Waste Management 219 (2026) 115555

Contents lists available at ScienceDirect

Waste Management

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

Environmental impacts minimization of mixed textile waste recycling process through life cycle assessment ☆

Caterina Barbiero [a], Gemma Cervantes [b], Anna Mazzi [a,*]

[a] Department of Industrial Engineering, University of Padova, via Marzolo 9, 35131 Padova, Italy
[b] Institute of Sustainability, Universitat Politècnica de Catalunya, Colom 1, 08222 Terrassa, Spain

ARTICLE INFO

Keywords:
Life Cycle Assessment
Circular Economy
Unsorted waste
Nonwoven
Gravity analysis
Sensitivity analysis

ABSTRACT

The global textile industry is facing an unprecedented sustainability crisis, driven by a linear production model and a surge in post-consumer waste. While most recycling research focuses on pure, pre-consumer fiber streams, the present study provides an original contribution by addressing the complex challenge of unsorted municipal textile waste. Characterized by high heterogeneity and poor structural quality, such a fraction is currently largely destined for incineration. Assessing the environmental feasibility of transforming this degraded waste into recycled nonwoven fabrics for industrial applications, a Life Cycle Assessment (LCA) was conducted using a waste-to-cradle perspective, grounded in primary inventory data from a laboratory-scale mechanical recycling pilot. Core novelty resides in the focus on unsorted textile fractions—typically excluded from high-value circular loops—and the introduction of an evaluative framework to quantify the environmental "break-even point" compared to incineration. Delivering an in-depth analysis at the experimental stage identifies critical hotspots, such as electricity consumption in defibration and aspiration, allowing for targeted process optimization. Although laboratory-scale recycling already demonstrates superior performance to incineration in terms of Global Warming Potential (GWP), upscaling-oriented sensitivity analysis reveals a significant paradigm shift. Transitioning to an industrial scale powered by renewable energy achieves impact reductions of over 60%, effectively transforming GWP-total into a net avoided impact. Ultimately, bridging the gap between bench-scale findings and industrial potential proves that mechanical recycling, when integrated with energy decarbonization, is a critical lever for achieving European circular economy and climate neutrality objectives.

1. Introduction

The global textile industry is currently facing an unprecedented environmental crisis, driven by a doubling of production between 2000 and 2015 and a subsequent surge in post-consumer waste (Oelerich & Mahy, 2021). This sector continues to face serious environmental challenges due to its heavily linear model of production and disposal. With over 92 million metric tons of textiles discarded annually – much of it ending up in landfills or incinerators, often mixed with household waste—the environmental burden has become unsustainable (UNEP, 2025). Consequently, there is a significant increase in scholarly attention toward textile waste management and circularity. Recent systematic reviews confirm a growing corpus of literature focused on quantifying the environmental burdens of the fashion life cycle, with a specific emphasis on transitioning from linear "take-make-dispose" models toward closed-loop recycling systems (Dhiwar & Bedarkar, 2025; Sharma et al., 2025; Sheng et al., 2026).

While reuse and garment life extension remain the most environmentally favorable options (Sandin & Peters, 2018), scaling textile-to-textile recycling is essential to handle the massive volumes of non-reusable waste (Kim & Lee, 2025). Evidence suggests an emerging focus on chemical and biological recycling to address the complexities of modern blends (Loo et al., 2023; Wang & Salmon, 2022). Chemical recycling enables the production of fibers chemically comparable to virgin materials, as demonstrated by studies on cotton (Hammar et al., 2024), regenerated cellulose (Lanot et al., 2025), and PET-based materials (Subramanian et al., 2020; Qian et al., 2021; Yasin et al., 2024; Muangmeesri et al., 2024). However, these processes typically require significant energy and solvents, often limiting their application to laboratory scales.

☆ This article is part of a special issue entitled: 'Textile waste' published in Waste Management.

* Corresponding author.

E-mail addresses: caterina.barbiero@phd.unipd.it (C. Barbiero), gemma.cervantes@upc.edu (G. Cervantes), anna.mazzi@unipd.it (A. Mazzi).

https://doi.org/10.1016/j.wasman.2026.115555
Received 25 November 2025; Received in revised form 6 April 2026; Accepted 21 April 2026
Available online 30 April 2026

A critical bottleneck remains the difficulty of processing unsorted or poorly differentiated textile waste. Unlike donation bins or take-back programs, “dumpster-sourced” textile waste entering mixed municipal streams is often heavily contaminated, entangled with non-textile items, and degraded by moisture or pests. This heterogeneity—characterized by complex fiber blends, chemical finishes, and non-textile trims—is a major barrier to high-value recycling (Pervez et al., 2021; Tadesse et al., 2025;). In this context, mechanical recycling offers a strategic advantage. Unlike chemical processes, mechanical shredding and carding significantly reduce impacts related to acidification and eutrophication while minimizing water footprints and toxicological risks (Uddin, 2025; Sandin & Peters, 2018). While mechanical recycling of PET (Fidan et al., 2024; Luedemann et al., 2022), cotton (Bekir, 2022), or wool (Wiedemann et al., 2022; Yavuzkasap Ayakta et al., 2024) often results in lower-quality fibers, these materials are particularly suitable for applications that do not require high-performance, such as thermal insulation (Islam et al., 2024; Karmakar et al., 2025) or nonwoven fabrics.

Nonwovens, formed by bonding loose fibers without weaving or knitting, allow for the inclusion of short, damaged, or blended fibers. Recent advances have shown that even lower-grade dumpster waste can be repurposed into nonwovens for insulation, soundproofing, hygiene, or industrial padding (Alves et al., 2024a, 2024b). Moreover, these fabrics are increasingly explored for apparel applications, such as protective garments or medical gowns, where long-term durability is not the primary requirement. By sidestepping energy-intensive spinning and weaving, these systems offer potential reductions in resource consumption.

However, the industrialization of new recycling routes requires rigorous verification to avoid unintended “burden shifting”. Life Cycle Assessment (LCA) offers a robust methodology for quantifying environmental impacts throughout each stage (ISO, 2020). As a multi-criteria tool, LCA allows researchers to evaluate the performance of innovative processes predictively, identifying environmental hotspots before large-scale implementation (Anceschi et al., 2026; Bisinella et al., 2024; Islam et al., 2026; Pranta et al., 2025). Although LCA is established in the textile sector, the need for further investigation into circular strategies for a broader range of textile materials is underlined by scientists (Hassan et al., 2025; Loshin et al., 2025; Lin & Ma, 2023). Targeted application of LCA to nonwoven garments made from dumpster-sourced waste remains an underexplored frontier (Amicarelli et al., 2022; Bertelli et al., 2026). Much of the existing literature still relies on idealized inputs or secondary data and rarely addresses contaminated waste streams, binder influences, or regional infrastructure (Abagnato et al., 2024; Bisinella et al., 2024; Anceschi et al., 2026).

This study addresses these gaps by providing an LCA of an innovative mechanical recycling process specifically designed for the challenges of undifferentiated, low-grade textile waste. The primary objective is to assess the environmental profile of new recycling process at a laboratory scale, using primary, context-specific data to ensure a realistic understanding of material loops. By explicitly considering binders, regional energy mixes, and cradle-to-grave scenarios, and aligning results with circular economy frameworks—including Extended Producer Responsibility (European Parliament News, 2025) —this research aims to provide actionable insights for scalability and real-world sustainability policy.

The research addresses existing research gaps by providing an LCA of an innovative mechanical recycling process designed for the challenges of undifferentiated, low-grade textile waste. Assessing the environmental profile of such technology at a laboratory scale, using context-specific data, ensures a realistic understanding of material loops. Core novelty resides in the focus on mechanical recovery of unsorted textile fractions from municipal waste—a stream typically excluded from high-value recycling routes—while introducing an evaluative framework to quantify the environmental 'break-even point' compared to incineration. Delivering an in-depth analysis of the process at the experimental stage identifies critical hotspots, allowing for targeted optimization and impact mitigation before transitioning to full-scale production. Ultimately, bridging the gap between bench-scale findings and industrial potential through upscaling-oriented sensitivity analysis offers an original contribution to the development of sustainable waste-to-resource pathways for the most problematic municipal textile fractions.

2. Methodology

2.1. *Textile waste recycling process*

The experimental procedure focused on a mechanical recycling process for mixed textile waste sourced from unsorted municipal streams. Upon extraction and transport to the recycling facility, the mixed fabrics underwent a washing and sanitization cycle to ensure safe handling and hygiene. The sanitized material was subsequently reduced into fragments of approximately 4–10 cm using a rotary cutter. These fragments were then processed through a shredding unit to achieve complete fiber disaggregation (Fig. 1.1). The resulting loose fibers were directly fed into an airlaid web-forming unit from Qingdao Kingtech Machinery Co., Ltd. (Fig. 1.2). Finally, the webs were consolidated via needle-punching using a DILO OUG-II6 unit from DILO Machines (Germany) to produce the final nonwoven fabrics (Fig. 1.3). Through this mechanical route, 100% recycled nonwoven materials were successfully obtained without the addition of virgin substrates.

2.2. *LCA of textile waste recycling process*

2.2.1. *Goal and scope*

The LCA was conducted in accordance with ISO 14040:2020 and ISO 14044:2021 standards (ISO, 2020; 2021), following the specific guidelines of the Product Category Rule (PCR) “Nonwovens for clothing, protective clothing and upholstery (v3.01)”. The study serves a dual purpose: (i) to evaluate the environmental profile of the current laboratory-scale recycling process and (ii) to benchmark its performance against the incineration of an equivalent mass of textile waste. Furthermore, a sensitivity analysis was performed to estimate the potential environmental impacts of an upscaled industrial plant operating under optimized efficiency conditions.

The functional unit (FU) was defined as the recycling of 300 g of mixed textile waste to produce 1 m^2 of nonwoven fabric, in accordance with the PCR for clothing and upholstery. The system boundaries encompass two primary scenarios:

- Recycling Scenario: This pathway models the diversion of textile waste from the municipal “dumpster” stream to a laboratory-scale mechanical recycling plant. The process transforms the waste into a nonwoven material suitable for high-value secondary applications, such as upholstery filler or automotive insulation. In this closed-loop approach, the textile fraction is recovered as a secondary raw material rather than being lost to the waste stream.
- Incineration Scenario (Baseline): This scenario represents the conventional “business-as-usual” approach, where textile waste remains integrated within the mixed municipal solid waste (MSW) stream and is sent to a Waste-to-Energy (WtE) plant for incineration.

By comparing these scenarios, the study quantifies the environmental benefits of material recovery versus energy recovery, accounting for the avoided impacts associated with conventional disposal and the displacement of virgin-equivalent materials.

The system boundaries include the transport of textile waste from the collection point (dumpster) to the sorting and recycling facility. Since the textile life cycle prior to disposal is identical for both scenarios, it was excluded from the assessment (cut-off approach). Similarly, the use phase of the secondary raw material was omitted as it is shared by both systems. In the recycling scenario, environmental credits were assigned for the avoided impacts of incineration during the waste separation step.

Fig. 1. Detailed configuration of the laboratory-scale mechanical recycling line: (1) Cutting and shredding module for feedstock size reduction; (2) Airlaid unit for web formation and fiber dispersion; (3) Needle-punching section for mechanical web bonding.

However, a conservative approach was adopted by excluding the avoided production of virgin nonwoven materials. This precautionary choice stems from the high heterogeneity of the feedstock and the variety of virgin materials (e.g., polyester, polypropylene, or cotton) that the recycled nonwoven could potentially displace. By not accounting for displaced virgin production, the study ensures that the benefits of the recycling scenario are not overestimated. The specific life cycle stages included and excluded within the system boundaries are illustrated in Fig. 2.

The study adopts a “grave-to-cradle” perspective, shifting the focus from the conventional cradle-to-grave approach to the processes that enable the transformation of end-of-life textiles into secondary raw materials. In this framework, “grave” represents the textile fraction at the point of disposal (waste), while “cradle” refers to the output of the recycling process as a secondary raw material ready for a new life cycle. Geographically, the study is localized to Spain, encompassing the entire value chain from the municipal waste collection point (the “garbage”) to the laboratory-scale recycling facility. This specific scope allows for a detailed analysis of the logistical and technical stages required to reintroduce discarded textiles into the production system.

The Life Cycle Inventory was modelled based on the primary data collected from the laboratory-scale recycling plant. The complete sequence of unit operations, with material and energy flows, is illustrated in Fig. 3 and includes the following operational stages:

Logistics and Pre-treatment: Mixed municipal waste is first moved via transport 1 to a sorting facility. During the separation step, powered by electricity and diesel, the textile fraction is isolated from other waste streams and byproducts (e.g., buttons, zippers). The sorted material is then delivered via transport 2 to the processing site.

Washing and Drying: The textile waste is sanitized using water, soap, and electricity. This stage produces clean textile waste (SP1) while generating water effluents and residual heat as outputs.

Mechanical Size Reduction: In the cutting step, the clean fabrics are reduced into fragments (SP2). These are subsequently processed during defibration to obtain fibers (SP3).

Fiber Handling and Web Formation: An aspiration unit conveys the fibers (SP3) to the loader, which propels them via compressed air into the airlaid unit. This process results in the formation of a fiber carpet

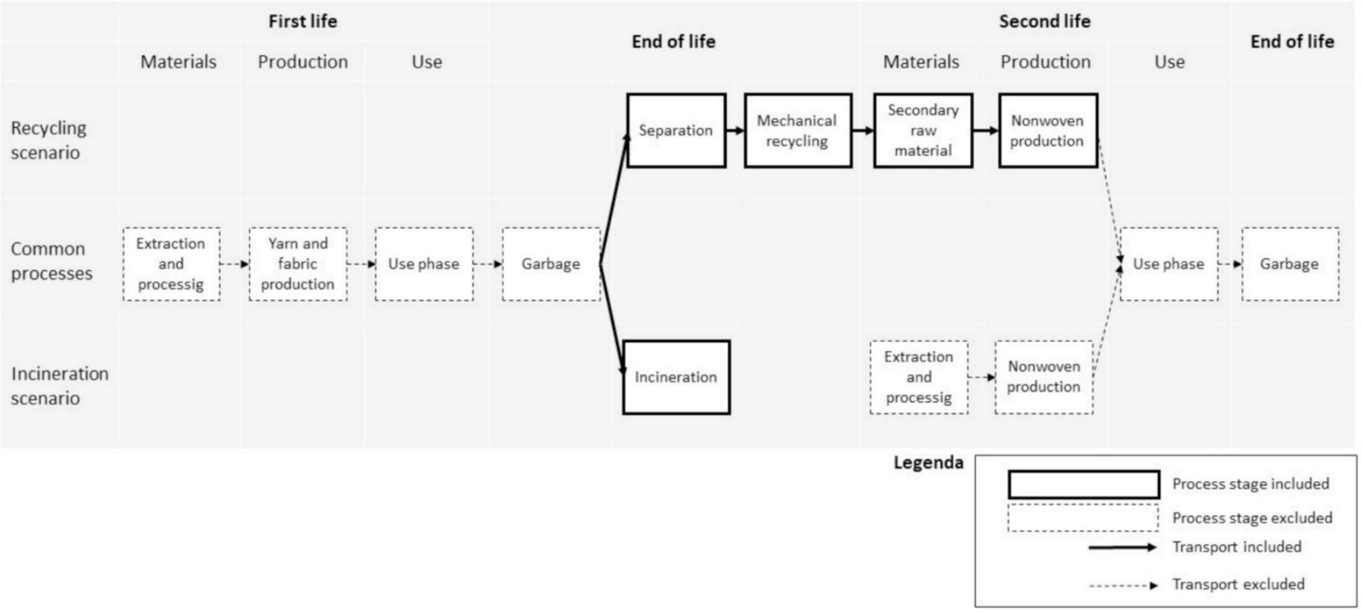

Fig. 2. System boundaries and life cycle stages for the incineration and mechanical recycling scenarios.

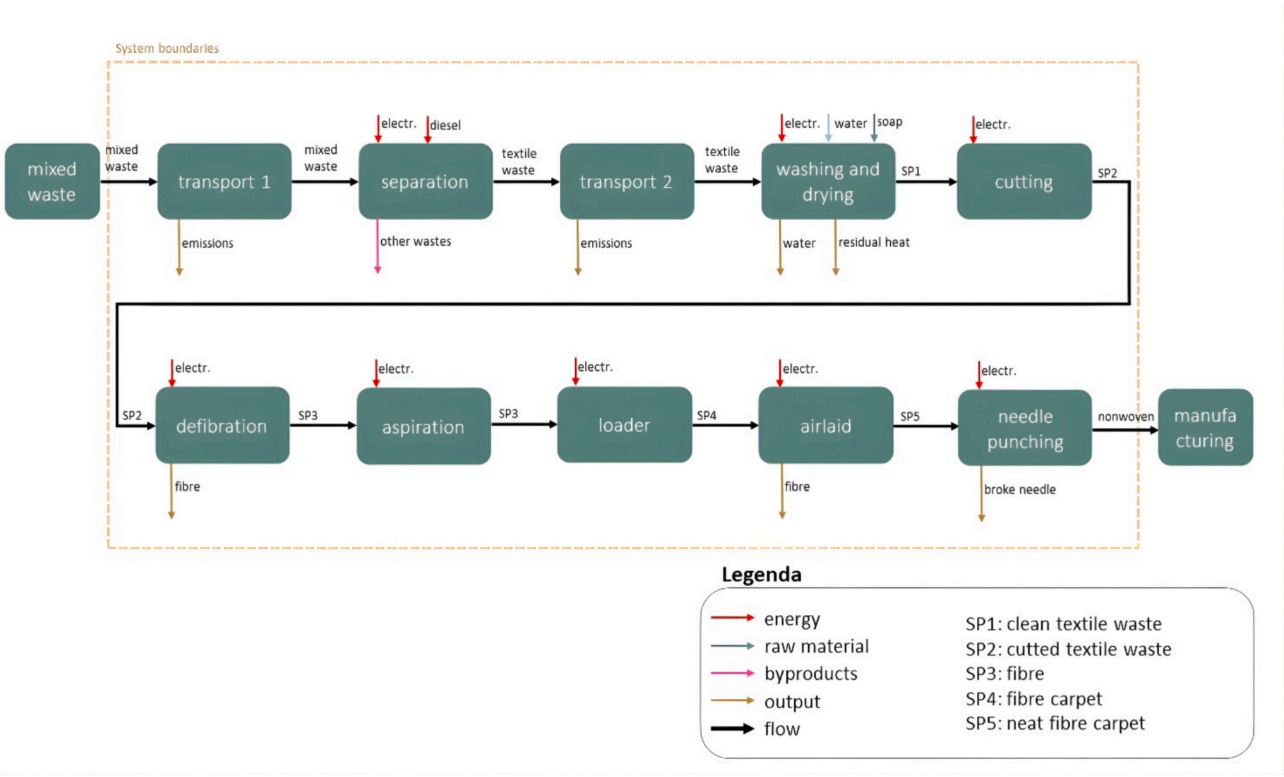

Fig. 3. System boundaries and input–output flows for the laboratory-scale textile recycling process.

(SP4), which is then refined into a neat fiber carpet (SP5). Small amounts of fiber are lost as output during these mechanical stages.

Consolidation: In the final needle punching stage, the fibrous structure is mechanically interlocked to produce the finished nonwoven fabric. Any broken needles are accounted for as specific process outputs.

2.2.2. *Life cycle inventory analysis*

In the recycling scenario, the Life Cycle Inventory (LCI) was developed by integrating primary data, directly measured at the laboratory-scale plant, with secondary data sourced from the Ecoinvent database v3.11 (Ecoinvent, 2025). Secondary data were specifically employed to account for upstream environmental loads, such as electricity generation and transport processes. The primary inventory data, normalized to the functional unit, are summarized in Table 1. To ensure methodological consistency, energy and material flows were allocated by mass. Consequently, all impacts are expressed per 1 m2 of nonwoven fabric, a versatile secondary raw material suitable for diverse industrial applications. To define the study's scope, the following key assumptions were

Table 1
Primary inventory data for the mechanical recycling of 300 g of textile waste.

Phase	Input	Output
Transport 1	Distance, 33 km by truck	
Separation	Energy, 0.018 kWh Diesel, 0.001 kg	
Transport 2	Distance, 50 km by van	
Washing and drying	Energy, 0.16 kWh Water, 3.84 l Soap, 0.003 l Sanitiser, 0.003 l	Waste water, 3.843
Cutting	Energy, 0.032 kWh	Waste fibre, 0.024 kg
Defibration	Energy, 0.993 kWh	
Aspiration	Energy, 0.794 kWh	
Loader	Energy, 0.1 kWh	
Airlaid	Energy, 0.332 kWh	Waste fibre, 0.0011 kg
Needle punching	Energy, 0.645 kWh	Nonwoven, 0.263 kg

made:

- Feedstock Composition: The textile waste diverted from the municipal stream was modeled as a heterogeneous mix of textile fibers.
- Energy Profile: The electrical energy consumption was modeled using the Spanish national residual mix, reflecting the geographical location of the recycling facility.
- Logistics: Waste transport was simulated assuming the use of Euro 5 compliant heavy-duty trucks and Euro 5 light commercial vans, representing standard European logistics for urban waste collection.

In the incineration scenario, the initial logistical phase remains identical to the recycling scenario to ensure comparability between the two systems. It is assumed that the transport 1 stage (from the collection point to the facility) is maintained; however, the mixed waste does not undergo a separation step. Instead, it is routed directly to a WtE unit located within the same facility. While the transportation parameters are based on primary data (consistent with the recycling scenario), the environmental impacts associated with the incineration process, including emissions and energy recovery, were modelled using secondary data from the Ecoinvent database.

2.2.3. Life cycle impact assessment

The impact assessment was performed using SimaPro 10.1 software to convert the inventory data collected during the study into potential environmental impacts (SimaPro, 2025). The EN 15804:2012 + A2:2019 method was selected for the assessment (CEN, 2019), as it is recommended by the relevant PCR; adopting this standardized method ensures methodological consistency and facilitates the comparison of results with existing literature. The primary objective of the LCIA phase is to transform the extensive list of LCI results into a consolidated set of indicator scores.

The environmental impact of the scenarios was evaluated according to all mandatory impact categories, including Acidification (AP), Climate change (GWP-total), Climate change – Biogenic (GWP-biogenic), Climate change – Fossil (GWP-fossil), and Climate change – Land use and LU change (GWP-luluc). Furthermore, the analysis accounted for Eutrophication in marine (EP-marine), freshwater (EP-freshwater), and terrestrial (EP-terrestrial) environments, as well as Ozone depletion (ODP), Photochemical ozone formation (POCP), Resource use of fossils (ADP-fossil), Resource use of minerals and metals (ADP-minerals&metals), and Water use (WDP). To satisfy the objectives of the study, the transition from the laboratory-scale process to an industrial operation (industrial scenario) was modelled through a sensitivity analysis.

Finally, a gravity analysis was conducted within selected impact categories to identify the key factors and environmental hotspots influencing the overall environmental impact.

3. Results and discussions

3.1. Life cycle impact assessment results

The results of the environmental profile for the base scenario are presented in Fig. 4. According to the assessment, the two most significant process stages across all selected impact categories are defibration and aspiration. The defibration phase is particularly critical, as it represents the stage where the most substantial degradation of fiber length and mechanical performance occurs, as highlighted by (Islam et al., 2025). These two steps operate in tandem and require significantly more processing time compared to the other stages of the cycle. For the GWP-LULUC and EP-freshwater categories, the washing and drying step emerged as the most impactful. Conversely, the process records avoided impacts during the separation step; this is attributed to the diversion of textile waste from incineration toward the recycling stream. In line with (Bertone et al., 2024), although incineration allows for energy recovery, it simultaneously results in substantially higher CO_2 emissions. This underscores the environmental advantage of diverting waste flows toward mechanical recycling. Additionally, the GWP-biogenic category also records an avoided impact during the washing and drying phase.

Table 2 summarizes the impact assessment results for both the recycling and incineration scenarios. The final column of the table indicates the percentage difference in environmental burden between the incineration of mixed textile waste and the mechanical recycling process. In general, the results suggest that incineration is preferable to recycling across almost all impact categories, with the notable exception of GWP. This discrepancy highlights the trade-offs inherent in the two waste management strategies, where the energy recovery benefits of incineration may outweigh the impacts of laboratory-scale recycling in several categories, despite the superior performance of recycling regarding greenhouse gas emissions.

It is important to note that the environmental benefits associated with the avoided use of primary raw materials were not considered in this assessment. This choice stems from the fact that the final product consists of recycled material for which a direct alternative application was not defined. These types of products are typically manufactured using a wide range of materials, which vary significantly in terms of functional properties and durability depending on their application (Othman et al., 2024). Therefore, identifying a specific primary material to be replaced by the recycled nonwoven fabric would require assumptions that could introduce an undue degree of uncertainty into the study. Despite this limitation, recycling proves to be advantageous in terms of Global Warming Potential (GWP). This conservative approach was adopted because current LCA databases do not yet include a material equivalent to the one produced through this specific laboratory-scale process. This lack of standardized secondary material datasets represents a common challenge in LCA studies of emerging recycling systems (Mazzi et al., 2024).

3.2. Gravity analysis results

A gravity analysis was carried out to identify the specific input and output elements most responsible for the environmental impacts in the recycling scenario. The GWP-total category was investigated due to its prominence in current literature (Sandin et al., 2025) and its unique avoided impact profile. Conversely, EP-freshwater was analyzed because of the significant impact recorded during the washing and drying stage. The results of the gravity analysis are illustrated in Fig. 5, with each category presented in its respective unit and scale. According to the findings, the environmental benefits for GWP-total are primarily attributed to the avoided municipal solid waste incineration. The environmental burdens, however, are mainly driven by electricity consumption across all production phases. This finding is consistent with the results reported by (Islam et al., 2024), who also identified electricity usage as the primary contributor to GWP. Similarly, the

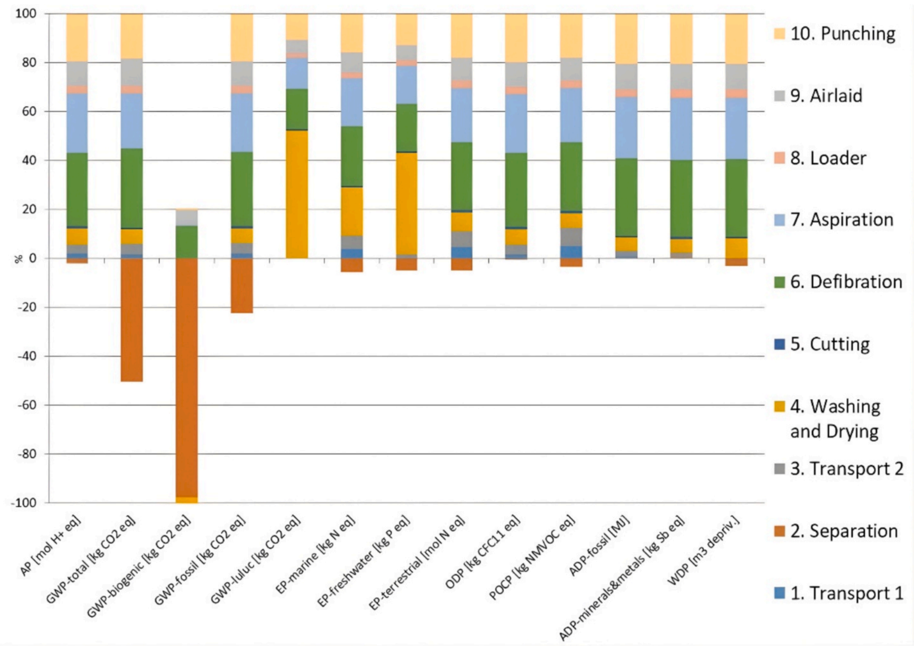

Fig. 4. Impact assessment results and process stage contribution for the mechanical recycling base scenario.

Table 2

Environmental profile of mechanical recycling and incineration scenarios including percentage impact deviation.

Impact Category	Unit	Recycling scenario [A]	Incineration scenario [B]	% $\frac{B-A}{A}$
AP	mol H + eq	3.67E-03	1.61E-04	−96%
GWP-total	kg CO_2 eq	3.63E-01	3.88E-01	7%
GWP-biogenic	kg CO_2 eq	−1.78E-01	2.18E-01	−222%
GWP-fossil	kg CO_2 eq	5.25E-01	1.70E-01	−68%
GWP-luluc	kg CO_2 eq	1.63E-02	4.26E-06	−100%
EP-marine	kg N eq	7.78E-04	8.00E-05	−90%
EP-freshwater	kg P eq	2.36E-04	1.36E-05	−94%
EP-terrestrial	mol N eq	7.18E-03	7.62E-04	−89%
ODP	kg CFC11 eq	1.37E-08	4.12E-10	−97%
POCP	kg NMVOC eq	2.62E-03	2.48E-04	−91%
ADP-fossil	MJ	2.14E + 01	2.89E-01	−99%
ADP-minerals&metals	kg Sb eq	1.39E-05	3.13E-08	−100%
WDP	m^3 depriv.	6.35E-01	2.35E-02	−96%

environmental burden for EP-freshwater was predominantly driven by electricity usage throughout the process. In this category, soap consumption during the washing and drying step represented the second most significant contributing factor. As highlighted by Gaurav et al. (2023), this impact category is heavily influenced by the soap use phase. During this stage, greywater containing high concentrations of nutrients is generated, which contributes to eutrophication. This process leads to abnormal algae proliferation, subsequently reducing dissolved oxygen levels in the water and potentially causing negative effects on aquatic ecosystems.

3.3. *Sensitivity analysis results*

For this study, a sensitivity analysis was performed to model the replication of the recycling process on an industrial scale, named "Scenario A". This scenario was developed based on the following hypotheses:

i. Expanded Collection Logistics: It was assumed that the waste collection area serving the plant would be larger than in the laboratory scale, leading to an increase in transport distances. Specifically, textile waste is assumed to be collected across the entire service area of the sorting facility under study, extending to a radius of approximately 50 km. This distance represents a significant increase compared to the laboratory scenario, which only included transport between the sorting facility and the recycling plant.
ii. Improved Process Efficiency: A reduction in waste generation is expected during industrial-scale processing due to optimized mechanical efficiency and continuous flow operations, as supported by Chand et al. (2023).
iii. Industrial Equipment Integration: The washing and drying stages were modeled assuming the use of high-capacity industrial machinery, which typically offers better energy and water efficiency per unit of product compared to laboratory-scale equipment.

Given that Scenario A reflects a large-scale configuration powered by the national energy mix, the resulting analysis confirmed that electricity consumption remains a primary hotspot in the environmental profile. Building on these results, a further investigation was necessary to evaluate the potential for impact mitigation through energy transition. Consequently, an additional sensitivity analysis, named "Scenario B",

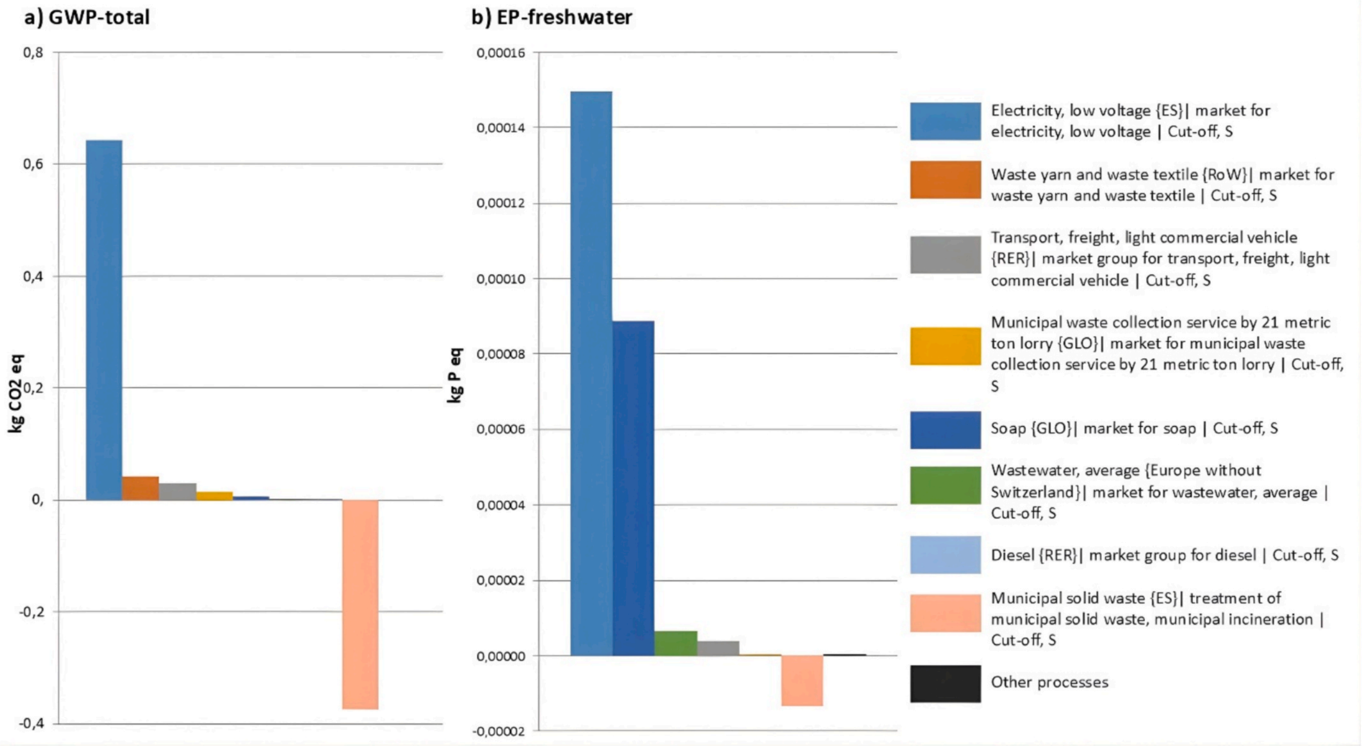

Fig. 5. Gravity analysis results for impact categories a. GWP total, b. EP freshwater.

was conducted. This alternative scenario aimed to explore the environmental shifts resulting from a fully renewable energy supply.

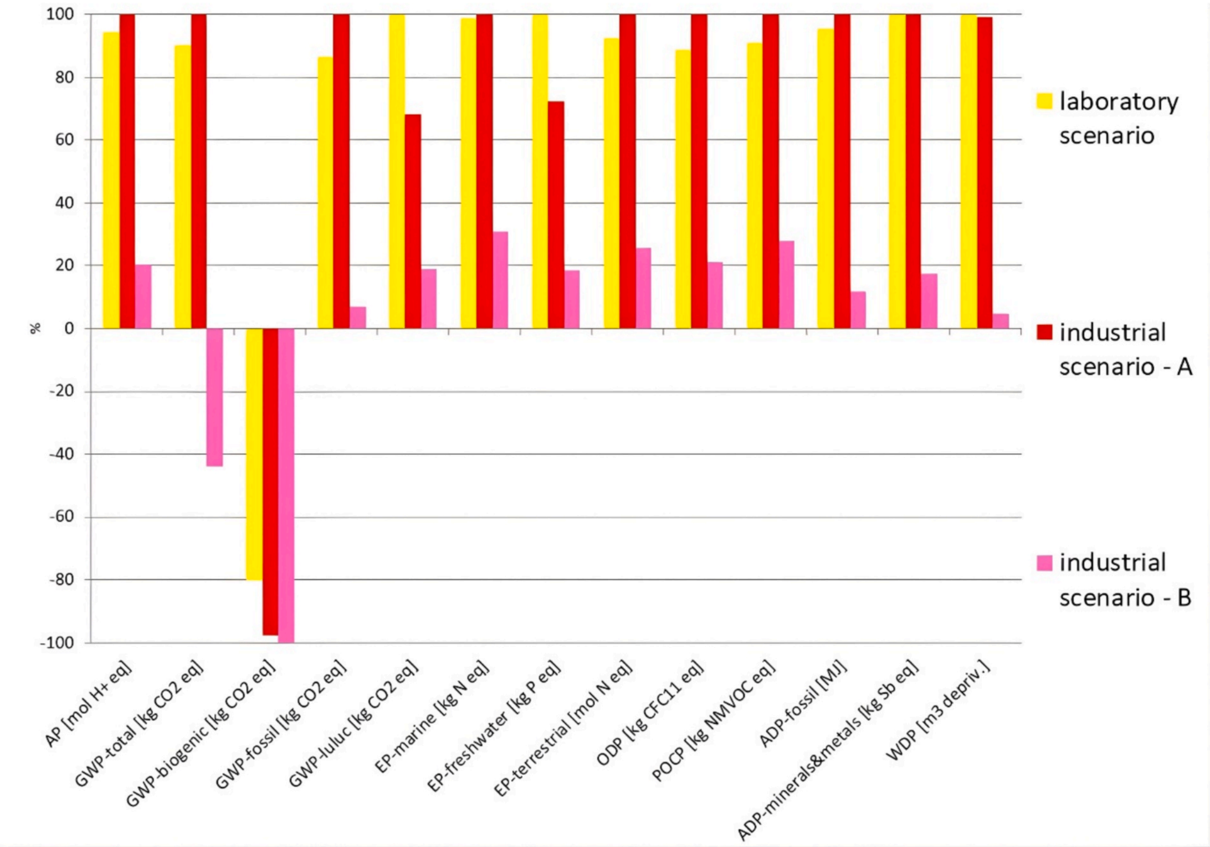

Fig. 6. Sensitivity analysis results: comparative environmental performance of laboratory-scale vs. Industrial-scale recycling for Scenario A (national energy mix) and Scenario B (offshore wind energy).

Specifically, it was assumed that the recycling plant is powered by offshore wind energy, a critical renewable source capable of meeting future industrial energy demands while significantly reducing greenhouse gas emissions (Fernández-Guillamón et al., 2019). Scenario B allows for a direct comparison of how modifying the energy mix influences the overall sustainability of the textile recycling process.

The results of the comparative assessment between the two industrial-scale configurations (Scenario A and Scenario B) and the initial laboratory scenario are illustrated in Fig. 6. This comparison was conducted to evaluate how the transition from a pilot-scale process to an optimized industrial operation, coupled with different energy strategies, influences the overall environmental performance of the mechanical recycling system. By normalizing the results against the laboratory baseline, it is possible to quantify the potential for impact reduction through process efficiency and the integration of renewable energy sources.

The transition from laboratory-scale experiments to industrial-scale recycling reveals a complex interplay between process efficiency and logistical burdens. The results from Scenario A highlight a critical "logistical threshold": while industrial machinery inherently reduces waste and optimizes energy use per unit of product, these gains can be easily offset by the environmental cost of collecting and transporting textile waste over larger areas (50 km radius). This finding suggests that for mechanical recycling to be truly sustainable, the localization of recycling plants relative to sorting facilities is a paramount strategic factor.

Furthermore, the comparison between Scenario A and Scenario B underscores that technological optimization alone is insufficient. The most significant environmental "leap" is not achieved through better machinery, but through a fundamental shift in the energy supply. The drastic reduction of 60% or more in most impact categories under Scenario B demonstrates that the "environmental break-even point" of textile recycling is strictly tied to the adoption of renewable sources, such as offshore wind energy.

The emergence of GWP-total as an avoided impact in Scenario B is a milestone in this analysis. It proves that when powered by clean energy, the mechanical recycling of textiles does not merely "pollute less" than incineration, but actively contributes to climate change mitigation by sequestering carbon in recycled products and avoiding the high-emission profile of waste-to-energy processes. This aligns with the broader Circular Economy objectives, where the goal is to decouple economic growth from resource consumption and environmental degradation.

As supported by Pranta et al. (2025) and Islam et al. (2024), the synergy between high-efficiency industrial equipment and decarbonized grids represents the only viable pathway for the textile industry to meet international sustainability targets. Consequently, these results provide a robust empirical basis for stakeholders and policymakers to prioritize investments not only in recycling technologies but also in the greening of the industrial energy infrastructure.

4. Conclusions

The present study offers an original contribution to the circular economy of textiles by providing a multi-scale LCA of mechanical recycling for mixed waste—a fraction often neglected in favor of mono-fiber streams. Bridging the gap between laboratory-scale empirical data and projected industrial scenarios, the research establishes a strategic framework for evaluating the environmental feasibility of transforming unsorted municipal textile waste into recycled nonwoven fabrics. Core findings underscore that while mechanical recycling is inherently superior to incineration in terms of climate change mitigation, overall sustainability remains highly sensitive to specific process parameters. Specifically, gravity analysis identified defibration and aspiration as primary environmental hotspots, with an incidence mainly attributable to electricity consumption across all production stages.

The core novelty of this work resides in the focus on unsorted and undifferentiated textile fractions—typically excluded from high-value circular loops—while introducing an evaluative framework to quantify the environmental "break-even point" compared to incineration. Delivering an in-depth analysis of this innovative process at the laboratory stage enables the identification of critical hotspots, allowing for targeted process optimization and impact mitigation before the technology is transitioned to full-scale industrial production. Such a preliminary assessment addresses the complex challenge of managing heterogeneous waste streams, providing a concrete pathway for aligning emerging recycling technologies with international waste management standards and producer responsibility frameworks.

The sensitivity analysis conducted reveals a crucial paradigm shift regarding industrial scalability. The transition to an industrial scale, as modelled in Scenario A, highlights a "logistical threshold" where the increased transport distances required for waste collection can offset the mechanical efficiency gains of high-capacity machinery. Conversely, the transition to renewable energy sources, such as offshore wind energy in Scenario B, emerges as the most decisive lever for environmental sustainability. This configuration not only achieves impact reductions of over 60% across most categories but also transforms GWP-total into a net avoided impact, proving that the environmental "break-even point" of textile waste valorization is strictly contingent on the decarbonization of the energy grid and logistical optimization.

Despite the rigor of the assessment, the study identifies several methodological challenges that must be considered. These limitations include the conservative exclusion of avoided impacts from virgin raw materials due to the lack of a direct functional substitute, the potential gaps in data granularity when moving from laboratory to continuous industrial-flow operations, and the general scarcity of standardized LCA guidelines for textile recycling. Such constraints highlight the difficulty of aligning emerging recycling processes with evolving regulatory frameworks, yet they also provide a transparent baseline for future methodological refinements.

The practical implications of this research are significant for a wide range of stakeholders. For designers and manufacturers, it serves as a concrete application of eco-design, demonstrating how processing stages like washing and drying directly influence the environmental footprint. For waste managers and practitioners, it emphasizes the necessity of localized circularity, suggesting that recycling hubs should be strategically positioned to minimize transport-related burdens. Finally, for scientists and policymakers, these results offer an empirical foundation for updating LCA databases and supporting investment decisions in green industrial infrastructures. Future developments will focus on expanding system boundaries to include the displacement effects of primary materials and integrating socio-economic indicators, ensuring that the industrialization of textile recycling provides a net-positive contribution to a sustainable circular economy.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Caterina Barbiero: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Gemma Cervantes:** Writing – review & editing, Validation, Supervision, Resources. **Anna Mazzi:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Data curation, Conceptualization.

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.

Acknowledgements

University of Padova was supported in this study by MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11-10-2022, PE00000004). Universitat Politecnica de Catalunya was supported in this study by AGAUR, Generalitat de Catalunya (Spain) with the project "Grup de Recerca Consolidat GRC per al Grup de Recerca en Ciència i Tecnologia de la Sostenibilitat". This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them. The authors thank Prof. Mònica Ardanuy and the Textile Technology Research Group-TECTEX (grant 2021 SGR 01056-Department of Research and Universities of the Generalitat de Catalunya) for the use of their mechanical recycling facilities during the experimental phase of research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2026.115555.

Data availability

Data will be made available on request.

References

Abagnato, S., Rigamonti, L., Grosso, M., 2024. Life cycle assessment applications to reuse, recycling and circular practices for textiles: a review. Waste Manag. 182, 74–90. https://doi.org/10.1016/j.wasman.2024.04.016.

Alves, D.I., Barreiros, M., Fangueiro, R., Ferreira, D.P., 2024a. Valorization of textile waste: non-woven structures and composites. Front. Environ. Sci. 12, 1365162. https://doi.org/10.3389/fenvs.2024.1365162.

Alves, D.I., Carvalho, Ó., Fernandes, N.A., Cosentino, L.T., Paula Junior, A.C., Fangueiro, R., Ferreira, D.P., 2024b. Upcycling of industrial footwear waste into nonwoven fibrous structures with thermal and acoustic insulation properties. J. Environ. Manage. 363, 121363. https://doi.org/10.1016/j.jenvman.2024.121363.

Amicarelli, V., Bux, C., Spinelli, M.P., Lagioia, G., 2022. Life cycle assessment to tackle the take-make-waste paradigm in the textiles production. Waste Manag. 151, 10–27. https://doi.org/10.1016/j.wasman.2022.07.032.

Anceschi, A., Mossotti, R., Patrucco, A., 2026. Assessing sustainability in the textile sector: a review of LCA, LCC, and S-LCA methodologies with a focus on polymeric textile materials and circular strategies along with future perspectives. Polymers 18, 534. https://doi.org/10.3390/polym18040534.

Bekir, Y., 2022. Quality assessment of fabrics obtained from waste. Ind. Textila 73, 405–410. https://doi.org/10.35530/IT.073.04.202164.

Bertelli, M., Giorgi, D., Morea, C., Incroci, L., 2026. Textile waste ad resource for relevant cross-sectoral applications, opening the cycle to reach circular economy. A review. Sustainability 18, 1464. https://doi.org/10.3390/su18031464.

Bertone, M., Stabile, L., Buonanno, G., 2024. An overview of waste-to-energy incineration integrated with carbon capture utilization or storage retrofit application. Sustainability 16, 4117. https://doi.org/10.3390/su16104117.

Bisinella, V., Schmidt, S., Varling, A.S., Laner, D., Christensen, T.H., 2024. Waste LCA and the future. Waste Manag. 174, 53–75. https://doi.org/10.1016/j.wasman.2023.11.021.

CEN, 2019. EN 15804:2012+A2:2019. Sustainability of construction works: environmental product declarations: core rules for the product category of construction products.

Chand, S., Chand, S., Raula, B., 2023. Textile and apparel industries waste and its sustainable management approaches. J. Mater. Cycles Waste Manag. 25, 3132–3143. https://doi.org/10.1007/s10163-023-01761-1.

Dhiwar, K., Bedakar, M., 2025. Life cycle assessment in fashion industry: a systematic review. Discover Sustainability 6, 1214. https://doi.org/10.1007/s43621-025-02050-7.

Ecoinvent, 2025. Ecoinvent 3. https://ecoinvent.org/ (accessed April 18,2025).

European Parliament News, 2025. Parliament adopts new EU rules to reduce textile and food waste. https://www.europarl.europa.eu/news/en/press-room/20250905IPR30172/parliament-adopts-new-eu-rules-to-reduce-textile-and-food-waste (accessed September 29,2025).

Fernández-Guillamón, A., Das, K., Cutululis, N.A., Molina-García, Á., 2019. Offshore wind power integration into future power systems: overview and trends. J. Mar. Sci. Eng. 7, 399. https://doi.org/10.3390/jmse7110399.

Fidan, F.Ş., Aydoğan, E.K., Uzal, N., 2024. Sustainability assessment of denim fabric made of PET fiber and recycled fiber from postconsumer PET bottles using LCA and LCC approach with the EDAS method. Integr. Environ. Assess. Manag. 20, 2347–2365. https://doi.org/10.1002/ieam.4979.

Gaurav, G., Dangayach, G.S., Meena, M.L., Chaudhary, V., Gupta, S., Jagtap, S., 2023. The environmental impacts of bar soap production: uncovering sustainability risks with LCA analysis. Sustainability 15, 9287. https://doi.org/10.3390/su15129287.

Hammar, T., Peñaloza, D., Hanning, A.-C., 2024. Life cycle assessment of a circular textile value chain: the case of a garment made from chemically recycled cotton. Int. J. Life Cycle Assess. 29, 1880–1898. https://doi.org/10.1007/s11367-024-02346-2.

Hassan, R., Acerbi, F., Terzi, S., Rosa, P., 2025. Enabling the twin transition of the textile industry: a systematic literature review. Waste Manag. 195, 94–307. https://doi.org/10.1016/j.wasman.2025.02.025.

Islam, S., Bhat, G., Mani, S., 2024. Life cycle assessment of thermal insulation materials produced from waste textiles. J. Mater. Cycles Waste Manag. 26, 1071–1085. https://doi.org/10.1007/s10163-023-01882-7.

Islam, N., Hall, M., MacMillan, C., Gordon, S., 2026. 2026 Life cycle assessment and the emergence of product circularity: a review with context to the textile supply chain in Australia. Environ. Impact Assess. Rev. 117, 108198. https://doi.org/10.1016/j.eiar.2025.108198.

Islam, M.M., Yin, R., West, A., 2025. A brief review of mechanical recycling of textile waste. Textiles 5, 41. https://doi.org/10.3390/textiles5040041.

ISO 14040:2020, 2020. ISO 14040:2020 - Environmental management: Life cycle assessment - Principles and framework.

ISO 14044:2021, 2021. ISO 14044:2021 - Environmental management: life cycle assessment - requirements and guidelines.

Karmakar, S., Majumdar, A., Butola, B.S., 2025. A sustainable recycling process and its life cycle assessment for valorising post-consumer textile materials for thermal insulation applications. Waste Manag. Res. J. Sustain. Circ. Econ. 43, 749–761. https://doi.org/10.1177/0734242X241270933.

Kim, E.H., Lee, H., 2025. Comprehensive review of textile waste recycling: from origins to innovations. Fibers Polymers 26, 1229–1464. https://doi.org/10.1007/s12221-025-00892-6.

Lanot, A., Tiwari, S., Purnell, P., Omar, A.M., Ribul, M., Upton, D.J., Eastmond, H., Badruddin, I.J., Walker, H.F., Gatenby, A., Baurley, S., Bartolo, P.J.D.S., Rahatekar, S.S., Bruce, N.C., McQueen-Mason, S.J., 2025. Demonstrating a biobased concept for the production of sustainable bacterial cellulose from mixed textile, agricultural and municipal wastes. J. Clean. Prod. 486, 144418. https://doi.org/10.1016/j.jclepro.2024.144418.

Lin, H.J., Ma, H., 2023. Analysis of green certification standards related to recycled materials involving textiles based on life cycle thinking. Sust. Prod. Cons. 41, 107–120. https://doi.org/10.1016/j.spc.2023.08.001.

Loo, S.L., Yu, E., Hu, X., 2023. Tackling critical challenges in textile circularity: a review on strategies for recycling cellulose and polyester from blended fabrics. J. Environ. Chem. Eng. 11, 110482. https://doi.org/10.1016/j.jece.2023.110482.

Loshin, A., Samarina, T., Vepsäläinen, V., Tervonen, A., Laatikainen, O., 2025. Valorisation scenarios of blended post-consumer textile waste with the focus on thermal processing strategies. Waste Manag. 204, 114966. https://doi.org/10.1016/j.wasman.2025.114966.

Luedemann, L., Felber, A., Golder, M., 2022. Development of a recycling process for textiles made from PET, and proof of its environmental preference with life cycle assessment. Int. J. Technol. Manag. 88, 134. https://doi.org/10.1504/IJTM.2022.121501.

Mazzi, A., Barbiero, C., Miserocchi, F., Nisato, F., Tassinato, G., Cerchier, P., 2024. Life cycle assessment of Al-Cu-Ag-Si recycling process from photovoltaic waste. Resour. Conserv. Recycl. 211, 107885. https://doi.org/10.1016/j.resconrec.2024.107885.

Muangmeesri, S., Baddigam, K.R., Navare, K., Apostolopoulou-Kalkavoura, V., Witthayolankowit, K., Håkansson, H., Mathew, A.P., Acker, K.V., Samec, J.S.M., 2024. Recycling of polyesters by organocatalyzed methanolysis depolymerization: environmental sustainability evaluated by life cycle assessment. ACS Sustain. Chem. Eng. 12, 4114–4120. https://doi.org/10.1021/acssuschemeng.3c07435.

Othman, H., Almouregi, M., Awad, E., Zaher, S., Mohamed, L., Dabour, E., Youssif, E., Hassabo, A., 2024. Nonwoven fabrics: manufacturing, finishing, applications, and possibilities. J. Text. Color. Polym. Sci. 0, 0–0. Doi: 10.21608/jtcps.2024.258911.1265.

Pervez, N., Mondal, I.H., Cai, Y., Zhao, Y., Naddeo, V., 2021. Chapter 21: Textile waste management and environmental concerns. In: Mondal, I.H. "Fundamentals of Natural Fibres and Textiles" 719-739. Doi: 10.1016/B978-0-12-821483-1.00002-4.

Pranta, A.D., Rahaman, M.T., Repon, M.R., 2025. Sustainable waste management of textiles and apparel in a circular economy: recent advances and future prospects of life cycle assessment. Mater. Circ. Econ. 7, 28. https://doi.org/10.1007/s42824-025-00167-8.

Qian, W., Ji, X., Xu, P., Wang, L., 2021. Carbon footprint and water footprint assessment of virgin and recycled polyester textiles. Text. Res. J. 91, 2468–2475. https://doi.org/10.1177/00405175211006213.

Sandin, G., Lidfeldt, M., Nellström, M., 2025. Exploring the environmental impact of textile recycling in europe: a consequential life cycle assessment. Sustainability 17, 1931. https://doi.org/10.3390/su17051931.

Sandin, G., Peters, G., 2018. Environmental impact of textile reuse and recycling. A review. J. Clean. Prod. 184, 353–365. https://doi.org/10.1016/j.jclepro.2018.02.266.

Sharma, R., Yadav, V., Gaur, T.S., Dixit, P., 2025. A systematic review on circular economy practices in the textile industries. Discover Appl. Sci. 7, 1153. https://doi.org/10.1007/s42452-025-07446-8.

Sheng, J., Chen, H., Yu, X., Zhao, S., Al-Hazmi, H.E., Xu, X., Li, X., Zou, X., Wang, Q., Li, X., Xue, G., 2026. A critical revies of textile waste recycling: focusing on global policies, recycling approaches, and recovery products application. Env. Science Pollu. Res. 33, 366–383. https://doi.org/10.1007/s11356-025-37335-x.

SimaPro, 2025. LCA Software For Informed-Change Makers. https://simapro.com/ (accessed May 28, 2025).

Subramanian, K., Chopra, S.S., Cakin, E., Li, X., Lin, C.S.K., 2020. Environmental life cycle assessment of textile bio-recycling – valorizing cotton-polyester textile waste to pet fiber and glucose syrup. Resour. Conserv. Recycl. 161, 104989. https://doi.org/10.1016/j.resconrec.2020.104989.

Tadesse, M.G., Abate, M.T., Lübben, J.F., Rauch, M., 2025. Recycling and sustainable design for smart textiles. A review. Adv. Sustain. Syst. 9, 2401072. https://doi.org/10.1002/adsu20241072.

Uddin, F., 2025. Enhancing the circular economy in textile fiber waste recycling. Mater. Circul. Econ. 7, 33. https://doi.org/10.1007/s42824-025-00190-9.

UNEP, 2025. United Nations Environment Programme https://www.unep.org/news-and-stories/press-release/unsustainable-fashion-and-textiles-focus-international-day-zero (Accessed February 25, 2026).

Wang, S., Salmon, S., 2022. Progress toward circularity of polyester and cotton textiles. Sustain. Chem. 3, 376–403. https://doi.org/10.3390/suschem3030024.

Wiedemann, S.G., Biggs, L., Clarke, S.J., Russell, S.J., 2022. Reducing the environmental impacts of garments through industrially scalable closed-loop recycling: life cycle assessment of a recycled wool blend sweater. Sustainability 14, 1081. https://doi.org/10.3390/su14031081.

Yasin, S., Hussain, M., Uddin, A., Zheng, Q., Shi, J., Song, Y., 2024. Recycling of binary polymer (PET/SBR) carpet into microfibrillar composites: a life cycle perspective with microplastics quantification. Sustain. Mater. Technol. 40, e00988. https://doi.org/10.1016/j.susmat.2024.e00988.

Yavuzkasap Ayakta, D., Altun Kurtoğlu, Ş., Yilmaz, D., 2024. Opportunities to reduce environmental burden by recycling fabric waste in a woollen fabric company. Int. J. Cloth. Sci. Technol. 36, 776–802. https://doi.org/10.1108/IJCST-07-2023-0107.