre also contribute to ecotoxicity, reflecting the broader environmental footprint of energy generation and agricultural activities.

Brass is the major contributor to both human carcinogenic and non-carcinogenic toxicity impacts, reflecting the emission-intensive extraction and processing of metals used in accessories, which become visible only when minor components are aggregated across total annual production.: alternatives such as aluminium may be less impactful under this profile [46]. Polyester resin and electricity also play significant roles, as their production processes emit hazardous chemicals and pollutants. In terms of land use, cotton fibre is the most significant contributor because of the extensive agricultural land required for its cultivation. Polyester resin also has an impact, given the land needed for petrochemical extraction and processing.

Mineral resource scarcity is driven by brass production, reflecting the extraction and depletion of metal resources. Polyester resin and electricity also contribute to it, as both require the mining of minerals for their production processes. Fossil resource scarcity is associated with polyester resin, which is derived from petrochemicals, while electricity contributes significantly when fossil fuels are used as energy sources.

Water consumption is overwhelmingly dominated by cotton fibre, as cotton agriculture demands substantial water inputs. Polyester resin also contributes to water consumption, though to a lesser extent, due to water-intensive production processes. By leveraging the normalization phase, the most impactful categories have been obtained as compared to the characterization ones.

Normalization is the calculation of the value of the category indicator results in comparison to some reference data [47]. The purpose is to better understand the relative size of each indicator issued in the product system under consideration.

In the normalization, illustrated in Fig. 3, shows that organic cotton fibre is the main contributor to freshwater eutrophication, whereas its impact on marine eutrophication is comparatively minor, with impacts coming primarily from polyester, brass, and the electricity. As for freshwater and marine ecotoxicity, they are impacted by polyester, brass, and organic cotton, which are linked to the discharge of harmful substances into the aquatic environments from agriculture and production phases. Human toxicity categories' impacts are primarily driven by polyester, brass, and electricity, during their production processes.

Normalization results highlight the impact of cotton on freshwater eutrophication, attributed to nutrient runoff from agricultural practices [48], suggesting that sustainable agricultural practices could mitigate significant environmental impacts. The organization's raw material sourcing, production, and waste management have a major impact on its environmental performance. From pattern making to garment assembly, and through the extensive use of polyethylene bags and cardboard packaging, several areas offer potential for greater efficiency. Strategic material substitutions, better energy management, and stronger recycling initiatives could significantly lower the ecological footprint.

Electricity accounts for 51.4 % of human carcinogenic toxicity, 51.1 % of marine ecotoxicity, and 43.5 % of global warming. Cotton fibre contributes 87.3 % to freshwater eutrophication and 37.8 % to water consumption. Polyester production adds 33.4 % to ozone depletion, 20.8 % to carcinogenic toxicity, and 11.1 % to marine ecotoxicity. Brass impacts human non-carcinogenic health (49.3 %) and marine ecotoxicity (15 %) due to toxic metal emissions. Organic cotton heavily influences marine eutrophication (96.8 %), underscoring the need for improved nutrient management in organic farming.

The environmental impact is particularly severe in regions where cotton is grown intensively, such as in parts of India, the United States, and China, where large-scale monoculture practices exacerbate the runoff problem. Studies have shown that cotton farming can significantly contribute to nutrient pollution, leading to the degradation of freshwater ecosystems [49].

The environmental impact of cotton is worsened by the heavy use of pesticides and agrochemicals, which pollute water bodies and increase eutrophication. Mitigation efforts include promoting organic cotton farming, which avoids synthetic fertilizers, and adopting precision agriculture to optimize fertilizer use and reduce runoff.

Electricity is the largest contributor to global warming potential, responsible for 43.5 % of the total impact. This results from electricity generation based on fossil fuels such as coal, oil, and natural gas, which emit high levels of CO_2 and other greenhouse gases. In fact, the company fully relies on the electricity mix offered by national providers, which has been analysed, and it is composed by fossil energy sourced, mixed with renewable ones. The analysis confirms electricity as the main driver of global warming in textile production, followed by polyester resin and cotton fibre.

The significant impact of electricity highlights the environmental benefits of shifting to renewable energy sources, while the contributions of polyester and cotton underscore the challenges associated with both synthetic and natural fibres. Reducing the global warming potential of textile production will require a combination of energy efficiency

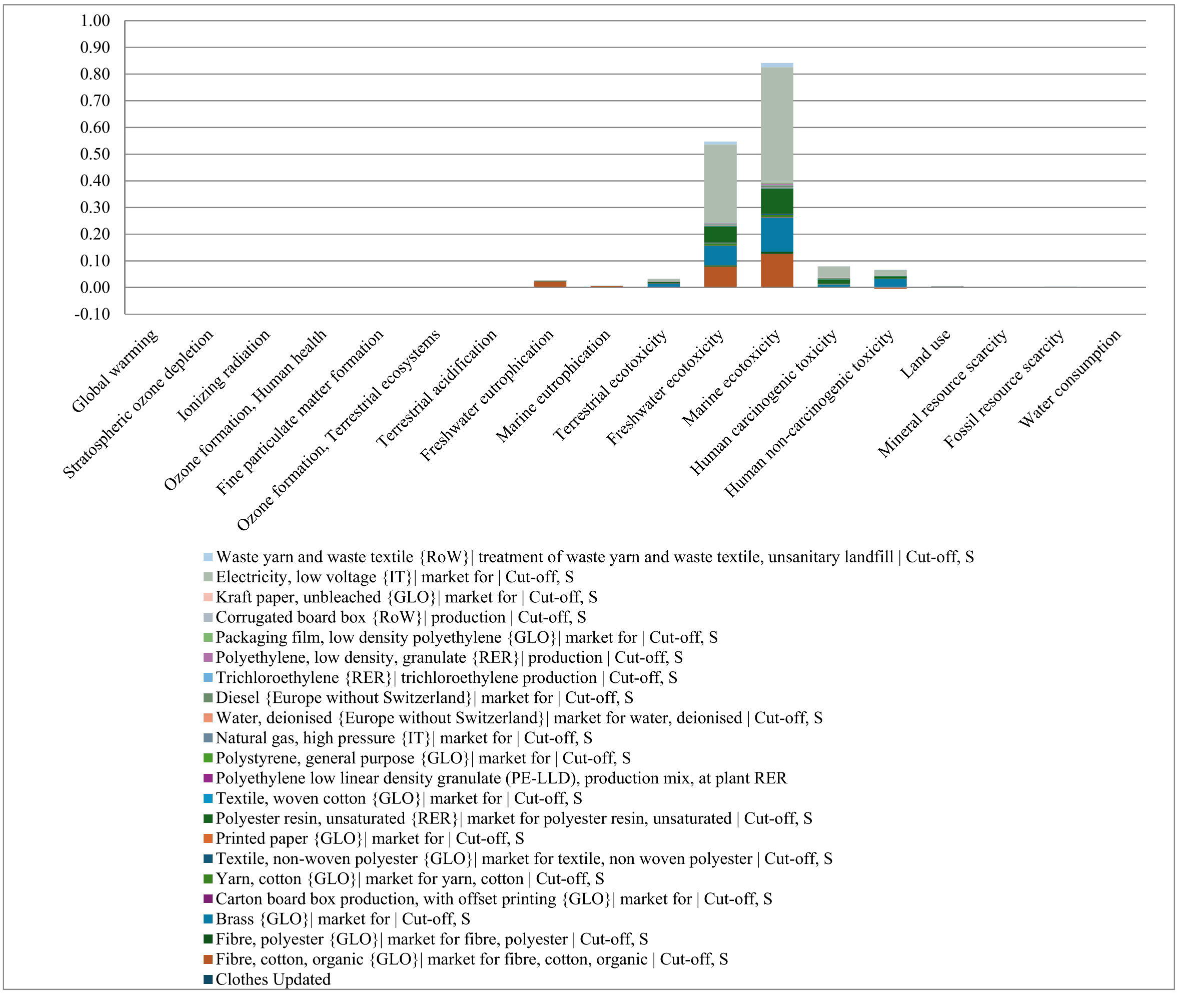

Fig. 3. Impact assessment results after normalization. Own elaboration from the modelling phase in SimaPro-Ecoinvent.

improvements, sustainable material choices [50], and enhanced waste management practices to address the full lifecycle emissions associated with clothing production [51].

Additionally, the production of brass components notably contributes to non-carcinogenic health impacts and marine ecotoxicity, accounting for 49.3 % and 15 %, respectively. Implementing cleaner production technologies such as supercritical CO_2 water-free demonstrating, which eliminates process water and can cut dye-stage GWP, ozone-plus-laser finishing for denim, trimming water and chemical use by up to 80 % [52] offer practical pathways the firm could evaluate in its next improvement cycle and more stringent emission controls could decrease these impacts to 34.5 % for human health and 10.5 % for marine life.

Furthermore, polyester is identified as a significant contributor to environmental burdens like ozone depletion, carcinogenic toxicity, and marine ecotoxicity. Advancements in recycling technologies and shifts to more sustainable materials could reduce these impacts by about 35 %, leading to a lower overall environmental degradation. Coupled with a shift to 100 % renewable electricity already shown to shave 30 % off organisational GWP this dual measure would lower the company's annual climate load by 34.6 %, matching the abatement ranges documented for apparel suppliers that decarbonise through renewables and recycled textiles [53].

Moreover, the introduction of more sustainable alternatives, such as bio-based materials or advanced recycling techniques, can help mitigate these impacts, while further enhancing resource efficiency, emissions reduction, and lowering production costs [54]. Fig. 4 visualises the two most relevant impact categories and the GWP in terms of contributors.

3.1. Interpretation

To address these environmental impacts, several sustainable practices may be recommended. Shifting to renewable energy sources can reduce the environmental burden from electricity generation, which is currently under consideration for the company. Electricity is purchased from the national grid, the production of which has a contribution of 43.5 % in the Global Warming Potential category. If the company transitions to using renewable energy resources, a reduction of around 30 % of 43.5 % can be achieved in the current contribution, resulting in new contribution of approximately 30.5 %, as supported by other analysis presented [55,56] and mirroring the 25–35 % whole-factory GHG reduction modelled in the apparel sector's 2024 net-zero roadmap [57]. Adopting water-efficient irrigation systems and sustainable fertilizer management in cotton production will help mitigate freshwater eutrophication and reduce water consumption [58], therefore this suggest that individuating suppliers that implement water-efficient irrigation and sustainable fertilizer practices can reduce freshwater eutrophication down to about 52.4 % and water consumption to 22.7 %. Precision-irrigated cotton from vetted suppliers can lower freshwater-eutrophication loads by˜35 %, echoing field-scale LCAs of cotton in China and the US [59]. For polyester, it is suggested to enhance recycling technologies and explore eco-friendly alternatives to lower its environmental impact. Switching to aluminium instead of brass and selecting suppliers that guarantee cleaner production methods and effective emission controls, could minimize toxic metal emissions. Additionally, collaborating with suppliers to improve nutrient management in organic farming can help address marine eutrophication issues. By integrating these strategies, the firm can significantly diminish its environmental burdens and strengthen its sustainability profile.

The OLCA identified two main environmental hotspots: electricity uses and cotton in apparel manufacturing. This leads to the first recommendation, which is to transition to renewable energy through solar or wind systems to cut emissions and strengthen long-term economic resilience by lowering energy costs.

Since cotton use heavily contributes to freshwater eutrophication and water consumption, shifting to organic or recycled cotton is another key step. This calls for collaborations with suppliers who follow sustainable practices and using certifications like the Global Organic Textile Standard (GOTS). The findings also support adopting circular economy principles such as designing durable, recyclable garments, promoting material recovery, and offering take-back or repair programs. Such measures reduce waste, conserve resources, and align the company with industry trends and consumer expectations, enhancing both reputation and market position.

Despite the potential of OLCA, some limitations were identified in this study. A major challenge is the lack of dedicated OLCA software [33], forcing organizations to rely on product LCA tools like SimaPro and Excel-based models, which require adaptation for data modelling to achieve accurate assessments. Defining precise system boundaries is another critical issue, as it requires careful identification of all relevant organizational activities, including whether to include indirect downstream processes. This complexity is further compounded by data

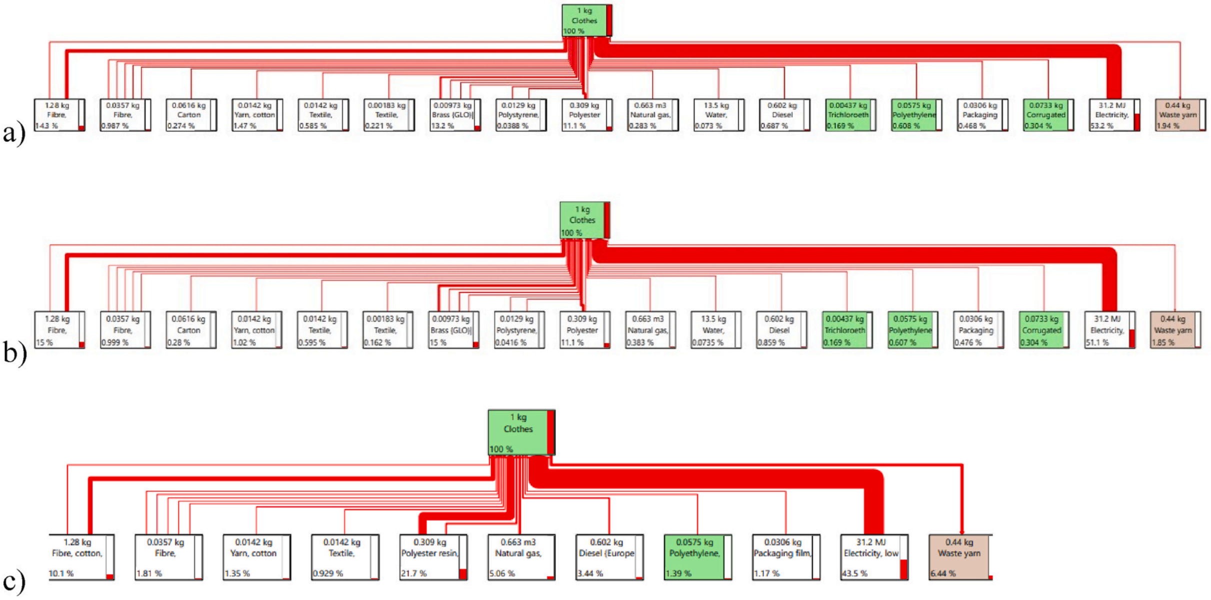

Fig. 4. Main contributors for the most relevant impact categories (Freshwater and Marine Ecotoxicity), respectively a) and b), and GWP, c).

availability challenges, with primary data often difficult to obtain, forcing reliance on secondary sources that may lack precision and relevance. Additionally, the general familiarity is below 15 % [60] with ISO standards among organizations presents obstacles in effectively interpreting and applying OLCA results, leading to inconsistencies in environmental performance reporting. Lastly, this study highlighted the lack of comprehensive inventory data, particularly for items such as office and technical equipment, which limits the scope and comparability of assessments. All the consumption material, mostly represented by printing paper, has been included in the analysis, while other stationery has not been included. Addressing these challenges is crucial for the broader adoption and refinement of OLCA methodologies.

3.1.1. Sensitivity of the impacts

A further analysis was conducted to test the sensitivity of the LCIA results with respect to key background assumptions and to assess the stability of the identified environmental hotspots. The analysis focuses on electricity supply, which represents both a dominant contributor to impacts and the most readily manageable input from an operational perspective. Electricity procurement can be modified in the short term through changes in supplier or contractual arrangements towards electricity mixes with a higher share of renewable sources, without requiring modifications to product design or manufacturing processes.

The contribution analysis shows that electricity is a major driver across the most relevant impact categories, accounting for 43.5 % of total Global Warming Potential (GWP), 53.2 % of freshwater ecotoxicity, and 51.1 % of marine ecotoxicity. These categories were selected for the sensitivity analysis as they represent, respectively, the most policy-relevant indicator for climate-related reporting and certification (GWP, expressed in kg CO_2-eq), and the most affected non-climate impact categories in the baseline results (freshwater and marine ecotoxicity, expressed in kg 1,4-DCB-eq, according to the ReCiPe 2016 Midpoint (H) method. Electricity modelling in Ecoinvent represents an average electricity mix for a given geography and voltage level. However, real-world electricity mixes can vary substantially depending on the relative contribution of fossil, nuclear, and renewable sources, as well as temporal and contractual factors. Methodological LCA literature consistently shows that the use of secondary datasets, as opposed to site-specific primary data, typically results in variations in midpoint impact indicators in the order of ±10–30 % for most categories [61]. Empirical studies further indicate that switching between generic and more detailed inventory data commonly leads to deviations of approximately 10–20 %, while preserving the relative ranking of major contributors [62]. Reviews of uncertainty propagation in LCA confirm that parameter uncertainty in background processes is among the dominant sources of variability, often yielding relative standard deviations between 10 % and 30 % in LCIA results [63].

To account for this variability while remaining consistent with the underlying inventory structure, a one-factor sensitivity analysis was implemented by varying only the electricity-related impacts by ±30 %, while keeping all other life cycle inventory inputs constant. The ±30 % range was selected to reflect realistic variability in electricity-related impacts observed across European electricity mixes and over time. This approach allows isolating the influence of electricity supply assumptions on the overall results without introducing speculative changes to unrelated parameters.

For each impact category, total impacts were recalculated using the following approach:

$I_{total} = I_{non\text{-}el} + I_{el} \times f$ where $I_{non\text{-}el}$ is the non-electricity contribution (kept constant), I_{el} is the baseline electricity contribution, and f is a scaling factor equal to 0.7 for the cleaner electricity scenario and 1.3 for the more fossil-intensive electricity scenario.

Applying this approach (see Fig. 5), total GWP varies from 7.36 to 9.56 kg CO_2-eq, compared to a baseline value of 8.46 kg CO_2-eq. Freshwater ecotoxicity varies from 0.56 to 0.78 kg 1,4-DCB-eq (baseline 0.67 kg 1,4-DCB-eq), while marine ecotoxicity ranges from 0.74 to 1.00 kg 1,4-DCB-eq (baseline 0.87 kg 1,4-DCB-eq).

To address the reliance on secondary data sources, identified as a key limitation in the research, implementing digital solutions for environmental monitoring is recommended. Tools such as IoT-enabled sensors and blockchain-based tracking systems provide real-time, accurate data that improve decision-making and support compliance with evolving regulations like the CSRD and the Digital Passport.

Beyond technical and operational solutions, the study highlights the importance of stakeholder engagement in meeting sustainability goals and aligning with ESG frameworks such as GRI and ESRS. Clear communication of environmental initiatives, supported by OLCA findings, strengthens market position, builds trust, and demonstrates proactive environmental responsibility. Internally, integrating environmental considerations into all operations, with OLCA as a

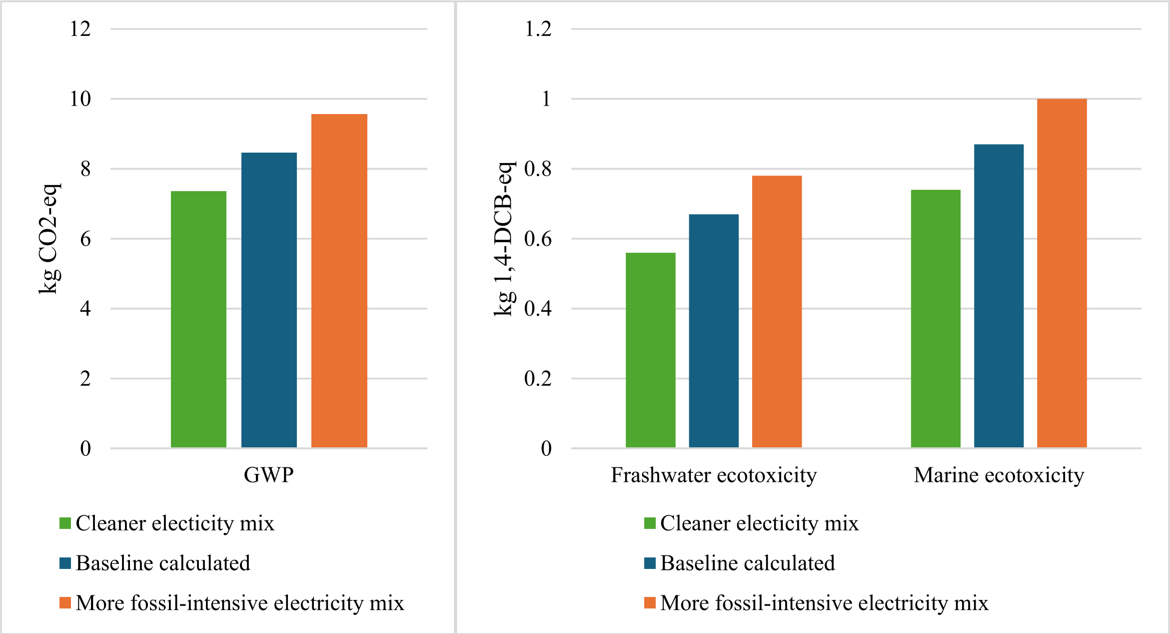

Fig. 5. *I_total* for each category addressed varying the contribution of Electricity mix.

strategic asset, ensures regulatory compliance while enhancing competitiveness and positioning the company ahead of the compliance curve for Italian SME apparel firms.

4. Conclusions

This study set out to assess whether OLCA can be effectively applied to a fashion SME operating under typical constraints of limited data availability, fragmented value chains, and increasing regulatory pressure. The results confirm that this objective has been achieved. The OLCA framework proved suitable for mapping organisational environmental hotspots, supporting strategic reflection, and translating life cycle evidence into concrete managerial actions, even in the absence of highly granular primary data.

OLCA has proven valuable in assessing the apparel company's environmental performance and identifying areas for improvement. Complementary to product-focused LCA, OLCA offers a broader view of the organization's environmental footprint, helping to spot inefficiencies, optimize processes, and uncover opportunities at company level rather than at individual product level. This organisational perspective enabled the firm to move beyond isolated product compliance and to frame sustainability as an integrated operational issue involving energy use, sourcing strategies, and supplier engagement.

From an applied perspective, one of the most relevant outcomes of the study lies in the direct feedback received from the company following the analysis. The identification of electricity use as a key organisational hotspot has already triggered internal discussions on adjusting the electricity mix, both to reduce environmental impacts and to lower long-term energy costs. In parallel, the company has started drafting its first sustainability report using part of the information structured through the OLCA process, signalling a shift from informal sustainability practices toward more systematic environmental reporting. Importantly, the firm has expressed its intention to repeat the OLCA in the following year, confirming the perceived usefulness of the method for year-on-year self-comparison and continuous improvement.

These developments highlight an additional contribution of the study: OLCA acted not only as an assessment tool but also as a capacity-building exercise. Through the modelling process and the interpretation of results, the organisation improved its internal awareness of environmental drivers, data needs, and strategic levers, laying the groundwork for more mature sustainability management practices aligned with upcoming CSRD and ESRS requirements.

At a broader level, the findings reinforce the role of OLCA as a bridge between environmental analysis and managerial decision-making in SMEs. By translating life cycle impacts into organisational priorities, OLCA supports more informed choices on investments, supplier selection, and operational planning, while remaining compatible with the realities of small firms embedded in subcontracting networks. This strengthens the case for OLCA as a practical instrument for supporting sustainability transitions in the European fashion sector.

Looking ahead, future work should build on this case by extending OLCA applications to multi-year assessments, deeper supply-chain tiers, and higher shares of primary data, potentially enabled through digital monitoring systems. Further research could also explore how OLCA outputs can be systematically integrated into sustainability reporting, digital product passports, and circular business model innovation. Expanding the empirical evidence base of SME-focused OLCA studies will be essential to support both evidence-based policymaking and the effective implementation of organisational sustainability strategies.

CRediT authorship contribution statement

Salik Ahmed: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Investigation, Formal analysis, Data curation. **Marco Ciro Liscio:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paolo Sospiro:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Irene Voukkali:** Writing – review & editing, Validation, Investigation, Formal analysis. **Antonis A. Zorpas:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. However, Professor Dr Antonis A. Zorpas is an editor of the journal and is not involved in the editorial and peer review process.

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Data availability

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

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