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Sustainable fashion: Mapping waste streams and life cycle management

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ABSTRACT

The fashion supply chain is a major contributor to global waste generation, with significant environmental and social implications. Addressing waste management challenges in this sector is crucial to achieve the Sustainable Development Goals (SDGs). Therefore, this paper proposes an integrated approach for modeling sustainable waste flow management in the fashion supply chain and consequently contributes to reducing the associated environmental impact. Firstly, Waste Flow Mapping (WFM) assessment is used to identify waste production at each stage of the fashion supply chain. Secondly, Life Cycle Assessment (LCA) is used to quantify environmental impact on resource consumption, waste generation, energy usage, and emissions. Finally, performance metrics and sustainability reporting are established to monitor and track environmental performance. Results show: i) a 25–30% reduction in environmental impacts across product life cycles, ii) a 20–25% improvement in resource efficiency iii) an increase of 15–20% in product's life extensions, and iv) approximately 40–50% of materials can be originated from recycled sources. The model represents a valuable tool for managers to define company strategies from the twin transition (green and digital) perspective.

1. Introduction

The Fashion industry, a significant contributor to global economic growth, faces a pressing challenge: the urgent need to adopt sustainable practices (Lombardi Netto et al., 2021). Despite its economic benefits, the industry is notorious for its substantial environmental footprint, characterized by excessive water consumption, chemical pollution, and high levels of waste generation (Lombardi Netto et al., 2021). This unsustainable trajectory not only jeopardizes environmental health but also raises concerns about the long-term viability of the industry itself (Lombardi Netto et al., 2021). Recent years have seen a growing awareness among consumers and stakeholders about these environmental impacts, creating a demand for sustainable fashion (Afanga et al., 2020). This shift has spurred numerous initiatives focusing on eco-friendly materials, energy-efficient production, and waste reduction strategies (De Falco et al., 2020). However, the implementation of these initiatives remains fragmented and often lacks a systemic approach that integrates various elements of sustainability into a coherent framework (Payet, 2021). This stresses the urgency of innovating green products and adopting sustainable materials. However, researchers still hold differing views on the predictors and outcomes of innovation in the industry (Sharma et al., 2021). For instance, Kant (2012) discovered that the fashion supply chain accounts for 20% of global industrial water pollution, primarily due to dyeing and finishing processes. Yang et al. (2020) further highlighted that untreated dyeing effluent adversely impacts soil productivity and contaminates water sources, rendering it unsuitable for human consumption. Addressing these pollutants before disposal is imperative. Additionally, Costa et al. (2018) emphasized that textile production contributes to 10% of global greenhouse gas emissions, primarily attributed to energy-intensive manufacturing processes. Notably, more than 50% of the total ecological footprint estimation is attributed to the energy category, with natural gas being the most

Abbreviations: AP, Acidification Potential; GWP, Global Warming Potential; KPIs, Key Performance Indicators; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; LCM, Life Cycle Management; MFA, Material Flow Analysis; SDGs, Sustainable Development Goals; WFM, Waste Flow Mapping.

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utilized fuel for these processes. These alarming statistics necessitate immediate sustainable interventions within the industry. Currently, garment waste and fibers are predominantly disposed of in landfills or incineration, leading to 30% environmental contamination (Sun et al., 2021). The fashion sector's substantial water demand and extensive chemical usage result in potentially toxic wastewater, posing environmental and human health risks. This emphasizes the critical need for integrated chemical and biological approaches to assess effluent toxicity and predict environmental hazards continually (Methneni et al., 2021). Particularly, denim fabric and cotton fiber production account for the highest carbon emissions and water consumption. Polyester blended denim, while having a 5% larger carbon footprint and a 72% lower water footprint than cotton denim, contributes to the escalation of embodied carbon emissions (from 4% in 2001 to 43% in 2018) (Zhao et al., 2021). There is an urgent need to adopt sustainable waste flow management techniques and embrace circular economic principles in the fashion industry to address these pressing challenges (Vasconcelos et al., 2022; Szajczyk et al., 2023; Ezhilarasan and Mishra, 2023). In response to this gap, our study introduces a novel integrated approach that combines Waste Flow Management (WFM) and the 5 S method, Life Cycle Assessment (LCA), and Key Performance Indicators (KPIs) to systematically reduce environmental impacts in the fashion supply chain (Salmi and Kaipia, 2022). While, existing research has separately explored these elements, there is a conspicuous absence of studies that examine their combined effect on achieving sustainable outcomes in the fashion industry. Our research aims to fill this void by providing a comprehensive model that not only assesses the current environmental footprint but also offers actionable strategies for improvement. Specifically, the present research aims to: 1) evaluate the current state of waste management practices in the fashion industry and identify key areas of inefficiency; 2) apply Life Cycle Assessment, a standardized method by the International Organization for Standardization (ISO 14040), to quantify the environmental impacts of denim production, providing a clear picture of the areas where intervention is most needed and 3) develop and implement a set of KPIs tailored to the fashion industry, enabling organizations to monitor and to improve sustainability performance effectively by integrating real-time data sources and advanced analytics for precise carbon emissions tracking. The integration of these three methods provides a robust framework for addressing sustainability in the fashion industry. WFM identifies key areas for waste reduction, the 5 S methodology facilitates the efficient implementation of these strategies, and LCA quantifies the environmental impact, ensuring a thorough and effective approach to sustainability. This combination not only addresses the immediate operational inefficiencies but also provides a long-term, sustainable solution for environmental impact reduction. The final aim is to contribute to the Sustainable Development Goals (SDGs), with a particular focus on waste reduction, recycling, and the adoption of circular economy principles, thereby revolutionizing sustainable practices in the fashion industry. Finally, our study emphasized the importance of embracing cutting-edge tools and technology within the fashion supply chain. The novelty of this research lies in its integrated approach to sustainable waste management in the fashion supply chain. Definitively, the present research aims to significantly contribute to the achievement of SDGs related to responsible consumption and production (SDG 12), clean water and sanitation (SDG 6), and climate action (SDG 13) by focusing on critical areas such as waste reduction, recycling, and the incorporation of circular economy principles. The rest of the paper is organized as follows: Section 2 presents the background related to approaches and methods for supporting and improving decision-making towards sustainability; Section 3 describes the proposed decision-making process for the fashion industry. Meanwhile, Section 4 introduces an application to an illustrative real case. Discussion of the main implications and practical implications are analyzed in Section 5 and Section 6, respectively. Finally, Section 7 summarizes the main conclusions of the research.

2. Background and literature review

The current body of literature on sustainable fashion primarily focuses on three areas: *material innovation*, *supply chain management*, and *consumer behavior*. Studies such as those by Mukherjee (2015) have explored the development of eco-friendly materials, emphasizing the reduction of environmental impact through alternative fabric choices. However, these studies often overlook the comprehensive lifecycle of these materials, missing critical stages like production, usage, and disposal. On the supply chain front, research by Chen et al. (2023) provides valuable insights into the optimization of production processes for sustainability. While, this research offers strategies for energy efficiency and waste reduction, it often fails to integrate these processes with broader environmental impact assessments, thereby limiting the scope of their applicability in real-world scenarios. Consumer behavior studies, like those conducted by Jang (2023), have shed light on the growing demand for sustainable fashion products. These studies, however, predominantly address the demand side, with limited emphasis on how industry practices can be reformed to meet this demand sustainably (Yalcin-Enis et al., 2019; Akter et al., 2022). In response to these challenges, integrating *circular economy principles* and *innovative techniques* has become imperative to promote resource efficiency, reduce environmental consequences, and foster a circular approach within the sector (James and Kent, 2019; F. Chen et al., 2021). Thus, our study lies in addressing *critical gaps* identified in the existing body of literature about sustainable waste management in the fashion industry. Through an extensive review of the state-of-the-art research, several key deficiencies have been identified. These gaps primarily revolve around the need for a comprehensive and systematic approach encompassing the entire supply chain, from raw material extraction to end-of-life disposal. Additionally, existing methodologies often need more integration with performance metrics and sustainability reporting within a closed-loop supply chain context. To define a comprehensive and well-informed perspective on the waste management of the fashion industry, an investigation of SCOPUS, an outstanding multidisciplinary citation database, was carried out. The review was made to pinpoint publications with a strong thematic coherence. To define the survey sample, *experts team* belonging to the field of fashion and sustainability were selected. The experts offered valuable guidance on the keywords to include in the survey (Table 1). Furthermore, the role of the team of experts was of fundamental support for the development of the methodological phases (described in Section 3).

The team of experts has identified a few inclusive keywords to have a heterogeneous analysis spectrum. Thus, the following string was used in the analysis: (TITLE (fashion) AND TITLE-ABS-KEY (supply AND chain) AND TITLE-ABS-KEY (waste)). The investigation returned **55** documents from 2009 to 2023 (Fig. 1).

The documents are distributed as follows: Article (30; 55%); Book

Table 1
Summary of the profiles of 5 experts.

Expert	Area of Expertise	Education	Professional Experience
Expert 1	Sustainability in Fashion	Ph.D. in Environmental Sciences	Over ten years in the sustainable fashion industry
Expert 2	Performance Metrics	Master's in Business Economics	15+ years in corporate consulting on performance metrics
Expert 3	Supply Chain Management	Ph.D. in Industrial Engineering	University professor with 20+ years of supply chain research
Expert 4	Waste Flow Mapping	Ph.D. in Environmental Engineering	Researcher at an environmental research institute
Expert 5	Life Cycle Management	Master's in Chemical Engineering	Over ten years of experience in process engineering and development

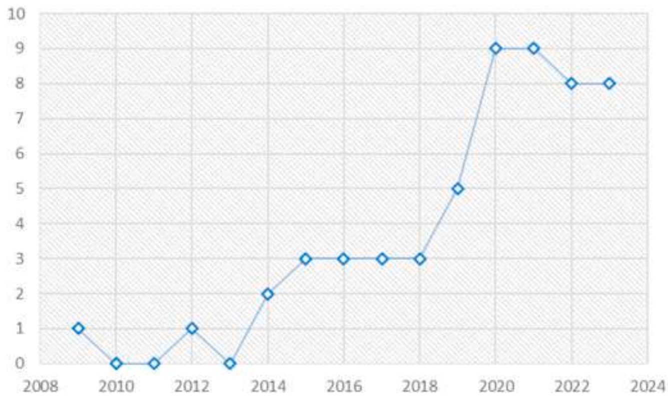

Fig. 1. Documents by year (source: Scopus).

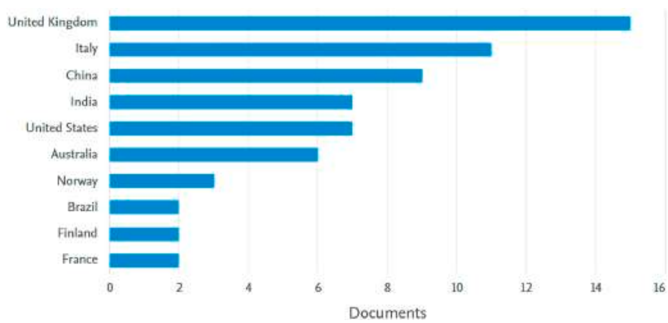

Fig. 2. Regional distribution of documents (source: Scopus).

Chapter (10; 18%); Review (8; 14%); Conference Paper (6; 11%) and Conference Review (1; 2%). Notably, the United Kingdom (15; 27%, Italy (11; 20%) and China (9; 16%) emerged as the pioneers of this intellectual subject matter, contributing significantly to the quantity and context of literature (Fig. 2).

The selection encompassed diverse knowledge domains, as shown in Fig. 3. Engineering with 26 documents (19,8%) is followed by Environmental Science (19; 14.5%).

To ensure the highest rigor and scientific integrity, only documents with these characteristics were considered: 1) articles published in scientific journals; 2) articles in English; 3) articles in the final stage and not in press. The analysis of the state of the art highlighted that the topic being researched is a continuously evolving topic, with significant progress and some gaps. Table 2 outlines advancements beyond the state of the art and identifies gaps in previous studies.

Considering the analysis of the state of the art, it is relevant to highlight that Nørup et al. (2019) pointed out the importance of material flow mapping, which helps identify waste generation points and potential areas for reduction and recycling. As suggested by several authors, integrating methodologies can support the development of sustainability strategies (Paras et al., 2023; Resta et al., 2016; Li et al., 2019; Moorhouse and Moorhouse, 2017). Therefore, the integration of Waste Flow Mapping (WFM) and Life Cycle Management (LCM) can be a significant step towards a more comprehensive assessment of environmental impact and the creation of more coherent sustainability strategies in the fashion supply chain (Mishra et al., 2020; De Falco et al., 2020). LCA is recognized as a robust tool to analyze the environmental impact of textile manufacturing processes, offering insights into resource consumption, energy usage, and emissions (W. Chen et al., 2021). In the strategy-planning and decision-making process, LCA has been utilized to analyze the environmental effect of textile waste management solutions at various stages of the supply chain (Ramos et al., 2018; Moazzem et al., 2018; Subramanian et al., 2020; Wiedemann et al., 2023; González et al., 2023).

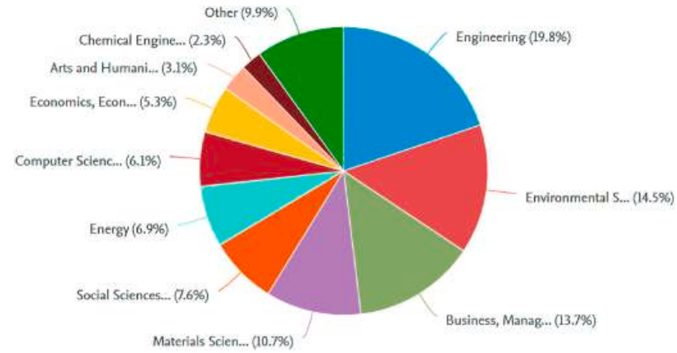

Fig. 3. Documents of subject area (source: Scopus).

Table 2
Advancements beyond the state of the art and identified gaps in previous studies.

Gap	Advancements Beyond the State of the Art	Identified Gaps in Previous Studies	References
Standardization	Development of industry-specific standards for performance metrics and sustainability reporting.	Lack of uniformity in metrics and reporting standards within the fashion supply chain.	Gbolarumi et al. (2021)
Data Availability	Integration of real-time data sources and advanced analytics for precise carbon emissions tracking.	There needs to have more reliable data on supply chain and emissions, hindering accurate reporting.	Abdelmeguid et al. (2022)
Waste Flow Mapping	Integration of AI and IoT technologies for real-time waste flow tracking and management.	Limited understanding of waste flows within the fashion supply chain and need for real-time monitoring.	Schmutz and Som (2022)
Integration of LCM	Development of a comprehensive framework that seamlessly integrates Waste Flow Mapping with Life Cycle Management.	Limited research on the effective integration of these methodologies to enhance sustainability.	Watson and Wiedemann (2019)
Fast Fashion Impact	Assessment of the environmental and social impact of fast fashion practices.	Inadequate examination of the impact of fast fashion on supply chain management and waste generation.	Coppola et al. (2021)
Tools and Technology	Development and utilization of advanced tools and technologies for more efficient measurement and management of sustainability metrics.	Limited exploration of cutting-edge tools and technology within the fashion supply chain.	Nobile et al. (2021)

Another aspect highlighted by the literature analysis is that digital transformation enables real-time monitoring and data analytics for optimized resource usage and supply chain transparency (Ślusarczyk et al., 2019; Han et al., 2021). While developing performance metrics and sustainability reporting, as proposed by Saxena et al. (2020), facilitates monitoring and continuous improvement, with benchmarking and knowledge exchange helping identify best practices (Wang and

Yang, 2020; J. Li and Leonas, 2021; Salmenperä et al., 2021). The present research aims to cover the literature gaps. Addressing these gaps is vital for establishing effective and sustainable waste management strategies in the fashion supply chain. This study bridges these gaps by integrating Waste Flow Mapping (WFM), Life Cycle Assessment (LCA), and performance metrics. By doing so, this research provides a solution for effective waste management in the garment supply chain. The proposed approach allows for a more detailed and systemic analysis of environmental impacts, extending beyond material innovation or isolated supply chain improvements. Thus, this research not only adds to the present academic literature but also gives concrete solutions such as enhanced recycling methods and targeted waste reduction strategies for minimizing environmental impacts inside the sector. Its potential impact extends to reducing pollution, conserving resources, and aligning with global sustainability goals, making it a crucial addition to academic discourse and industry practices. This study goes beyond existing manuscripts in providing a comprehensive and systematic approach to tackle waste generation in the entire garment supply chain.

3. Materials and methods

The methodological approach to assess performance metrics and sustainability reporting in the fashion supply chain integrates two principal components: waste flow mapping and life cycle management (LCM). This comprehensive framework aims to quantify the environmental footprint across the supply chain and provide actionable insights for sustainability improvements.

3.1. Waste flow mapping and 5 S

Waste Flow Mapping (WFM) is a systematic process used to track and analyze waste material's generation, accumulation, and movement within a production system or throughout an entire supply chain (Schoeman et al., 2021). This process is particularly relevant to industries like fashion, where waste can occur at multiple stages from raw material extraction to production, distribution, consumer use, and ultimate disposal. By mapping these flows, organizations can identify inefficiencies, opportunities for waste reduction, and potential areas for implementing circular economy principles. Waste Flow Mapping (WFM) relies on quantitative data to trace and optimize material flows within the fashion supply chain (Kurdve et al., 2015). Various equations and mathematical representations are used to support the considerations and analyses in WFM, particularly those derived from principles of mass balance and Material Flow Analysis (MFA).

The basic premise of WFM is that mass is neither created nor destroyed, and hence, the mass balance equation is central to the process according to Mass Balance Equations (1) and (2)

$$\text{Input} + \text{Generation} - \text{Output} - \text{Consumption} = \text{Accumulation} \tag{1}$$

$$\text{Input} + \text{Generation} - \text{Output} - \text{Consumption} = \text{Accumulation} \tag{2}$$

Where.

- Input is the mass of raw materials entering a system.
- Generation is the mass of waste generated within the system.
- Output is the mass of products (and waste) leaving the system.
- Consumption is the mass of materials consumed during the process.
- Accumulation is the mass of materials (if any) that remains within the system.

To understand the efficiency of a process or the impact of waste generation, the following rate equation can be applied (Equation (3)):

$$\text{Waste Generation Rate} = \frac{\text{Total Waste Generated}}{\text{Total Production Output}} \tag{3}$$

A critical aspect of WFM is understanding the proportion of waste that is recycled or recovered (Equation (4)):

$$\text{Recycling Rate} = \frac{\text{Total Waste Recycled}}{\text{Total Waste Generated}}\ x\ 100\% \tag{4}$$

The economic benefit of reducing waste can be quantified as (Equation (5)):

$$\text{Cost Savings} = \text{Waste Reduction Achieved} \times \text{Unit Cost of Waste Disposal} \tag{5}$$

By employing these equations, it was possible to quantify the flow and impact of waste within the fashion supply chain, thus enabling more informed decision-making and reporting.

From a lean manufacturing perspective, it is helpful to integrate Waste Flow Mapping (WFM) and the 5 S methodology to enhance both the efficiency of the production process and the sustainability of the fashion supply chain (Teplická et al., 2021). The 5 S method focuses on five Japanese principles: **Seiri** (Sort), **Seiton** (Set in order), **Seiso** (Shine), **Seiketsu** (Standardize), and **Shitsuke** (Sustain), which collectively aim to promote organization, cleanliness, and standardization in the workplace. Integrating WFM with the 5 S methodology creates and synergistic approach that optimizes waste handling and fosters a proactive culture of waste reduction and sustainability in the fashion supply chain. This holistic strategy can lead to more effective resource utilization, cost savings, and improved environmental performance. Translating this integration into quantitative terms requires a set of metrics and equations that bridge both methodologies, as defined below:

Sort (Seiri) and Waste Sorting Efficiency: Measuring how effectively waste is being sorted at the source is a critical first step in waste management and aligns with the principle of Seiri (Equation (6)).

$$\text{Waste Sorting Efficiency} = \frac{\text{Total Waste Generated}}{\text{Total Waste Correctly Segregated}}\ x\ 100\% \tag{6}$$

Set in Order (Seiton) and Time Saved through Organization: This represents the time saved due to better organization of waste management tools and pathways, reflecting Seiton's emphasis on orderliness (Equation (7)).

$$\text{TimeSaved} = \text{TimebeforeSeiton-TimeafterSeiton} \tag{7}$$

Shine (Seiso) and Cleaning Efficiency: By measuring the area cleaned per unit of time, this equation can help quantify the efficiency improvements Seiso applied to the waste processing areas (Equation (8)).

$$\text{Cleaning Efficiency} = \frac{\text{Time Spent Cleaning}}{\text{Area Cleaned}} \tag{8}$$

Standardize (Seiketsu) and Consistency of Waste Management: This metric assesses how well waste handling procedures are standardized and followed in alignment with Seiketsu (Equation (9)).

$$\text{Standardization Index} = \frac{\text{Total Number of Standardized Tasks}}{\text{Number of Standardized Tasks Followed}}\ x\ 100\% \tag{9}$$

Sustain (Shitsuke) and Waste Reduction Trend: A negative value would indicate a positive trend in waste reduction, demonstrating the discipline of maintaining and improving standards as per Shitsuke (Equation (10)).

$$\text{Waste Reduction Trend} = \left(\textit{Waste Generated}_{\text{Previous Period}} - \textit{Waste Generated}_{\text{Current Period}}\right) / \textit{Waste Generated}_{\text{Previous Period}}) \times 100\% \tag{10}$$

3.2. Life cycle management (LCM) and life cycle analysis

Life Cycle Management (LCM) is a business management approach that all types of businesses and organizations can use to improve their sustainability performance (Tariq et al., 2021). The goal of LCA is to minimize environmental and socio-economic burdens over the whole life cycle of a product or service, from raw material extraction, manufacturing, and distribution to use, reuse, and end-of-life management. LCM is a dynamic, iterative process requiring many stakeholders' engagement. It is informed by LCA data but includes considerations beyond environmental factors, such as economic and social dimensions, to ensure a comprehensive approach to sustainable development. Implementing LCM can help businesses reduce their ecological footprint, improve their brand image, innovate new products, and comply with regulations, all while contributing to sustainable development goals. In this context, LCA is a methodology that quantitatively assesses the environmental impacts associated of all the stages of a product's life. LCA is a structured, comprehensive, and internationally standardized process (ISO 14040/14044) quantifying the environmental impacts associated with the different stages of a product's life cycle (Petrillo et al., 2022). The core phases of LCA are: Goal and Scope Definition, Inventory Analysis (LCI), Impact Assessment (LCIA), and Interpretation. The LCI phase involves data collection and calculations to quantify relevant inputs and outputs of a product system. The basic equation to calculate the inventory of a particular environmental flow (e.g., emissions, resource use) is shown in Equation (11):

$$Environmental\ Flow = \sum_{i=1}^{n} (Qi - EFi)\ 1 \tag{11}$$

Where.

- E is the total environmental flow (e.g., kg of CO_2, MJ of energy)
- Q_i is the quantity of the process input or output (e.g., kWh of electricity, kg of raw material)
- EF_i is the environmental factor associated with the input or output (e.g., kg CO_2/kWh for electricity, kg CO_2/kg for material)

While, LCIA essentially involves the calculation of GWP and AP as defined in Equation (12) and Equation (13):

$$Global\ Warming\ Potetial = \sum_{i=1}^{n} (Ei - GWPi)\ 1 \tag{12}$$

Where.

- E_i is the emission of gas *i* (e.g., kg of CH4)
- GWP_i is the global warming potential factor of gas *i* relative to CO_2 (e.g., CH4 has a GWP of 28–36 over 100 years)

The potential of emissions to cause acidification in the environment can be calculated by:

$$Acidification\ Potetial = \sum_{i=1}^{n} (Ei - APi)\ 1 \tag{13}$$

Where.

- E_i is the emission of gas *i* (e.g., kg of SO_2)
- AP_i is the acidification potential factor for emission *i*

WFM integrates into LCA by contributing detailed information about waste streams, which is vital for a thorough environmental impact assessment. From a practical point of view, a company in the fashion industry can use LCA to assess the environmental footprint of its products and apply WFM to target specific waste streams for improvement. Together, these two elements create a robust system for environmental management that promotes sustainability throughout the entire life cycle of a product.

3.3. Integrated modeling approach based on waste flow mapping and life cycle management

The proposed integrated approach comprises **three main steps**. In the initial phase, the focus is on implementing **Process Mapping** to understand the textile industry's environmental impact and need for sustainable practices (De Oliveira Neto et al., 2022; Arnold et al., 2023). This phase incorporates two methodological approaches: WFM and the 5 S methodology. This phase conducts a comprehensive examination of waste generation within the fashion supply chain to gain a detailed understanding of waste dynamics by WFM. This step involves detailed waste flow mapping across the entire supply chain, from raw material extraction to garment manufacturing, distribution, consumer use, and end-of-life disposal or recycling. Table 3 summarizes the principles of the 5 S method integrated with WFM.

Subsequently, the framework incorporates LCM principles to evaluate the environmental impacts associated with the entire lifecycle of fashion products. **Life Cycle Assessment** (LCA) is employed to assess the environmental footprint of the whole denim lifecycle of denim products, considering all four phases of LCA (goal and scope definition, life cycle inventory, impact assessment, and interpretation). The final step involves ongoing **monitoring and improvement** efforts (Contini et al., 2023; Assad et al., 2019). Key Performance Indicators (KPIs) are implemented to quantitatively assess the reduction in environmental impacts, material efficiency gains, and improvements in supply chain transparency. This involves regular audits and assessments to identify areas for further enhancements. Feedback loops are established to gather input from stakeholders at various stages of the supply chain, allowing for real-time adjustments and refinements. The proposed approach ensures methodological rigor and a profound enhancement in the depth and breadth of sustainable innovation within the Fashion supply chain. Fig. 4 presents the integrated methodology for modeling sustainable waste flow management in the fashion supply chain. It combines Waste Flow Mapping (WFM), 5 S, Life Cycle Assessment (LCA), and sustainability KPIs to provide a more detailed knowledge of the industry's environmental effect, allowing for targeted interventions and developing a sustainability culture.

Table 3
Principles of the 5 S method integrated with Waste Flow Mapping (WFM).

5 S Principle	Description	Integration with Waste Flow Mapping (WFM)
Seiri (Sort)	Eliminate what is unnecessary or not needed in the workplace.	Identify and remove unnecessary waste or obsolete materials.
Seiton (Set in order)	Organize and place objects and materials efficiently to facilitate access and reduce waste.	Create an organization system that considers waste generation areas and collection points.
Seiso (Shine)	Maintain a clean and orderly workplace.	Use regular cleaning to prevent waste accumulation and detect any leaks or spills.
Seiketsu (Standardize)	Establish standard procedures to maintain improved conditions.	Standardize waste management procedures to ensure uniformity and consistency.
Shitsuke (Sustain)	Maintain a long-term commitment to uphold standards and continually improve.	Implement a continuous monitoring system to assess the effectiveness of waste reduction actions.

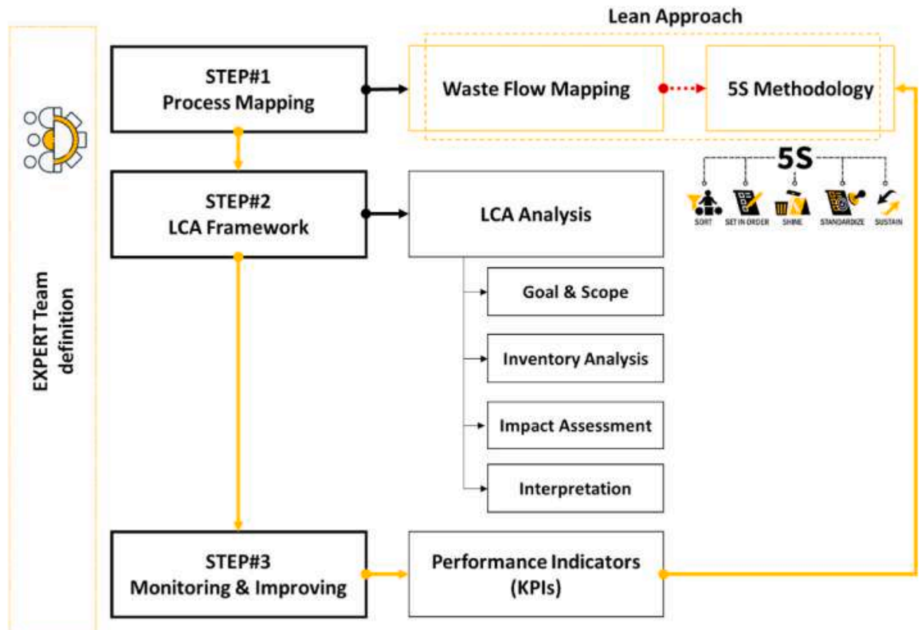

Fig. 4. Main stages of the proposed methodology (Source: Authors' elaboration).

4. A pilot experimental scenario

4.1. Denim fashion industry

The global fashion industry is a cornerstone of the world economy, experiencing substantial growth in recent years. The market size of the apparel and footwear industry surged to $1.71 billion in 2021, showcasing an 18.1% increase in current prices from the previous year (Shin and Lee, 2023). This growth is projected to continue, with an estimated 6.1% increase by 2023, reaching a market size of $1.95 billion (Zayed et al., 2023). The surge in fashion production is staggering, with global output surpassing 100 to 150 billion clothing items annually (Remy et al. (2016). Moreover, the trajectory is set to continue, with global online retail sales projected to surpass $7 trillion by 2025 (Yan et al., 2021; Muratore and Marques, 2021). In light of these trends, strategic efforts to improve global sourcing policies and prioritize sustainable practices are crucial for fashion companies to establish a responsible brand sourcing reputation (Arrigo, 2020). The focus of the present research is on the production of **denim fabric**. Denim is one of the most widespread fabrics in the world of fashion (3 and a half billion garments produced yearly), but it has a high environmental impact. Denim is one of the most used fabrics, but also one of those that require the highest commitment of resources. It is now known to everyone that to produce a pair of jeans, it is necessary to use 3.800 L of water, while to produce one kilo of cotton fibers 10,000 L of water, 12 m^2 of land, and 18.3 Kwh of energy are needed electric, compared to emission of 33.4 kg of CO_2 equivalent during the entire life cycle of the product (Khan and Jintun, 2021). Fig. 5 shows the denim production process. A real case study in Sindh, Pakistan, has been analyzed. This region, known for its rich textile heritage and robust industry, provided an ideal environment for our research. Our primary data was precisely gathered through on-site investigations within the company and direct collaboration with the company's management and relevant departments. A comprehensive analysis of secondary sources, including industry reports, scholarly publications, and governmental records complemented insights. This rigorous extraction of data from primary, secondary, and tertiary sources strengthened the credibility and reliability of our findings, ensuring a comprehensive examination of the company's operational dynamics.

Fig. 5. Denim production process.

The denim production process can be visualized as a flow diagram starting from the acquisition of raw materials such as natural or synthetic fibers (Juanga-Labayen et al., 2022). These fibers undergo preparation and spinning stages to create yarns, which may be dyed if needed at this juncture (Schumacher et al., 2020). The resulting threads are then woven or knitted into fabric and may undergo additional dyeing, printing, and finishing processes. Finally, the finished material is rolled and packaged for distribution to garment manufacturers and retailers, as shown in Fig. 6.

4.2. Process Mapping: WFM and 5 S

In this research, the WFM procedure in the fashion industry was conducted using Wondershare Edrawmax software 11.5.0®, as shown in Fig. 7. WFM involved collecting statistics on current waste production, encompassing waste generated during plain fabric processing, yarn and material production, dyeing and finishing procedures, and garment manufacturing. This includes trimming excess cloth, off-cuts during pattern slicing, and discarded clothes. Identifying these factors facilitates understanding the root causes of waste and identifies potential areas for waste reduction. Furthermore, the WFM technique provides insights into how managing waste, waste flow patterns, and considerations for recycling, reuse, disposal in landfills, or incineration.

The integration of 5 S and WFM methodologies was implemented to significantly improve operational efficiency and sustainability in the working environment. Fig. 8 shows how each of the five principles of the 5 S methodology has been integrated with Waste Flow Mapping to improve organization, cleanliness, and waste management.

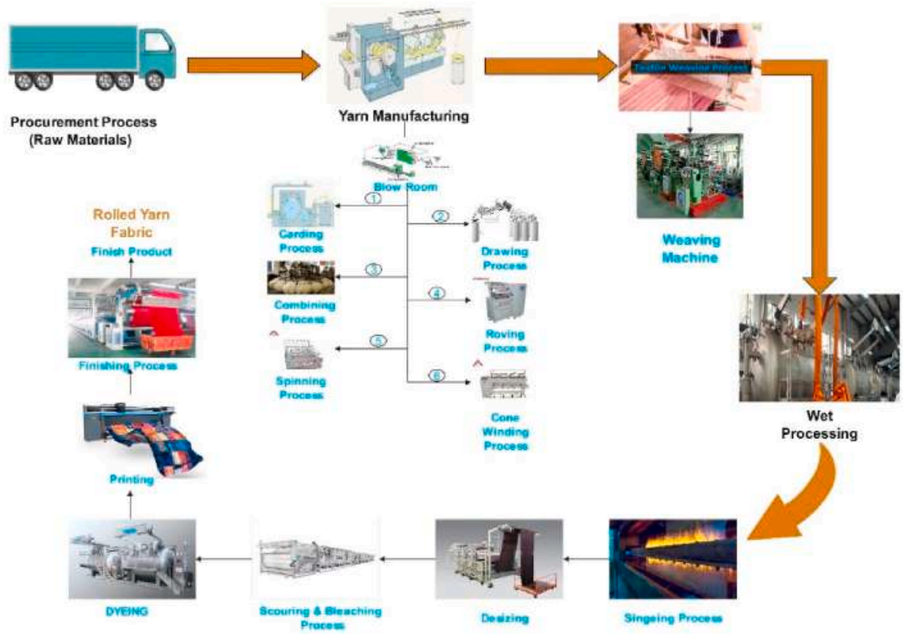

Fig. 6. Flow diagram of denim manufacturing from fiber to fabric (Source: Authors' elaboration).

4.3. LCA framework

4.3.1. Goal and scope

This research evaluates the environmental impact of "**1 kg of denim fabric produced**" entire life cycle, mirroring real-world consumer behavior (Sarı et al., 2023). The open LCA software, open-source Life Cycle and Sustainability Assessment software was used to develop the model. A *cradle-to-grave* approach was adopted to assess the environmental impact of the entire life cycle of denim, including production, distribution, use, and end of life. In this context, *system boundaries* specify the stages and processes included in the assessment from where the data is collected on raw material extraction, material production, fabric furnishing, transportation, use phase, and end-of-life scenarios. Table 4 represents the life cycle phases of the denim industry with a cradle-to-grave approach.

4.3.2. Inventory Analysis

The second phase involves Inventory Analysis for LCA. This method entails identifying the current waste generated in the fashion supply chain. The data collection phase adhered to established protocols and drew upon literature on environmental assessment methodologies (Jia et al., 2020). Inventory Analysis for LCA aims to quantify the environmental impacts of producing 1 kg of denim fabric. The research used an integrated approach that combined Waste Flow Mapping (WFM) and Inventory Analysis for Life Cycle Assessment (LCA) to improve resource utilization and emission assessments. WFM identified critical stages and activities in the fashion supply chain where waste is generated, while LCA quantified waste and identified areas with maximum resource utilization and emissions. This allowed for a more detailed understanding of environmental impact and targeted strategies to optimize processes and reduce environmental footprints. Table 5 summarizes the initial parameters for producing 1 kg of denim.

In Table 6, sources of data collected within the entire supply chain are shown. Meanwhile, Table 7 depicts the denim life cycle impact. Finally, Table 8 presents electricity consumption (all energy data for processes in kWh per kg spun yarn).

4.3.3. Impact assessment

The LCA framework examines resource utilization, waste generation, energy consumption, and emissions at each stage of denim production (Li et al., 2021). The Environmental Footprint database (EF3.0) proposed by the European Commission has been adopted. EF is based on 16 impact categories, which quantify the effects on the environment (8 categories), on human health (4 categories), and the depletion of resources (4 categories), with the intent to include the broadest spectrum of problems potentially caused by each supply chain. In this experimental research, a comprehensive LCA has been conducted to evaluate the environmental impacts associated with the complete life cycle of a denim product, as shown in Fig. 9. The life cycle was defined as the functional unit of "1 kg of denim fabric produced" encompassing all stages from raw material extraction to end-of-life treatment.

Table 9 provides a detailed environmental impact assessment of various stages in denim production. It outlines the input and output flows for each step, offering a comprehensive overview of resource consumption, outcomes, and emissions throughout the production process.

Fig. 10 illustrates how each stage of the product life cycle, from Raw Material Extraction to End-of-Life, contributes to the overall environmental impact, providing valuable insights for targeted sustainability improvements.

Meanwhile, Fig. 11 shows the assessment of environmental impacts using normalized results and contributions. EF 3.0 sets as a benchmark for comparison have been used.

Fig. 12 illustrates the weighted comprehensive environmental effects, offering a clear overview of the overall ecological footprint throughout the product's life cycle.

Our targeted environmental factors throughout the study included greenhouse gas emissions (CO_2, CH_4), as shown in Fig. 13.

Table 10 presents a detailed breakdown of a normalized and weighted environmental impact, covering entire life cycle of denim fabric (1 Kg) from creation to disposal. It includes various impact categories such as acidification, climate change, ecotoxicity, and resource use.

Meanwhile, Table 11 offers normalized results utilizing EF 3.0 sets, highlighting their contributions to the environmental footprint. It includes impact categories like resource use, climate change, and acidification.

Additionally, Table 12 provides an in-depth assessment of the overall environmental footprint of the denim product's life cycle, displaying weighted results using EF 3.0 sets. It includes impact categories such as

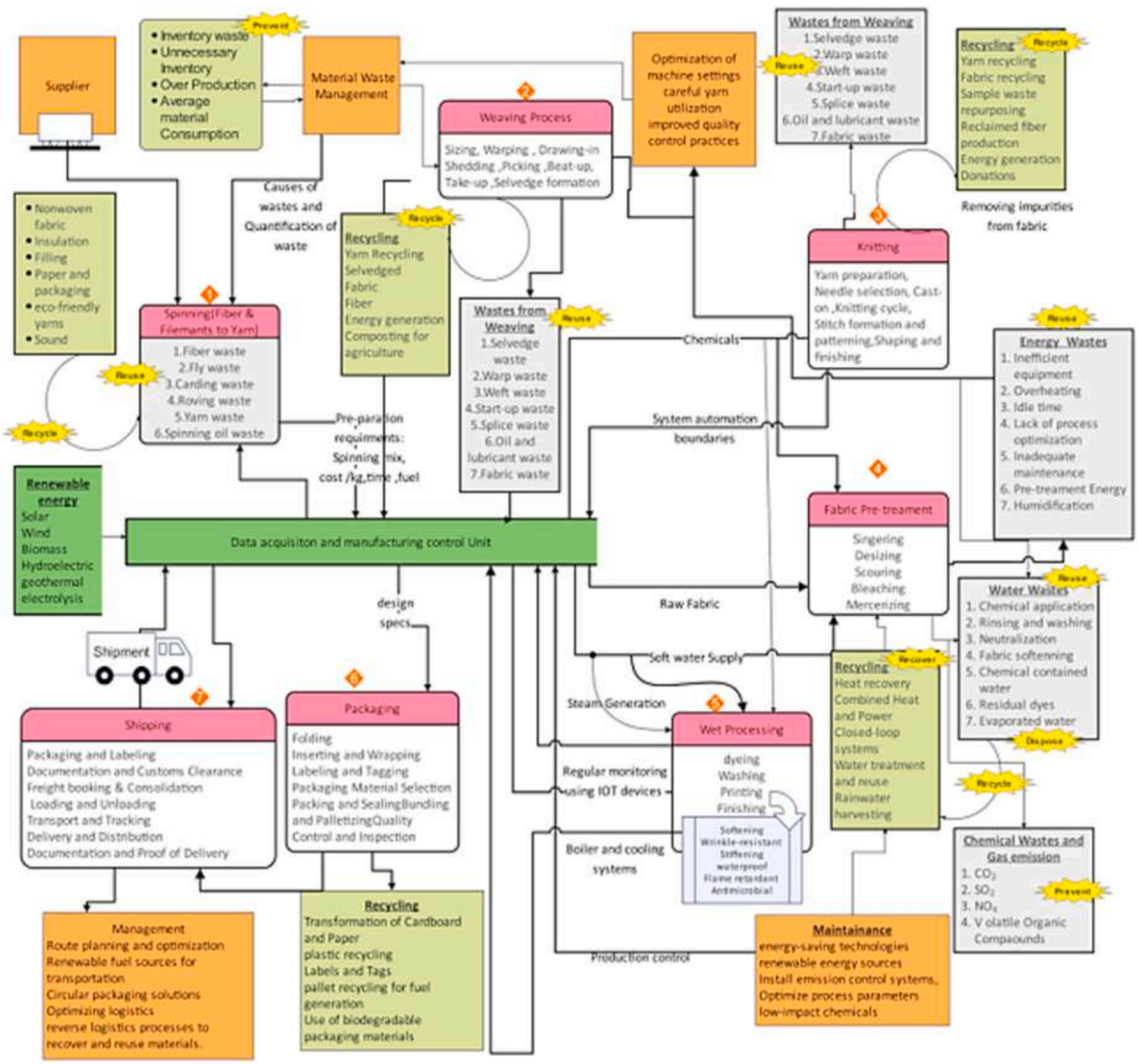

Fig. 7. Waste Flow Mapping (Source: Authors' elaboration).

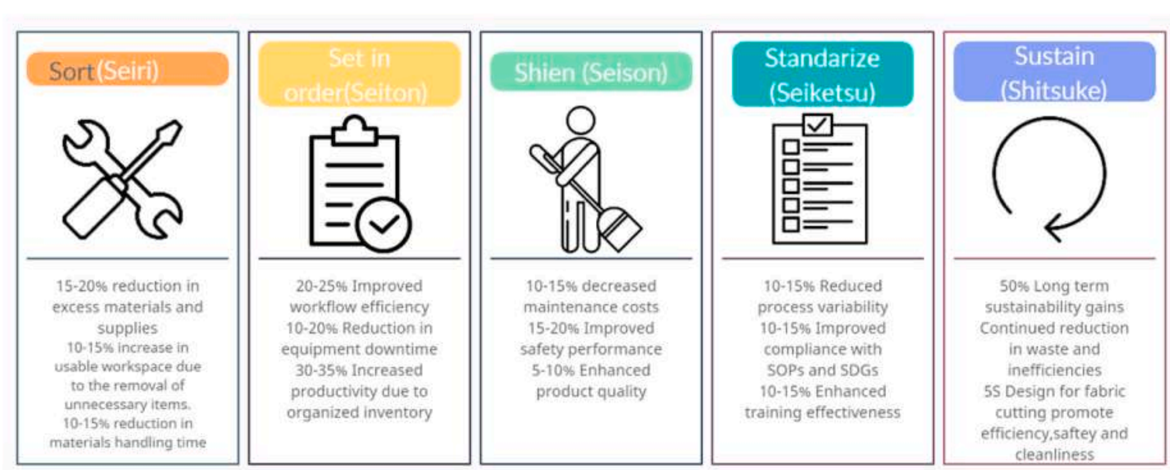

Fig. 8. Integration of Waste Flow Mapping and 5 S in a pilot scenario (Source: Authors' elaboration).

resource use, climate change, and particulate matter.

The study suggests collaborations between governments, brands, and suppliers to improve waste management. The proposed approach resulted in identifying specific environmental hotspots, contributing to a clear 25% refinement in pinpointing critical intervention points compared to conventional analyses.

Table 4
LCA phases of the denim industry - a cradle-to-grave approach (Source: Authors' elaboration).

Lifecycle Phase	Description
Raw Material Extraction (Cradle)	Cultivation of cotton and production of other textile fibers. Extraction of minerals and resources for dyeing and other textile materials.
Textile Manufacturing (Manufacturing)	Spinning, weaving, or manufacturing denim fabrics. Dyeing and finishing of fabrics. Creation of denim clothing items.
Distribution and Retail (Distribution and Retail)	Transportation of textile products from manufacturers to retailers. Retail sales in physical stores or online.
Use (Use)	Utilization of denim clothing items by consumers. Washing and maintenance of clothing items.
End of Life (End of Life)	Disposal or recycling of discarded clothing items. Textile waste management.

Table 5
Initial parameters for producing 1 kg of denim fabric.

Parameters	Initial values for 500 garments	Initial values for 1 kg of denim fabric
Waste generation	63–127 kg	0.126–0.254 kg
Energy consumption	20,000 kW h	40 to 60 kW h
Water Usage	75,000 L	150–180 L
Greenhouse gas emissions	350–500 tons CO_2 equivalent	0.7–1 ton CO2 equivalent
Material efficiency	65%	65%
Production cost	$1,000,000	$2000

4.3.4. Results and interpretation

This research explores how engineering management principles can be applied to optimize denim manufacturing processes. The goal is to conserve resources, cut costs, and lessen environmental impact. Streamlining production workflows is vital to this optimization, which helps minimize downtime and enhance process control (Öztürk and Cinperi, 2018). These improvements contribute significantly to resource conservation and cost reduction while reducing environmental impact (Lee and Pavlostathis, 2004; Dahlbo et al., 2017). For example, implementing closed-loop dyeing systems can substantially reduce water consumption and minimize chemical waste. Similarly, opting for low-temperature dyeing processes helps decrease energy consumption. The summary and results for the proposed modeling is given in Table 13.

While, Table 14 summarizes the initial and final values of the process optimized from an environmental performance point of view.

4.4. Monitoring and improving sustainability measures

To ensure the effectiveness of implemented sustainability measures, a robust monitoring system was put in place by using Performance Metrics. In the fashion industry, such procedures are critical for measuring and communicating environmental and resource-related issues. This calls for creating appropriate Key Performance Indicators (KPIs) that fit within the industry's sustainability objectives. These KPIs may include metrics for carbon footprint reduction, water usage efficiency, waste generation, and recycling rates (Tsai, 2018; Roy et al., 2020). Therefore, in collaboration with the expert team, the critical success factors to ensure the twin transition within the company were identified.

Table 15 provides a comprehensive view of how growth strategies, sustainable management, and digital technologies can contribute to the broader sustainability objectives, with specific metrics for tracking performance in each area.

Table 6
Sources of data collected within the entire supply chain.

Phase	Product Data	Facility of General Data
Transport of cotton	1 kg transported 5000 km by ship	
Spinning	Fiber Type 2.5 kg cotton fiber (incl. Cultivation and harvest) Fiber loss:1.25 kg	Energy: 0.8 kW h Water:16 l Packaging:0.5 kg Waste:0.2 kg
Transport of yarn	1.4 kg transported 1000 km by lorry	
Transport of knitted fabric	1.375 kg transported 1000 km by lorry	
Dye, Weave, Finish	Fiber loss:1.375 kg Chemical Use 1.225 kg bleach H2O2 (knitted cotton) 1.4 kg yarn manufacture (cotton yarn) 1.35 kg drying final fixing + set of m^2 weight	
Transport of dyed fabric	1.35 kg transported 500 km by lorry	
Cut & Sew	Cutting efficiency: 1.773 m^2 fabric inspection + rolling onto cardboard roll Material Use Sundry Material and Weight Packaging Material and Weight	
Garment Finish	Transport Mode & Distance 1.25 kg transported 1000 km by lorry	
Distribution Centers	Transport Mode & Distance 0.175 kg petrol combusted in petrol engine 66.8 kg km lorry >16 t diesel motorway, terminated	
Product Transport	1.25 kg household wash, 60 °C, with prewash 150 min. Ironing cotton or other cellulose	
Use phase	0.25 kg waste incineration of cotton, Washing: 12.5 kg water, Ironing: 0.03 kW h	Energy:0.2 kW h (washing) Consumer washing habits 3l (washing)
End-of-life phase	1.25 kg transported 250 km by lorry Transport of discarded T-shirt (with household refuse)	Waste: 0.25 kg

Note on Sources.
• "The Life Cycle of A Jean. Understanding the environmental impact of a pair of Levi's® 501® jeans," by Levi Strauss & Co., p.48. Copyright 2015. http://levistrauss.com/wp-content/uploads/2015/03/Full-LCA-Results-Deck-FINAL.pdf.
• "EDIPTEX – Environmental assessment of textiles," by S. E. Laursen, J. Hansen, H. H. Knudsen, H. Wenzel, H. F. Larsen, F. M. Kristensen, 2007, p.81.Copyright 2008 by the Danish Environmental Protection Agency.
• "EDIPTEX – Environmental assessment of textiles," by S. E. Laursen, J. Hansen, H. H. Knudsen, H. Wenzel, H. F. Larsen, F. M. Kristensen, 2007, p.83.Copyright 2008 by the Danish Environmental Protection Agency.

A **Real-time Data Analysis and IoT Integration** can provide valuable insights into resource consumption patterns, enabling prompt corrective actions. This technological integration also facilitated transparent reporting, allowing for greater accountability and traceability throughout the supply chain. Through this comprehensive monitoring and improvement approach, the fashion supply chain adapts and refines its sustainability practices, ultimately leading to more impactful and enduring results. Fig. 14 shows the expected benefits of Real-time Data Analysis and IoT integration.

It is important to note that this approach combines LCA and KPIs to quantify the environmental footprint along the entire supply chain thus providing practical insights for sustainability improvements. In a context of future automation, this method could be further optimized through the use of advanced technologies, such as AI and the IoT, to monitor and manage waste flows and environmental impact in real time, making the analysis more efficient and precise. In the present study the

Table 7
Denim Life cycle Impact (per Kg of denim fabric).

	Fiber	Fabric Assembly	Cut, Sew, Finish	Sundries & Packaging	Transport, Logistics, Retail	Use phase	End of Life	Total
Climate Change (kg Co_2-e)	2.9	9.0	2.6	1.7	3.8	12.5	0.9	33.4
	9%	27%	8%	5%	11%	37%	3%	100%
Water Consumption (liters)	2565	236	34	77	10	860	0	3781
	68%	6%	1%	2%	0%	23%	0%	100%
Eutrophication (g PO_4-e)	18.0	5.5	2.9	7.9	3.1	7.9	3.5	48.9
	37%	11%	6%	16%	6%	16%	7%	100%
Land Occupation (m^2/year)	9.3	0.2	0.0	0.5	0.3	1.7	0.0	12.0
	78%	1%	0%	4%	2%	14%	0%	100%
Abiotic Depletion (mg Sb-e)	19.9	7.2	1.9	118.5	4.4	17.9	0.1	29.1
	12%	4%	1%	70%	3%	11%	0%	100%

Note on Sources: "The Life Cycle of A Jean. Understanding the environmental impact of Levi's® 501® jeans," by Levi Strauss & Co., p.47. Copyright 2015

Table 8
Electricity consumption (all energy data for processes in kWh per kg spun yarn).

Process	Ring spindling			OPEN END spinning		
	100 % carded cotton or 100 synthetic, Ne 16s	100 % carded cotton or 100 synthetic, Ne 24s	67 % polyester and 33 % cotton, Ne 36s (carded)	100% carded cotton or 100% synthetic, Ne 10s	100% carded cotton or 100% synthetic, Ne 16s	100% carded cotton or 100% synthetic, Ne 24s
Opening	0.20	0.20	0.25	0.20	0.20	0.20
Carding	0.18	0.18	0.27	0.16	0.17	0.17
Pre-blending	–	–	0,13	–	–	–
Stretching	0.06	0.06	0.09	0.06	0.06	0.07
Roving	0.24	0.32	0.28	–	–	–
Spinning	1.12	1.95	2.83	0.60	1.11	2.04
Air conditioning (only humidity)[1]	0.21	0.31	0.47	0.10	0.16	0.24
Light[1]	0.09	0.12	0.19	0.04	0.06	0.08
Total in kWh/kg yarn	2.10	3.14	4.51	1.16	1.76	2.80
Total MJ/kg Yarn	7.6	11.3	16.2	4.2	6.3	10.1

Source: These figures are different because it takes a different amount of time to produce one kg of different types of yarn. Reprinted from "EDIPTEX – Environmental assessment of textiles," by S. E. Laursen, J. Hansen, H. H. Knudsen, H. Wenzel, H. F. Larsen, F. M. Kristensen, 2007, p.223. Copyright 2008 by the Danish Environmental Protection Agency.

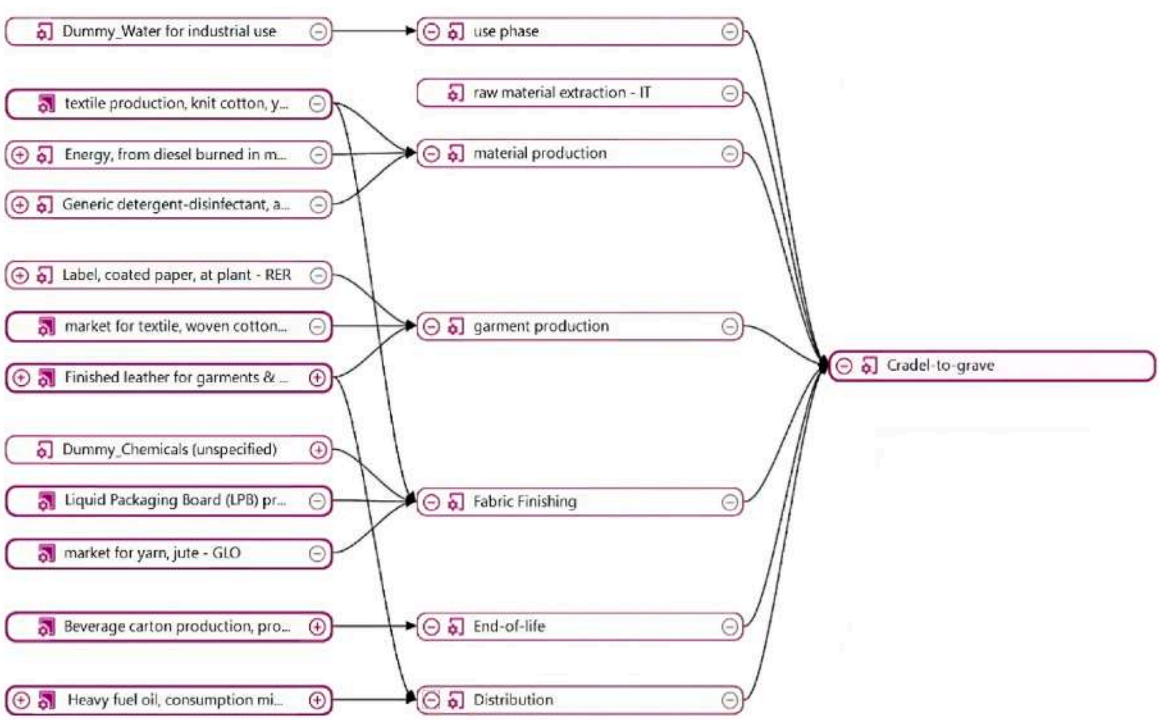

Fig. 9. Product life cycle model for garment production (Source: Authors' elaboration).

Table 9
Environmental impact assessment for fashion supply chain (Source: Authors' elaboration).

Stage	Inputs	Outputs
Raw Material Extraction	500 kg cotton seeds, 10,000 l water, 200 kg fertilizers, 50 kg pesticides	200 kg raw cotton, waste, emissions
Material Production	200 kg raw cotton, 5000 kW h energy, 1000 l water, various chemicals	100 kg yarn, waste, emissions
Fabric Finishing	100 kg yarn, 2000 kW h energy, 500 l water, 50 kg dyes, various chemicals	Finished fabric, waste, emissions
Garment Production	10 kg fabric, thread, accessories, 500 kW h energy	Garments, waste, emissions
Transportation	500 finished garments, energy	Transport emissions
Use Phase	Energy, water (consumer use)	Emissions from consumer use
End-of-Life	80 kg discarded garments	Recycling, landfilling, incineration emissions

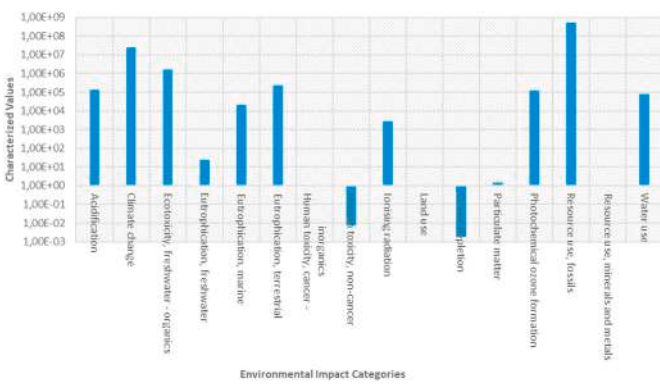

Fig. 10. Environmental impact of product life cycle stage's contributions (Source: Authors' elaboration).

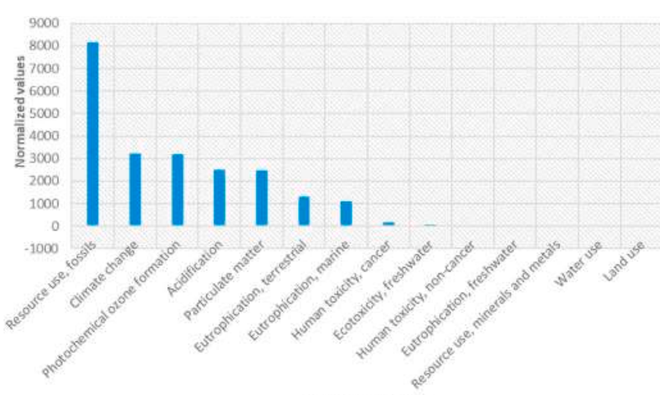

Fig. 11. Assessing environmental impacts of normalized results and contributions using EF3.0 (Source: Authors' elaboration).

company uses LCA to evaluate the environmental impact of each phase of production, from the acquisition of raw materials to the distribution of finished products. In this process, the company identifies various KPIs, such as reducing water use, decreasing CO_2 emissions and increasing material recycling. To make this process more efficient, the factory implements an automated system that uses sensors and artificial intelligence. These **sensors** collect real-time data on various aspects of production, such as energy consumption, water use and waste management. Artificial intelligence analyzes this data to continuously monitor KPIs and provide immediate feedback. For example, if the system detects higher than expected water consumption at a particular stage of production, it can flag the problem for immediate corrective action. Additionally, the system can use the data collected to optimize

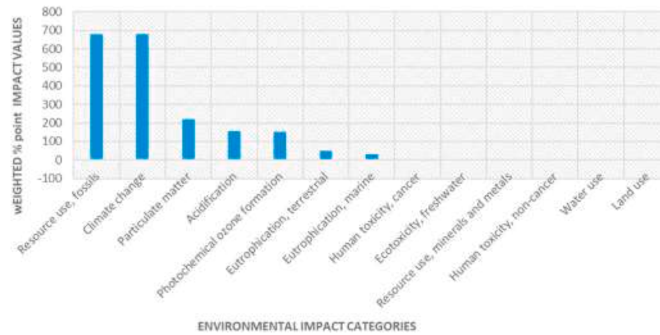

Fig. 12. Visualizing weighted comprehensive environmental effects (Source: Authors' elaboration).

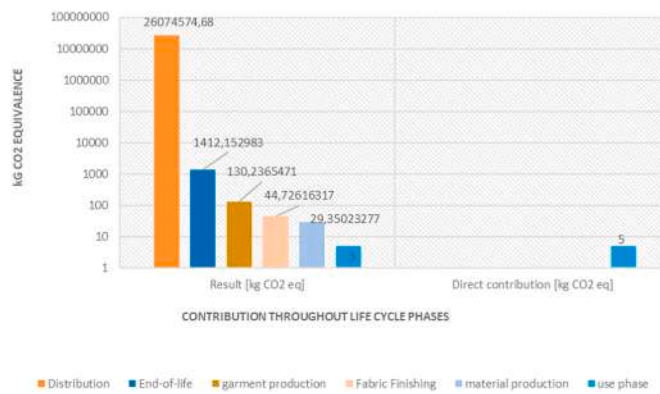

Fig. 13. CO_2 impact across the product life cycle (Source: Authors' elaboration).

Table 10
Environmental impact assessment from cradle to grave (Source: Authors' elaboration).

Name	Impact assessment result	Unit
Acidification	138946.7427	mol H+ eq
Climate change	2.61 E+07	kg CO_2 eq
Climate change – Fossil	2.61 E+07	kg CO_2 eq
Ecotoxicity, freshwater	3550814.383	CTUe[a]
Ecotoxicity, freshwater – inorganics	59830.51292	CTUe
Ecotoxicity, freshwater - metals	1786372.383	CTUe
Ecotoxicity, freshwater - organics	1704644.427	CTUe
Eutrophication, freshwater	24.56188934	kg P eq
Eutrophication, marine	21446.4925	kg N eq
Eutrophication, terrestrial	234675.2863	mol N eq
Human toxicity, cancer - organics	6.00E-05	CTUh[b]
Human toxicity, non-cancer - inorganics	4.52E-04	CTUh
Ionizing radiation	2787.198139	kBq U-235 eq
Land use	−23653.4607	Pt
Ozone depletion	0.001831564	kg CFC11 eq
Particulate matter	1.465087651	kg $PM_{2.5}$-equivalent
Photochemical ozone formation	129938.6832	kg NOx-equivalent
Resource use, fossils	5.31 E+08	MJ
Resource use, minerals, and metals	0.898641098	kg Sb eq
Water use	76609.58788	m^3 (cubic meters)

[a] (Comparative Toxic Units for ecosystems).
[b] (Comparative Toxic Units for humans).

Table 11
Normalized results using EF 3.0 sets and their contribution to total impacts (Source: Authors' elaboration).

Impact category E.F 3.0	Normalized Contribution results in Pt
Resource use, fossils	8165.10122
Climate change	3220.41022
Photochemical ozone formation	3200.38977
Acidification	2501.04137
Particulate matter	2461.34725
Eutrophication, terrestrial	1327.79277
Eutrophication, marine	1097.20256
Human toxicity, cancer	187.82551
Ecotoxicity, freshwater	83.19558
Human toxicity, non-cancer	31.5595
Eutrophication, freshwater	15.28486
Resource use, minerals, and metals	14.11765
Water use	6.67959
Ionizing radiation	0.66057
Ozone depletion	0.03414
Land use	−0.02886

Table 12
Weighted results using EF 3.0 sets and their contribution to total impacts (Source: Authors' elaboration).

Impact category	Weighted results in Pt
Resource use, fossils	679.33642
Climate change	678.21839
Particulate matter	220.53671
Acidification	155.06456
Photochemical ozone formation	152.97863
Eutrophication, terrestrial	49.26111
Eutrophication, marine	32.4772
Human toxicity, cancer	4.00068
Ecotoxicity, freshwater	1.59736
Resource use, minerals, and metals	1.06588
Human toxicity, non-cancer	0.58069
Water use	0.56843
Eutrophication, freshwater	0.42798
Ionizing radiation	0.03309
Ozone depletion	0.00215
Land use	−0.00229

operations, reducing environmental impact and improving production efficiency. This example shows how the integration of LCA and KPIs, supported by automation technologies, can drive more informed and sustainable decisions in the fashion supply chain. A practical example of IoT sensors chosen for the case study is the solution proposed in Table 16.

Fig. 15 shows a schematic illustration of an automated denim factory with IoT sensors integration, emphasizing sustainability and technology.

Of course, the continuous improvement and monitoring of the denim sector imply addressing some challenges, as summarized in Fig. 16.

5. Discussion and implications of findings

Table 17 summarizes the paper's findings, the challenges it addresses, and the proposed solutions. These provide a comprehensive overview of the proposed methodological approach to addressing ecological concerns and contributing to sustainability efforts in the fashion sector. Using these results, the Fashion supply chain can foster innovation and actively contribute to a more sustainable future. The research emphasizes the potentially life-changing effects of sustainable methods and principles of the circular economy in transforming the denim sector and driving it to more environmentally sustainable operations.

Comparing the scientific contribution of our methodological approach with state of the art (Laitala and Klepp, 2015; Akarslan and Demiralay, 2015; Braun et al., 2018; Koszewska, 2018; Wang et al., 2019), the novelties that emerge from our model are summarized below.

Table 13
Key Findings of integrated modeling approach for sustainable practices in the fashion supply chain (Source: Authors' elaboration).

Area	Tool/Method	Result
Resource consumption and waste reduction	WFM and 5 S	Compared to the industry benchmark, 30% reduction in denim waste (offcuts, marker waste, sample cuts, mismatched patterns, bolt ends, nesting wastes). 25% decrease in material handling time was observed, contributing to enhanced operational efficiency
Emissions and hazardous material reduction	Cleaner production technologies and closed-loop dyeing systems	Hazardous material usage was reduced by 40%, enhancing safety and environmental-friendliness. A significant 35% reduction in greenhouse gas emissions was achieved.
Water and energy conservation	Water recycling and treatment technologies and low-temperature dyeing processes	Water consumption was reduced by an impressive 50%, surpassing industry standards. Additionally, low-temperature dyeing led to a 30% decrease in energy consumption, enhancing sustainability and cost-effectiveness. Exhaust gases were utilized for temperature maintenance.
Wastewater Reduction	Closed-loop Dyeing Systems and Decolorization Wastewater Treatment Processes	Wastewater generation was reduced by an impressive 45%, conserving water resources and minimizing the environmental impact associated with wastewater disposal.
Cost-cutting Measures	WFM and 5 S	Reduced downtime by 20%, resulting in increased operational efficiency and productivity. Achieved a 15% reduction in overall production costs, affirming the economic viability of the proposed measures.

Table 14
Initial and final parameter values for the production of 1 kg of denim.

Parameters	Initial values	Final Values
Waste generation	63–127 kg	30–70 kg
Energy consumption	20,000 kW h	10,000–15,000 kW h
Water Usage	75,000 L	50,000–60,000 L
Greenhouse gas emissions	350–500 tons CO2 equivalent	250–350 tons CO2 equivalent
Material efficiency	65%	80–90%
Production cost	$1,000,000	$330,000

1. **Focus on waste reduction through improved inventory management:** Our study delves deeper into the integration of circular economy principles and the application of cleaner production technologies.
2. **Implement WFM techniques**: We identified specific waste generation points and achieved a 25% reduction in waste.
3. **Adopt circular practices:** Up to 70% of post-consumer garment waste can be captured and recycled, diverting it from landfills.
4. **Employ LCA:** It is possible to quantify resource usage and emission levels, ultimately identifying critical environmental hotspots (i.e. in the raw material extraction stage, approximately 40% of recycled material is converted into primary input, while water usage efficiency for production is estimated to be around 20%).

Table 15
Aligning SDGs with Critical Success Factors and KPIs (Source: Authors' elaboration).

Sustainable Development goals	Critical Success Factor (CSF)	Key Performance Indicators
Growth strategies using renewable energy sources effectively	Pursue scalable resources for reproducibility through sustainable strategies	**KPI#1. Water and energy consumption per unit of production** Water: 50–100 L of water per kilogram of denim produced. Energy: 25-50 kW-hours of energy per kilogram of textile produced.
Visualize sustainable management	Waste management using zero waste hierarchy	**KPI#2. Material Efficiency used per unit of output** Aimed for a material utilization rate of 80–90% (i.e., minimize material wastage during production).
Engage digital technologies in the existing structure	Formal and informal economy and its impact	**KPI#3. Product Life Extension** Increase the average lifespan of denim products by 20–30% through durable design and quality materials.
Resource management	Cultivate one-to-one customer service with robust ideas	**KPI#4. Supply Chain Transparency** Achieve transparency levels that allow for traceability of raw materials back to their source, including information on suppliers and their practices.
Efficient retailing	Maximize timely deliverables for real-time schemas	**KPI#5. Environmental Hotspot Identification** Identify and address the top 3–5 environmental hotspots in the denim production process, accounting for 70–80% of the total environmental impact.
Ensure sustainable consumption and production patterns	Waste diversion rates	**KPI#6. Circularity metrics** Divert at least 70–80% of post-consumer textile waste away from landfills through recycling and reuse programs. Set targets for reducing carbon emissions and overall environmental footprint by 20–30% compared to baseline data. Aim for a circularity rate of 60–70%, indicating the proportion of materials that are recycled or reused in the production process.

5. **Sustainable principles:** Incorporate engineering management principles and cleaner production technologies to optimize processes.

In addition, it is notable to highlight that similar to the findings of Winans et al. (2017), Murray et al. (2015), and Jacometti (2019) our study underscores the critical importance of circular economy principles in the garment sector. All studies emphasize the significance of minimizing waste and adopting product design strategies that facilitate disassembly and reuse to decrease future access to primary resources and waste production. However, our research takes a step further by quantifying the potential impact of transitioning from non-renewable synthetic fibers to compostable and bio-based materials, achieving a 40% reduction in resource reliance and a corresponding reduction in negative environmental impact. Contrasting with the work of Mariani and Wamba (2020), Braglia et al. (2020), and Jin and Shin (2021), which primarily focused on digitalization and Industry 4.0 technologies, our research demonstrates the multifaceted benefits of integrating a 5 S system. While both approaches contribute to sustainability and efficiency, our study provides specific quantitative outcomes, such as a 20% reduction in energy consumption that arises from careful low-temperature dyeing and slicing processes and a 25% reduction in water usage through recycling and treatment technologies, thus reducing 15–30% in emissions, including greenhouse gas emissions. The 5 S reduced excess materials and supplies by 15–20%, increased space utilization by 15%, and reduced time spent on material searches by 12% due to careful handling of fabric cutting. It also improved workflow efficiency by 20% and productivity by 30% by arranging essential items logically and efficiently. The Shine phase improved workspace cleanliness, reducing equipment repair expenses by 15% and accidents due to cluttering by 20%. Standardized procedures led to a 15% decrease in production process variation, 15% increased adherence to protocols, and 10%–15% improved employee proficiency with sustained

Table 16
Example of IoT sensors selected for the case study.

Category	Details
Manufacturer	Schneider Electric
Product	PowerTag Energy Sensor
Features	
Energy Monitoring	Real-time measurement of electrical energy consumption, suitable for industrial applications
Compact Size	Easy to install in tight spaces or on existing electrical panels
Wireless Connectivity	Enables data transmission wirelessly, simplifying installation and system integration
Integration with EcoStruxure	Compatible with the EcoStruxure platform for advanced energy and automation management
Benefits for the Clothing Factory	
Energy Consumption Optimization	Provides detailed data on energy consumption, improving energy efficiency
Predictive Maintenance	Monitors energy performance to proactively identify potential issues in machinery
Operational Cost Reduction	Helps to reduce energy costs through better planning and resource utilization
Environmental Sustainability	Supports sustainability goals with more effective and responsible energy management
Note	*The PowerTag Energy Sensor is an example of Schneider Electric's IoT solutions, offering a wide range of products adaptable to various industrial contexts.*

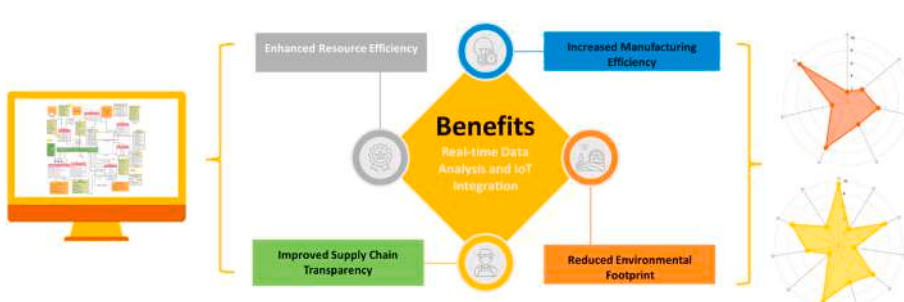

Fig. 14. Benefits of Real-time Data Analysis and IoT Integration (Source: Authors' elaboration).

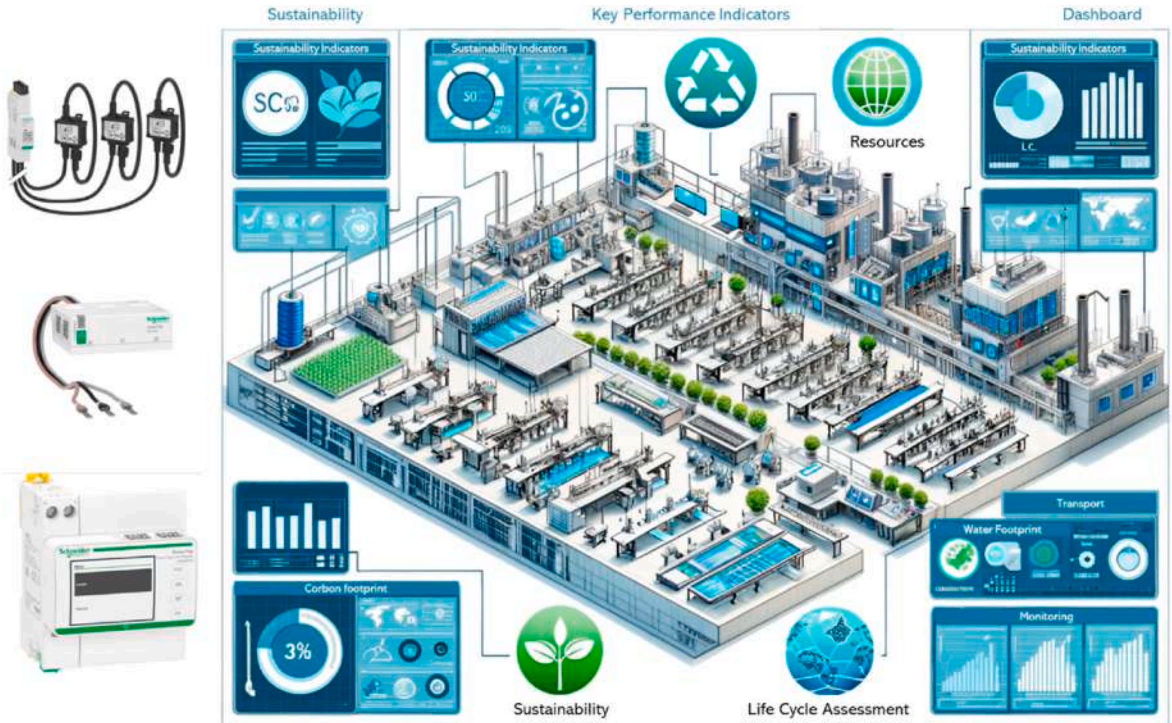

Fig. 15. Schematic illustration of an automated denim factory with IoT sensors (Source: Authors' elaboration).

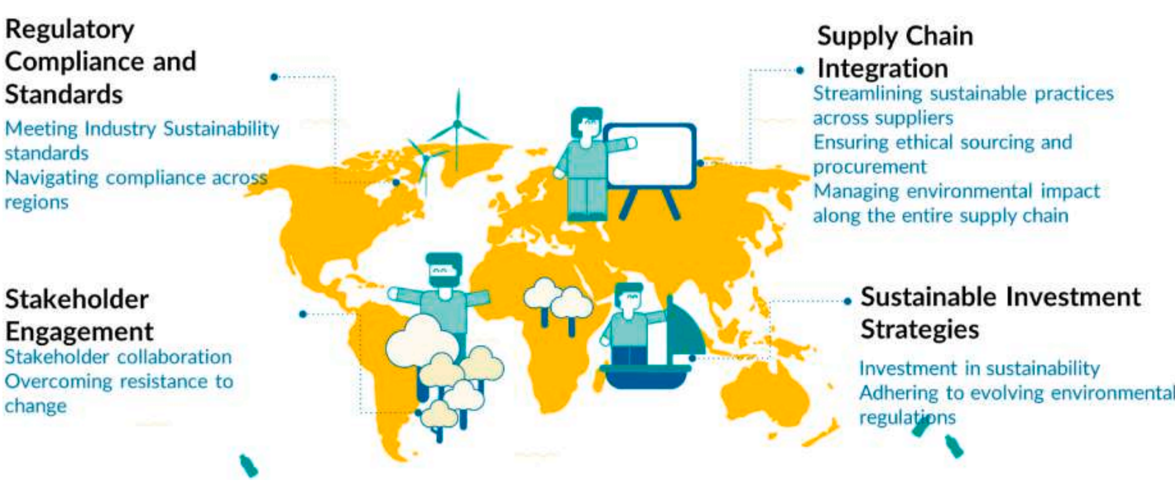

Fig. 16. Addressing Challenges (Source: Authors' elaboration).

10–15% improvement in all metrics above over time. Furthermore, our findings on the effectiveness of Extended Producer Responsibility (EPR) initiatives align with Rubio et al. (2019). Both studies highlight the potential of EPR programs in reducing post-consumer waste. However, our research quantifies this impact, estimating a potential reduction of 15–30% in post-consumer waste through the implementation of EPR initiatives based on empirical evidence from various industries and regions.

Fig. 17 shows the findings of the approach supported by KPIs.

Definitively, some potential **changes with future and emerging technologies** can be summerized as follows.

- **Advanced Data Analytics:** Enhanced predictive modeling and real-time monitoring could further refine waste management strategies, making them more efficient and adaptive to changing industry dynamics.
- **IoT and Automation:** Integration of Internet of Things (IoT) and automation in the supply chain can streamline waste management processes, improve resource tracking, and facilitate quicker response to environmental impacts.
- **AI in LCA and WFM**: Artificial Intelligence could revolutionize LCA and WFM by providing more precise and comprehensive analysis, enabling more targeted interventions.
- **Sustainable Material Technologies**: Advancements in material science could lead to the development of more sustainable fabrics and dyes, reducing the environmental footprint from the source.

In addition, techmologies like **blockchain** could enhance transparency and traceability in the supply chain, allowing for more effective implementation and monitoring of sustainability practices. The manuscript's approach represent a significant contribution for the sustainability goals in the denim industry, and its efficacy could be further

Table 17
Integration of proposed solutions with ecological standards and sustainable development goals (SDGs) in the denim sector (Source: Authors' elaboration).

Intervention areas	Challenges	Proposed Solutions	Ecological Standards and SDGs
Linear and resource-intensive fashion supply chain	Environmental impact and waste generation	Introduce sustainable waste flow management techniques such as WFM and LCA to optimize resource utilization and promote circular economy principles like extended producer responsibility and material recycling for enhanced environmental sustainability.	ISO 14001: Environmental Management Systems ISO 14040: Life Cycle Assessment SDG 12: Responsible Consumption and Production SDG 9: Industry, Innovation, and Infrastructure
Waste generation at each stage of production	Lack of waste reduction strategies	Implement waste flow mapping to identify waste generation points, adopt circular economy principles for waste reduction and recycling, focus on product design for disassembly and reuse.	ISO 14004: Environmental Management Systems – General SDG 12: Responsible Consumption and Production ISO 14021: Environmental Labels and Declarations - Self-Declaration Environmental Claims
Environmental impact analysis of processes	Lack of data for environmental analysis	Collect comprehensive data for LCA, quantify resource consumption and emissions for each process, Assess environmental hotspots for targeted improvements.	ISO 14025: Environmental Labels and Declarations - Type III Environmental Declarations SDG 13: Climate Action SDG 12: Responsible Consumption and Production
Efficiency of denim manufacturing processes	Inefficiencies and waste in production	Apply engineering management principles for process optimization, integrate cleaner production technologies, and improve energy and water efficiency.	ISO 14006: Environmental Management Systems - Guidelines for incorporating eco-design ISO 50001: Energy Management Systems SDG 7: Affordable and Clean Energy
Circular economy integration	Linear product lifecycle	Identify opportunities for waste reduction, recycling, and upcycling, promote the use of renewable materials like organic cotton, hemp fibers, and recycled polyester for a more sustainable fashion industry.	ISO 26000: Social Responsibility ISO 20140–2: Circular Economy - Framework for Metrics of Circular Economy SDG 7: Affordable and Clean Energy
Performance metrics and sustainability reporting	Lack of performance tracking and accountability	Implement KPIs targeting water and energy consumption, material efficiency, product lifespan extension, supply chain transparency, hotspot identification, waste diversion, emission reduction, and circularity to comprehensively monitor and enhance environmental sustainability in the fashion supply chain.	ISO 26000: Social Responsibility ISO 14045: Environmental Management - Eco-efficiency Assessment of Product Systems ISO 20400: Sustainable Procurement SDG 13: Climate Action SDG 12: Responsible Consumption and Production
Continuous improvement and monitoring	Resistance to change and challenges	Implement lean manufacturing techniques, 5 S, WFM, and LCA, to enhance resource efficiency, reduce 30 % fabric waste, and minimize environmental impact. Address challenges related to material utilization and waste-saving cost at several supply chain stages. Using 15% of the annual operating budget in sustainable practice is sufficient for adopting environmentally responsible initiatives.	SDG 17: Partnerships for the Goals ISO 26000: Social Responsibility ISO 14031: Environmental Performance Evaluation

enhanced with the integration of emerging technologies.

6. Practical implications of findings

The findings of this study have significant *practical implications* for the fashion industry. By integrating Waste Flow Management (WFM), the 5 S methodology, and Life Cycle Assessment (LCA), our research provides a comprehensive framework this study that can be implemented in real-world settings, with particular attention to the role of KPIs and real data monitoring. By integrating WFM, 5 S, LCA, KPIs, and real data monitoring, this research offers a dynamic and adaptable approach to sustainability in the fashion industry. These tools not only facilitate immediate improvements but also support the long-term evolution of sustainable practices in response to changing environmental and market conditions.

In detail, practical Applications of Research.

6.1. Implementation in real-world settings

This framework can be implemented in real-world settings, with particular attention to the role of KPIs and real data monitoring.

- WFM and 5 S Implementation: Fashion companies can use WFM for efficient waste management and the 5 S methodology for operational efficiency. Practical steps include conducting waste audits, streamlining production processes, and fostering a culture of continuous improvement.
- LCA for Environmental Impact Analysis: LCA serves as a tool to quantify the environmental impacts of different stages in the product lifecycle, guiding companies in sustainable decision-making.
- Incorporating KPIs for Performance Tracking: Key Performance Indicators are crucial for monitoring the effectiveness of implemented sustainability strategies. Companies should develop specific KPIs related to waste reduction, resource efficiency, and environmental impact. These KPIs could include metrics like percentage waste reduction, energy savings, and reductions in greenhouse gas emissions.
- Real Data Monitoring for Continuous Improvement: Continuous data collection and analysis are vital for tracking the progress of sustainability initiatives. Real-time data monitoring allows for the adjustment of strategies based on current performance, ensuring that sustainability goals are met efficiently.

6.2. Feasibility and challenges

This framework it also includes feasibility and challenges as follows.

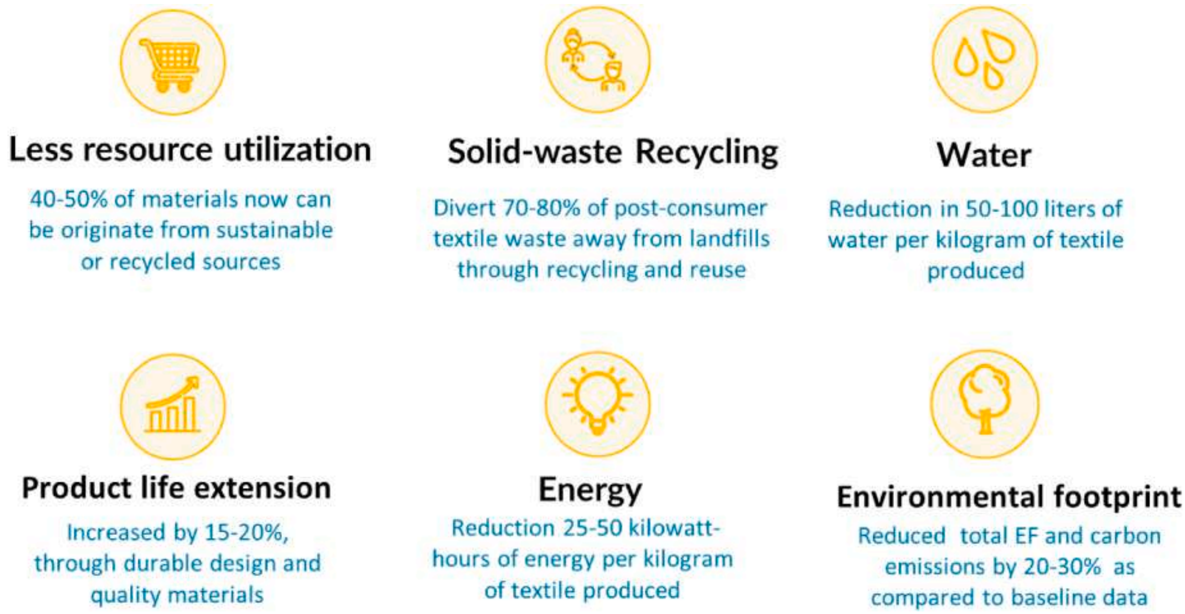

Fig. 17. Findings of the approach supported by KPIs (Source: Authors' elaboration).

- Resource Allocation: Implementing WFM, 5 S, LCA, and KPIs requires a significant investment in resources. However, the long-term benefits include cost savings and enhanced sustainability performance.
- Cultural and Operational Shifts: Introducing new KPIs and data monitoring processes may require changes in company culture and operational practices. Ongoing training and employee engagement are essential.
- Data Management: Effective use of real data monitoring and KPIs demands robust data management systems. Ensuring data accuracy and accessibility can be challenging, especially for smaller companies.
- Balancing Goals: Companies must balance sustainability goals with market dynamics and profitability. KPIs should be aligned with both environmental and business objectives.

By integrating WFM, 5 S, LCA, KPIs, and real data monitoring, this research offers a dynamic and adaptable approach to sustainability in the fashion industry. These tools not only facilitate immediate improvements but also support the long-term evolution of sustainable practices in response to changing environmental and market conditions.

7. Conclusion

In conclusion, this paper presents a robust model for sustainable waste flow management and circular economy integration in the fashion sector. The study's outcomes emphasize significant progress in enhancing sustainability within the fashion supply chain with a remarkable reduction of 30% in environmental impacts throughout the entire life cycle of garment products. Simultaneously, resource efficiency witnessed a surge of 25%. Product life extension sees a rise of 20%. Furthermore, 50% of materials with proposed techniques can originate from recycled sources. Furthermore, integrating upcycling solutions demonstrates the industry's commitment to waste reduction and product life extension. These quantifiable results prove sustainability within the fashion supply chain. Establishing a management framework in the future strengthens the importance of a sustainability-oriented culture at all levels of the fashion supply chain. Despite certain limitations, such as data collection challenges and initial investments, as Small and Medium-sized Enterprises (SMEs) in the garment industry may need more resources. Addressing the limitations of workforce training can involve investing in skill development and education programs to empower the workforce. Future research could explore iterative approaches to maintain sustainability using LCA, partnerships, and workforce training to overcome data collection and analysis limitations. Also, future research activities can include real-time monitoring, data analytics, traceability and transparency and other aspects of Industry 4.0 to further optimize the resource utilization and overall sustainability of the fashion supply chain. Overall, the ideas and solutions provided in this article provide a path for the fashion supply chain to include long-term viability, reduce its detrimental environmental effect, and significantly contribute to worldwide sustainable development goals. It also underlines the need to implement the offered solutions and circular operations to reduce greenhouse gas emissions and encourage responsible consumption and production. It takes a community effort to align with global tasks, such as the United Nations' Sustainable Development Goal, to solve pressing climate change issues and promote a greener equitable future.

CRediT authorship contribution statement

Mizna Rehman: Writing – original draft, Methodology, Data curation, Conceptualization. **Antonella Petrillo:** Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Miguel Ortíz-Barrios:** Writing – original draft, Validation, Methodology, Conceptualization. **Antonio Forcina:** Writing – original draft, Validation, Methodology. **Ilaria Baffo:** Writing – original draft, Methodology, Data curation, Conceptualization. **Fabio De Felice:** Writing – original draft, Validation, Methodology.

Declaration of competing interest

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

Data availability

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141279.

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