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Towards circular textiles: Life cycle assessment of homewear produced from regenerative cotton and post-industrial waste versus conventional cotton

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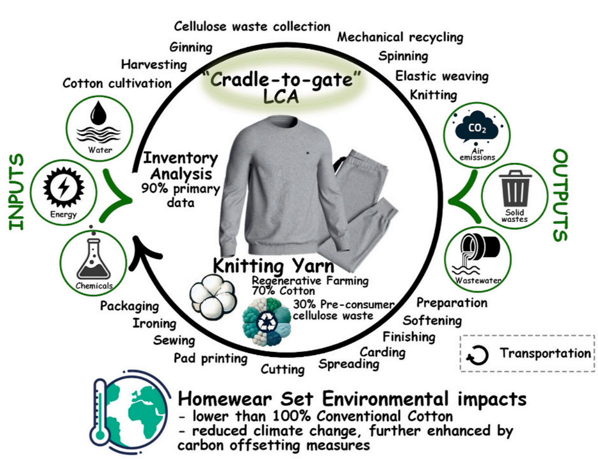
HIGHLIGHTS

- Circularity integrated through a nearly vertical and traceable production value chain.
- Yarn blend: 30 % post-industrial cellulose waste, 70 % regenerative cotton; no dyeing.
- Use of cellulose waste lowers energy demand and reliance on virgin raw materials.
- Homewear set exhibits reduced environmental impacts vs. conventional cotton apparel.
- Climate impact 54 % lower; water consumption 67 % lower than the reference product.

GRAPHICAL ABSTRACT



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ABSTRACT

The textile industry is a major contributor to global and local environmental impacts, particularly due to high water consumption, greenhouse gas emissions, and land use. These impacts are driven by several factors, most notably cotton cultivation and energy-intensive processes such as spinning and dyeing. To address these sustainability challenges, the Life Cycle Assessment (LCA) methodology provides a comprehensive framework for

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evaluating products and processes in the textile sector. In this study, LCA is applied to assess the environmental performance of a homewear set produced from a yarn blend consisting of 30 % recycled post-industrial cellulosic waste and 70 % virgin cotton sourced from regenerative agriculture. A comparative analysis was conducted with a similar homewear set composed entirely of conventional cotton, globally sourced and dyed using traditional methods, to assess the potential benefits of using more sustainable materials. The functional unit (FU) is defined as one medium-sized homewear set, consisting of a sweatshirt and pants. The life cycle inventory was primarily based on primary data gathered directly from the manufacturer's supply chain, complemented with secondary data from the literature and recognized databases where necessary. Overall, primary data covered approximately 90 % of the product system. Environmental impacts were assessed using the ReCiPe 2016 (v1.03) method at the midpoint level under the egalitarian perspective, focusing on seven impact categories relevant to the textile sector. Results show that cotton cultivation is the most impactful life cycle stage, contributing 32.0 % to climate change, 92.5 % to water consumption, and 33.9 % to land use. Other significant contributors include knit finishing processes (24.1 % of climate change impact) and spinning (18.9 % of climate change). The homewear set incorporating recycled and regenerative materials demonstrated a 53.9 % lower climate change impact compared to the conventional alternative, increasing to 81.5 % when carbon offsetting in the cotton cultivation stage was considered. Water consumption decreased substantially, from 4.66 m^3/FU to 1.54 m^3/FU. Despite these improvements, further efforts are needed to reduce fossil energy use and mitigate ecotoxicity. These findings highlight the potential of incorporating recycled content, regenerative agricultural practices, and renewable energy to reduce the environmental footprint of textile products while maintaining quality, thereby supporting sustainability goals and guiding future research and development in sustainable textile production.

1. Introduction

The global textile sector is undergoing a profound transformation driven by stricter environmental regulations, growing consumer awareness, and rising societal demands for sustainability and transparency (Bibi et al., 2024; Ellen MacArthur Foundation, 2017; Siliņa et al., 2024; UNEP, 2023). Key policy frameworks, including the EU Strategy for Sustainable and Circular Textiles (European Commission, 2022a), the European Green Deal (European Commission, 2021), and the Circular Economy Action Plan (CEAP) (European Commission, 2020), aim to decouple economic growth from environmental degradation by fostering circular business models that reduce CO_2 emissions, enhance resource efficiency, and generate employment (3R, 2021; Schiaroli et al., 2025). These initiatives emphasize the need for sustainable production practices, including the adoption of recycled and regenerative raw materials.

Sustainability is increasingly seen as a strategic driver of innovation and competitiveness. Sustainable product innovation and corporate sustainability frameworks stress integrating environmental considerations early in product development, while circular economy approaches highlight the influence of material sourcing, design, and end-of-life management on environmental impacts (Schiaroli et al., 2025).

Regulatory measures such as the Corporate Sustainability Reporting Directive (CSRD) and the Eco-design for Sustainable Products Regulation (ESPR) reinforce the role of LCA in evaluating environmental performance, informing eco-design, and supporting transparency through Digital Product Passports (DPPs) (European Commission, 2022a, 2022b, 2024). LCA enables holistic assessment across the product lifecycle, from raw material extraction to end-of-life, identifying hotspots and guiding improvements in resource efficiency and material selection (Munasinghe et al., 2021).

Despite extensive LCA studies in textiles (Ahmed et al., 2025; Jain et al., 2023; Mata et al., 2025), critical gaps remain. Many analyses rely on outdated datasets, poorly defined system boundaries, or focus on descriptive outcomes without linking findings to innovation, circular economy strategies, or business models (De Felice et al., 2025; Moazzem et al., 2022; Niinimäki et al., 2024; Van Der Velden et al., 2014). Particularly, studies evaluating innovative materials that combine post-industrial waste with regenerative cotton are scarce (De Felice et al., 2025; Mayya Saliba, Andrew Keys, Megan Mudie, 2024; Sandin and Peters, 2018).

This study addresses these gaps by assessing the environmental performance of a homewear set commercialized under the Revive brand, produced by the Portuguese textile company Impetus. The Revive set incorporates N-Lyfe yarn, a blend of 30 % post-industrial (pre-consumer) cellulose waste (cotton, viscose, modal, lyocell) and 70 % cotton cultivated through regenerative agricultural practices in Australia. Impacts are compared with a conventional cotton alternative to evaluate the benefits of recycled content, regenerative agriculture, and circular design practices.

Using an attributional LCA approach, this research aims to: (1) quantify the environmental impacts of recycled and regenerative fibers, (2) identify the most impactful life cycle stages, (3) compare results with conventional cotton alternatives, and (4) demonstrate LCA as a strategic tool to support sustainable innovation and circularity in textiles. By addressing data gaps and providing actionable insights, the study contributes to both theory and practice, informing sustainable production, material selection, and policy implementation.

2. Materials and methods

2.1. Study goal

This study aims to assess the life cycle environmental impacts of a homewear set produced by Impetus, a Portuguese textile manufacturer, and commercialized under the Revive brand. The product is made using N-Lyfe yarn, a branded fiber blend composed of 30 % pre-consumer cellulosic waste - including cotton, viscose, modal, and lyocell - recovered from internal production processes, and 70 % cotton cultivated through regenerative agricultural practices in Australia.

The environmental performance of this product is compared with a conventional homewear set made from 100 % conventional cotton sourced globally. The study aims to quantify the environmental benefits of using recycled inputs and regenerative raw materials (De Felice et al., 2025; Mayya Saliba, Andrew Keys, Megan Mudie, 2024; Sandin and Peters, 2018). Additionally, it identifies life cycle stages with the greatest environmental impact, highlighting opportunities for improvement in the production and supply chain.

2.2. Study scope

2.2.1. Functional unit

The functional unit (FU) is defined as one medium-sized homewear set, consisting of a sweatshirt (317 g) and a pair of pants (326 g, including accessories such as elastic bands and drawstrings), with a total mass of 643 g. Both garments are made from a textile blend comprising 70 % regenerative cotton and 30 % pre-consumer cellulosic waste. This FU, defined by mass and material composition, enables consistent and scalable comparison of the environmental performance of the product with equivalent homewear sets made from conventional cotton.

2.2.2. System boundaries

This study adopts a cradle-to-gate approach, encompassing all stages from raw material extraction to packaging. The system boundaries are structured as follows.

- Foreground processes (depicted in purple in Fig. 1): Operations directly managed by Impetus, where opportunities for operational improvements exist.
- Background processes (shown in orange): Activities outside Impetus's direct control, yet relevant for capturing the full environmental burden.
- Circularity-enhancing actions (highlighted in green): Measures aimed at improving resource efficiency, such as the reintegration of pre-consumer textile waste into the production system.

2.2.3. Overview of main production stages

2.2.3.1. Cotton cultivation. Cotton was produced on an Australian farm under certified regenerative-agriculture protocols, employing both irrigated and rainfed systems. Primary, on-farm measurements informed the LCA of the cultivation stage; the inventory covers land occupation, energy consumption, agrochemical inputs (fertilizers, insecticides, and others) and irrigation volumes, and includes all key field operations - soil preparation, sowing, crop management and harvesting. In the absence of farm-specific data for the ginning process, values were drawn from peer-reviewed LCA literature (Funk and Hardin, 2017; Ismail et al., 2011). Because both cultivation and ginning occurred on site, no intra-stage transport was modelled.

For downstream operations, it was assumed that the harvested cotton is first trucked from the farm to the Port of Brisbane, then shipped by container from Brisbane to the Port of Leixões in Portugal, and finally delivered by road to the spinning facility. Each transport leg was modelled using ecoinvent v3.9.1 datasets and quantified in tonne-kilometres: distances were estimated via online routing tools and default load factors from the ecoinvent database were applied to ensure consistency and comparability in the transport emissions assessment.

2.2.3.2. N-Lyfe yarn production. Cellulosic textile waste generated from Impetus's operations is collected at three distinct stages of the production process: knitting, finishing, and cutting. Waste from knitting and finishing is collected manually, while waste from the cutting stage is collected automatically. Although manual collection does not involve direct energy inputs, this study accounts for the electricity consumption associated with the automated collection during cutting, as well as the transport of waste from the off-site finishing unit.

Following consolidation, the collected textile waste is transported by truck to a mechanical recycling facility, where it is processed into recycled fiber. This study accounts for fuel consumption and emissions associated with transportation, electricity use during the recycling process, treatment of process residues, and the subsequent transport of the recycled fiber to the spinning facility.

The recycled fiber, representing 30 % of the final yarn by weight, is blended with 70 % virgin cotton sourced from regenerative agricultural practices and spun into N-Lyfe yarn using an open-end spinning method. This production stage encompasses electricity consumption, paraffin application, treatment of process waste, and transportation, all of which are accounted for in the present LCA study.

2.2.3.3. Knit manufacturing. The N-Lyfe yarn is subsequently used by Impetus to manufacture two types of knits.

1. Jersey knit for the main garment body, which is left undyed to minimize environmental impacts.
2. Ribbed knit for cuffs, collars, and waistbands, which contains 1 % elastane to ensure dimensional stability and is also processed without dyeing.

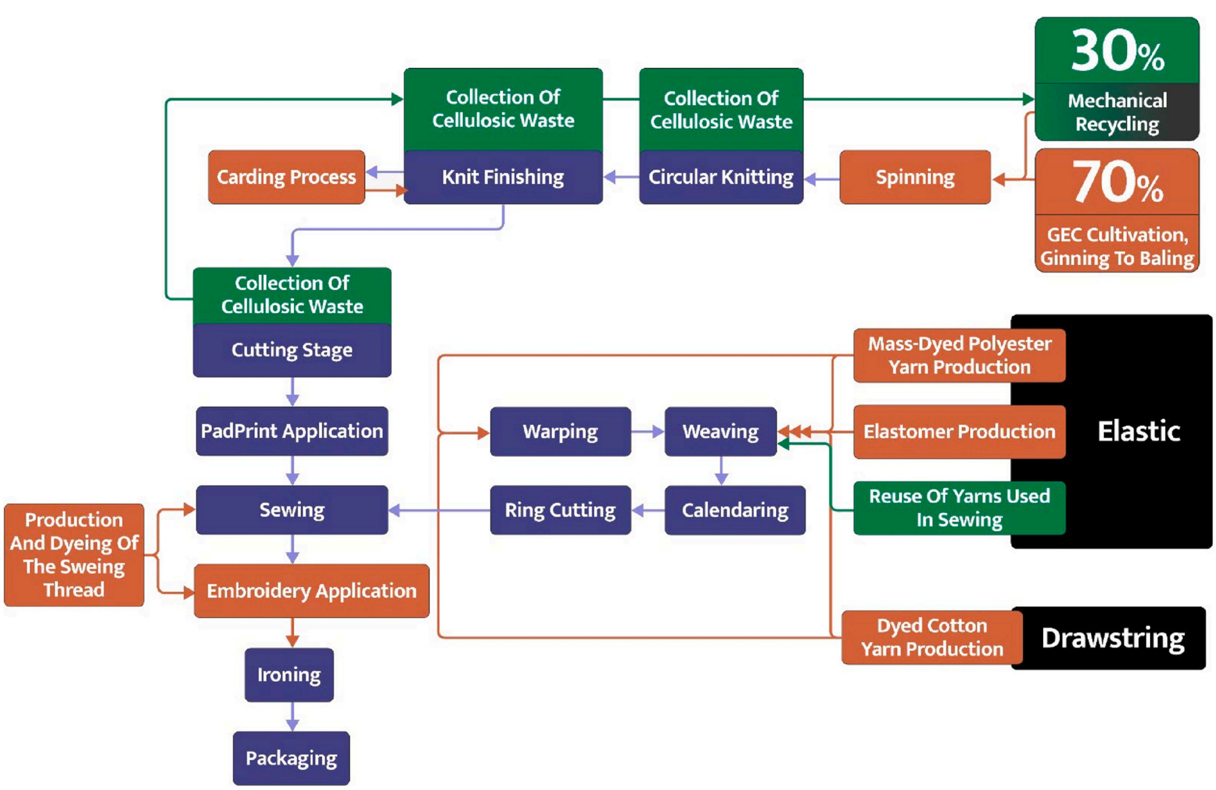

Fig. 1. Overview of the system boundaries and key processes considered in the LCA of the Impetus homewear set.

Given that elastane constitutes less than 0.5 % of the total product mass, its contribution to life cycle environmental impacts is considered negligible. As such, it was excluded from the assessment in accordance with standard LCA practice, which prioritizes the modeling of dominant material flows (Van Der Velden et al., 2014).

2.2.3.4. Production of elastic bands and drawstrings. The elastic bands and drawstrings used in the pants are produced through circular processes that integrate waste materials from the assembly phase, thereby enhancing material efficiency and reducing waste. Production begins with the warping of mass-dyed polyester yarn, followed by weaving, during which elastomer and recycled polyester threads recovered from the garment manufacturing stage are incorporated. The process then proceeds to calendaring, performed by two machines operating under pressure at approximately 145 °C and 120 °C, respectively. Finally, the bands are cut and looped into rings, ready for garment integration.

Drawstrings are produced through a similar process involving warping, weaving, and calendaring, but are processed in a single machine operating at around 145 °C. After calendaring, the material is cut to the required shape and length.

2.2.4. Knit finishing, garment assembly, and packaging

Knits undergo finishing processes to remove impurities and achieve the desired texture and functionality. For the jersey knit, the finishing sequence includes unwinding, washing, squeezing, drying, softening, and scouring. As the homewear set is made from carded knit, the material is additionally sent to a specialized carding facility before undergoing stentering, after which it is returned to Impetus for further processing.

For the ribbed knit, the finishing steps comprise unwinding, opening, thermo-fixing for dimensional stability, closing, washing, squeezing, drying, scouring, and sanforization to reduce shrinkage and enhance hand feel.

After finishing, both knits are unwound, stretched, and cut using automated machinery. Pad printing is applied exclusively to the sweatshirt component. During the assembly phase, all garment components are sewn together, incorporating accessories such as elastic bands, drawstrings, and labels. The production and transport of sewing thread are included in the life cycle assessment.

Embroidery for the sweatshirt is subcontracted to a specialized company. Once embroidered, garments are returned to Impetus, where both the sweatshirt and pants undergo final ironing. The complete homewear set is then manually packaged, with all packaging-related environmental impacts included in the assessment. Additionally, the impacts associated with embroidery thread production and transport are accounted for in the analysis.

2.2.5. Reference product: 100 % conventional cotton homewear set

For comparison purposes, a conventional homewear set made from 100 % virgin cotton was defined as the reference product. Unlike the N-Lyfe set - which uses pre-colored recycled fibers that yield a consistent natural grey tone - this conventional product requires an external dyeing process to achieve a similar aesthetic. The omission of the dyeing stage in the N-Lyfe system significantly reduces the need for additional energy, water, and chemicals, thereby lowering its environmental impact.

Fig. 2 presents a comparative overview of the key inputs and processes for both products. This enables an attributional life cycle analysis of the environmental implications associated with the use of recycled content and the elimination of the dyeing phase. Additionally, it facilitates the identification of environmental hotspots and contributes to a broader understanding of how material choices and production strategies influence overall life cycle performance.

2.2.6. Data limitations

Post-packaging stages - namely distribution, use, and end-of-life -were excluded from the system boundaries due to significant variability and limited data availability. These stages are heavily influenced by factors such as consumer behavior, geographic context, and local waste management practices, which pose significant challenges for consistent modelling and regional generalization. In particular, the use phase is highly context-specific and lacks standardized, reliable datasets, making its inclusion in a robust and comparative assessment impractical. Consequently, this study focuses solely on upstream and production-related stages, where data availability and consistency are

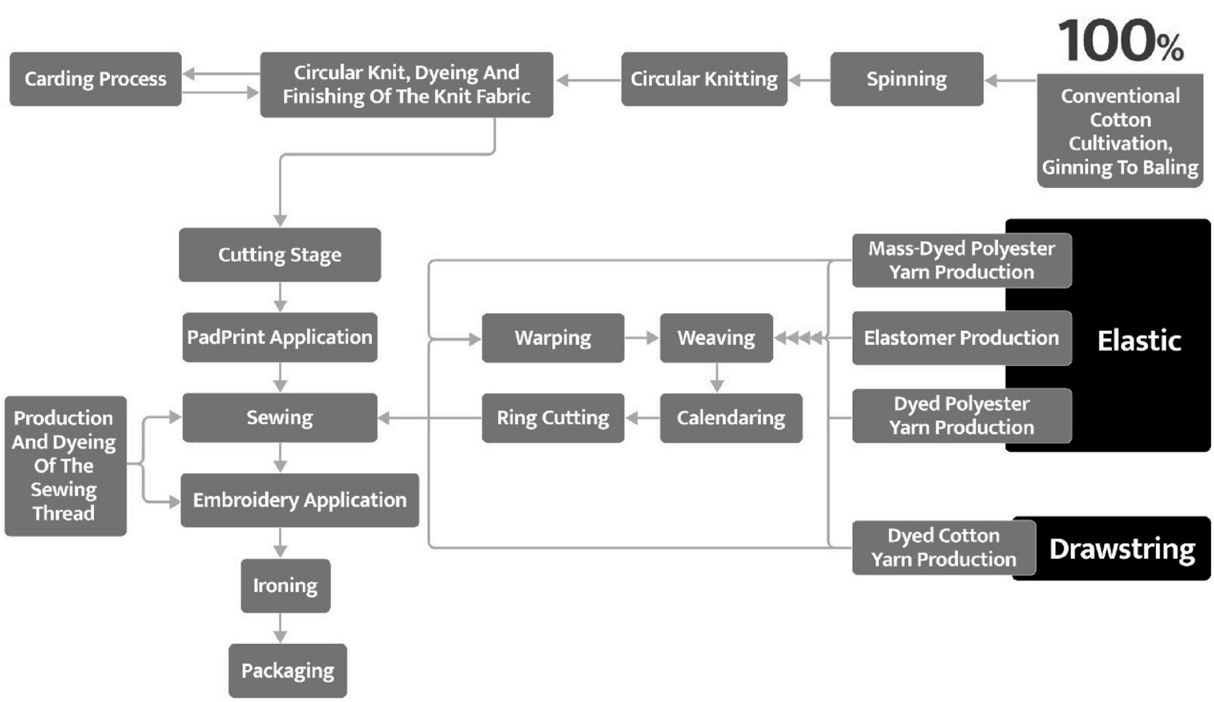

Fig. 2. – System boundaries and key processes considered in the LCA of a conventional 100 % cotton homewear set (knit dyed in solid color), defined as the reference product for comparison with the Impetus homewear set.

greater.

The analysis combines primary and secondary data sources, detailed in the Supplementary Materials. Where primary data were unavailable, high-quality secondary datasets - mainly for background processes - were used. Life cycle modelling was conducted using the ecoinvent v3.9.1 database within SimaPro v9.6 software (Pré Consultants). Despite efforts to employ the most current and regionally relevant data, reliance on secondary sources introduces uncertainties related to geographic representativeness and data completeness. These limitations may affect the accuracy and generalizability of results; therefore, caution is advised when extrapolating findings to other contexts.

A comprehensive list of the ecoinvent v3.9.1 datasets applied in this LCA study is provided in the Supplementary Materials to ensure transparency and reproducibility of the life cycle modelling.

2.3. Life cycle inventory: data, assumptions, and limitations

The life cycle inventory (LCI) for the Impetus homewear set was developed with a strong emphasis on primary data collection, achieving approximately 90 % coverage across the product's value chain. Primary data were obtained directly from Impetus and its suppliers for all relevant foreground and background processes. High-quality secondary sources, such as peer-reviewed literature and the ecoinvent v3.9.1 database integrated into SimaPro v9.6, were utilized in cases where direct measurements were unavailable.

Inventory data were systematically collected across all production stages. Key parameters included.

- Energy consumption, disaggregated by type and process, with monthly data on the electricity mix to reflect the proportion of renewable vs. grid-supplied energy.
- Chemical inputs, including types and quantities, based on Safety Data Sheets (SDS) provided by suppliers.
- Water consumption, recorded for each individual processing step.
- Transport logistics, including transport modes and distances for raw materials, intermediate products, and final items.
- Process losses and waste flows, detailing types of waste generated and their end-of-life treatment routes (e.g., recycling, landfill, incineration).
- Packaging materials, including material types and corresponding mass.
- Cotton cultivation, with data on land occupation and agrochemical inputs (e.g., fertilizers, herbicides, insecticides), water and energy consumption.

This thorough and transparent data collection strategy enabled the construction of a detailed and representative LCA model of the system under study.

Electricity-related environmental impacts were modelled using specific energy mix data extracted from electricity bills, supplemented by information on on-site renewable energy production. In 2023, the year in which the Self-Consumption Production Unit (UPAC) became operational, Impetus achieved a self-consumption rate of 21.8 %. This proportion was uniformly distributed across all electricity-consuming stages. Consequently, it was assumed that 78.2 % of the electricity demand was covered by the national grid and 21.8 % by photovoltaic self-generation.

Given the extensive nature of the inventory data, full LCI tables are provided in the Supplementary Materials. These include detailed inputs, outputs, and flows for all relevant processes, ensuring transparency and enabling reproducibility of the assessment.

2.4. Life cycle impact assessment

The life cycle impact assessment (LCIA) was carried out in SimaPro 9.6 using the ReCiPe 2016 (v1.03) midpoint method with an egalitarian perspective (Huijbregts et al., 2016). This perspective follows a precautionary principle, prioritizing long-term environmental protection and accounting for potential impacts on future generations, including those that are uncertain or may manifest over extended time horizons. It assumes equal importance across all impact categories, thereby avoiding prioritization based on short-term or anthropocentric concerns. The midpoint–egalitarian combination provides a comprehensive and balanced framework for evaluating environmental performance.

Although ReCiPe defines 18 midpoint impact categories, this study focuses on a subset of seven (listed in Table 1). These were selected based on their (i) alignment with known environmental hotspots in textile production, (ii) relevance to key sustainability challenges in the textile sector, and (iii) consistency with industry-recognized frameworks, particularly the Higg Index indicators (Watson and Wiedemann, 2019). This targeted selection enhances the sectoral relevance of the analysis while maintaining methodological rigor.

Midpoint indicators represent environmental impacts at an intermediate stage in the cause-effect chain - between elementary flows and broader damage to human health, ecosystems, or resources. Compared to endpoint indicators, midpoint results offer more detailed, mechanism-specific insights, supporting the identification of environmental hotspots and enabling more effective improvements in product design, material selection, and process optimization.

An attributional LCA approach was applied to quantify the environmental impacts associated with the production of one functional unit of the homewear set, covering the cradle-to-gate life cycle - from raw material extraction to packaging. Environmental burdens were allocated across the various life cycle stages, enabling the evaluation of each process's contribution and supporting the identification of opportunities for impact reduction throughout the system.

3. Results and discussion

3.1. Overall environmental impacts of the regenerative and recycled cotton homewear set

Fig. 3 illustrates the percentage contribution of each life cycle stage to the total environmental impacts of producing the regenerative and recycled cotton homewear set. This breakdown facilitates the identification of environmental hotspots - the life cycle stages with the highest impact - and highlights key areas for targeted environmental improvement.

The analysis identifies cotton cultivation, spinning, knit finishing, and cutting as the most impactful life cycle stages, collectively accounting for the majority of the product's environmental footprint. Key

Table 1
Potential environmental impact categories selected for this study, calculated according to the ReCiPe 2016 method (Huijbregts et al., 2016).

Impact Category	Description	Unit
Climate change (carbon footprint)	Global warming potential due to greenhouse gas emissions over a 1000-year horizon.	kg CO_2-eq
Freshwater ecotoxicity	Potential impact of toxic substances on freshwater ecosystems.	kg 1,4-DCB-eq
Energy resources: non-renewable, fossil (abiotic depletion)	Potential depletion of fossil resources.	kg oil-eq
Freshwater eutrophication	Potential impact caused by excess nutrients, especially nitrogen and phosphorus, from emissions.	kg P-eq
Land use	Potential impact associated with the occupation and transformation of agricultural land.	m^2a crop-eq
Ozone layer depletion	Potential of atmospheric emissions to deplete the ozone layer.	kg CFC-11-eq
Water consumption	Potential water consumption based on water scarcity factors.	m^3

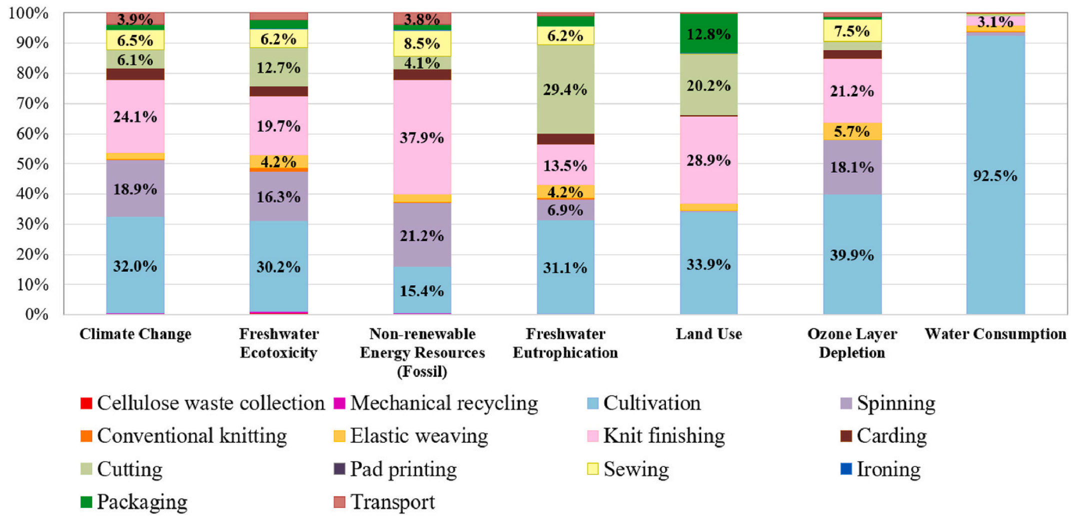

Fig. 3. Percentage contribution of each life cycle stage to the total environmental impacts associated with the manufacturing of the Impetus homewear set.

contributing factors include water and land use, energy consumption, and chemical inputs.

Cotton cultivation emerges as the largest contributor to climate change impacts, responsible for 32.0 % of total greenhouse gas emissions. This impact is largely driven by extensive land use and the substantial application of agricultural chemicals such as fertilizers, and herbicides. Notably, nitrogen-based fertilizers contribute significantly to nitrous oxide emissions, a potent greenhouse gas. Furthermore, land-use changes associated with cotton farming - such as soil degradation and deforestation - further increase CO_2 emissions.

Following cultivation, the knit finishing stages account for 24.1 % of the climate change impact. These processes involve intensive chemical treatments, requiring considerable amounts of water, heat, and chemicals, underscoring the need to adopt energy-efficient technologies and less resource-intensive alternatives.

Spinning contributes 18.9 % to climate change impacts, primarily due to high electricity consumption during the energy-intensive mechanical processing of raw cotton fibers into yarn. This finding highlights the importance of reducing energy use, especially in contexts where electricity generation relies heavily on fossil fuels.

Other processes, including cutting, sewing, and packaging, also contribute to climate change. Cutting and sewing require energy to operate machinery, with impacts depending on the energy mix used. In the cutting stage, paper and plastic are the main materials, while in sewing, thread is the primary material. The production of paper, plastic, and sewing threads is energy-intensive and typically relies on fossil fuels, releasing greenhouse gases and contributing to climate change. Packaging, done manually, mainly contributes through the materials used, such as paper and plastics, which emit greenhouse gases during production. Since it's difficult to measure the environmental impacts of manual labor, only the impacts from producing the packaging materials were considered. Although the environmental impacts of cutting, sewing, and packaging are relatively small individually, their combined effect contributes to the overall environmental footprint of textile manufacturing. This emphasizes the importance of energy efficiency and sustainable material choices throughout the production process.

Freshwater ecotoxicity is primarily driven by the cotton cultivation (30.2 %) and knit finishing (19.7 %) stages, with significant contributions from spinning (16.3 %) and cutting (12.7 %). The use of fertilizers and chemicals in cultivation can leach into water bodies, causing nutrient pollution and damaging aquatic ecosystems. In the knit finishing stage, chemical use from knit treatments further exacerbates these environmental impacts.

Freshwater eutrophication is primarily driven by the cotton cultivation (31.1 %) and cutting (29.4 %) stages, with knit finishing (13.5 %) and spinning (6.9 %) contributing to a lesser extent. These impacts are largely linked to the use of agricultural inputs and chemical treatments, particularly nutrient runoff - such as nitrogen and phosphorus - during cotton cultivation, as well as the paper production required in the cutting stage.

In terms of non-renewable energy consumption, the knit finishing stage accounts for the largest share (37.9 %), mainly due to energy-intensive chemical treatments and natural gas use. Spinning contributes 21.2 %, driven by high electricity demand for machinery operation. Other stages, including cultivation and sewing, also add to overall energy use. Cultivation's energy intensity stems largely from producing and applying agricultural chemicals, especially fertilizers derived from non-renewable minerals like phosphorus and potassium. Similarly, the sewing stage's energy consumption is dominated by the production and dyeing of thread and other inputs, with thread use accounting for over 80 % of the impact across nearly all categories.

Land use is predominantly driven by cotton cultivation (33.9 %), followed by knit finishing (28.9 %), with cutting (20.2 %) and packaging (12.8 %) also making notable contributions. This reflects the significant dependence of these stages on agricultural and land-based resources, including materials such as paper used in the cutting and packaging processes.

A similar pattern is observed for ozone layer depletion, with cotton cultivation accounting for the largest share (39.9 %) and knit finishing contributing 21.2 %, while spinning and sewing also present notable impacts. These results reflect emissions associated with agricultural inputs and chemical processes in these stages.

Water consumption is overwhelmingly dominated by cotton cultivation, which accounts for 92.5 % of the total, while knit finishing (3.1 %) and elastic weaving (2.1 %) contribute only marginally. This highlights the substantial water demands of agricultural processes, consistent with previous studies emphasizing the high water footprint of cotton cultivation (Demeke et al., 2024; Jans et al., 2021). Since the homewear set analyzed in this LCA study contains only 70 % virgin cotton - with the remaining 30 % made of recycled fibers - and is not dyed, these factors further contribute to reducing the product's overall water consumption.

In summary, cotton cultivation is the main driver of environmental impacts, particularly regarding climate change, water use, and land occupation. Other stages - spinning, knit finishing, and cutting - also contribute notably, affecting energy use (spinning), water consumption, chemical use (knit finishing), and material consumption (cutting). Improving farming practices, enhancing energy and water efficiency, and reducing chemical inputs can markedly reduce the environmental footprint of cotton textiles (Vitale et al., 2025).

Additionally, using alternative materials, renewable energy, and energy-efficient technologies can further reduce impacts. Cellulose waste collection and mechanical recycling have minimal environmental effects, making them relatively sustainable. Focusing on cotton cultivation and finishing stages offers the greatest potential for reducing the environmental impact of textile production.

Fig. 4 illustrates the percentage contributions of various foreground processes controlled by Impetus in the manufacturing of the homewear set to the overall environmental impacts. The figure highlights the relative importance of each process, providing a clear view of which stages contribute most significantly to environmental concerns. By presenting this breakdown, the figure helps identify key areas where improvements can be made to reduce the overall environmental footprint of the product. These insights are essential for guiding future sustainability efforts within the production chain.

For climate change, the knit finishing stage contributes the most at 61.6 %, followed by sewing (16.7 %), and cutting (15.6 %). These stages are energy-intensive, primarily due to machinery and chemical use. Sewing also has a significant impact due to the large amount of thread used, which requires high energy for production and dyeing, as well as water and chemicals.

For freshwater ecotoxicity, the largest impacts come from cutting (28.9 %) and knit finishing (44.7 %) due to chemical use, waste, and their potential harm to freshwater ecosystems. Sewing (14.2 %) also contributes, mainly from chemicals used in dyeing thread, which can pollute water. Packaging (6.3 %) has a smaller impact, indicating that materials and chemicals in packaging production can affect freshwater ecosystems.

For freshwater eutrophication, cutting (55.1 %) is the dominant contributor, followed by knit finishing (25.3 %). This is primarily due to the high use of paper in the cutting process, which requires significant water and energy for production. Additionally, chemical runoff from textile treatments contributes to eutrophication in freshwater systems. Sewing (11.6 %) also contributes, due to chemicals used in the production and dyeing of sewing thread, which can runoff into water systems and cause nutrient pollution.

In the non-renewable energy resources (fossil) category, the highest contributions come from knit finishing processes (71.7 %), reflecting heavy fossil energy use in this stage, primarily due to heating, chemical processes, and machinery. Sewing (16.0 %) also contributes significantly, as the production and dyeing of large quantities of thread require substantial energy, water, and chemicals, resulting in increased fossil energy consumption.

Land use is primarily driven by knit finishing (46.2 %) and cutting (32.2 %). The knit finishing processes require significant natural resources, including water and chemicals, while cutting relies heavily on paper, which is sourced from agricultural land. Both processes contribute to land use, as land is needed to grow the raw materials, such as paper. Packaging also contributes (20.5 %), as the raw materials for packaging require substantial land resources.

For ozone layer depletion, knit finishing (64.7 %) is the largest contributor due to the chemical treatments used, which release ozone-depleting substances. Sewing (22.9 %) also plays a significant role, due to the high energy, water, and chemical consumption involved in the production and dyeing of sewing thread, which contributes to the release of ozone-depleting chemicals.

In terms of water consumption, knit finishing (75.6 %) is the largest contributor, mainly due to the significant water usage during washing and chemical treatments in the process.

Overall, knit finishing and cutting are the most influential processes across several environmental impact categories, due to the chemicals used in knit finishing and the paper consumption in cutting. These stages, characterized by high chemical use, energy consumption, and water requirements, present key opportunities for sustainability improvements in the production of the Impetus homewear set, particularly in areas such as climate change, freshwater eutrophication, land use, and water consumption.

3.2. Key life cycle stages driving environmental impacts of regenerative and recycled cotton homewear set

3.2.1. Cultivation

The Impetus homewear set analyzed in this study is made using a yarn composed of 30 % pre-consumer cellulose-based textile waste - including cotton, viscose, modal, and lyocell -recovered from internal production processes. This circular approach contributes to reducing reliance on virgin raw materials and minimizing textile waste. The remaining 70 % of the yarn is derived from cotton cultivated in Australia under regenerative agricultural practices such as crop rotation and reduced tillage. These practices are known to improve soil health, enhance water retention, increase carbon sequestration, and support biodiversity, while also reducing the need for synthetic inputs and lowering the environmental impact when compared to conventional cotton farming.

However, cotton cultivation remains a critical stage in the life cycle of the homewear set. Despite the benefits of regenerative practices,

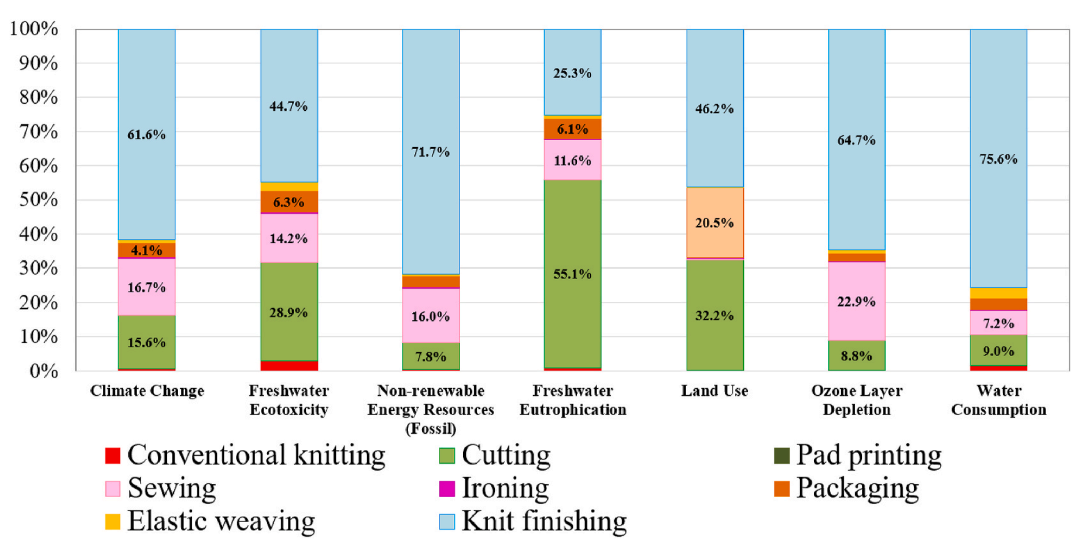

Fig. 4. Percentage contributions of various Impetus foreground processes to the environmental impacts in the manufacturing of the homewear set.

cotton's inherent water and land demands continue to be the largest contributors to the product's environmental footprint, particularly in multiple impact categories. Fig. 5 provides a detailed breakdown of these contributions, highlighting the percentage impact of each key stage - cultivation, chemicals, diesel, irrigation, and ginning - on the overall environmental footprint. This analysis reveals the most significant contributors to the product's environmental performance.

In cotton cultivation, the cultivation area is the dominant factor, accounting for 55.8 % of climate change impacts and 96.4 % of land use impacts. Land conversion for cotton farming generates substantial greenhouse gas emissions and disrupts local ecosystems. Additionally, the use of agricultural inputs - especially fertilizers - significantly contributes to environmental impacts, with the cultivation area responsible for 44.0 % of ozone layer depletion.

Chemical use remains a major concern despite the adoption of regenerative practices. This is particularly evident in freshwater ecotoxicity, where chemicals contribute 92.1 % of the impact, and in non-renewable energy consumption, which accounts for 87.8 %. Additionally, freshwater eutrophication - 62.4 % of which is attributed to chemical use - is primarily driven by the runoff of nutrient-rich fertilizers. A notable contributor to this impact is the ginning stage of cotton processing, which alone accounts for 36.6 % of freshwater eutrophication. Ginning is energy-intensive, relying heavily on electricity and natural gas. In Australia, where electricity is largely generated from natural gas, lignite, and coal, this significantly increases associated emissions, as reported in the ecoinvent database.

Irrigation represents 98.5 % of water consumption in cotton farming. Given cotton's high water requirements, particularly in low-rainfall regions, this dependence places considerable pressure on local water resources and drives overall water use. These findings underscore the substantial water demands of cotton cultivation, in line with previous studies highlighting its high water footprint (Demeke et al., 2024; Jans et al., 2021).

Fig. 6 illustrates the environmental impacts of chemical inputs used in cotton cultivation for the homewear set. It shows the percentage contribution of various chemicals - including fertilizers, insecticides, herbicides, growth regulators, defoliants, and adjuvants - across several impact categories, such as climate change, freshwater eutrophication, and chemical use.

The results clearly demonstrate the substantial environmental burden posed by agrochemicals, with fertilizers emerging as the predominant contributor across nearly all impact categories. Specifically, fertilizers are responsible for 94.0 % of climate change impacts, 96.0 % of freshwater ecotoxicity, 93.9 % of non-renewable energy use, 79.7 % of freshwater eutrophication, 93.3 % of land use, 98.7 % of ozone layer depletion, and 95.7 % of water consumption. In contrast, the contributions of herbicides and insecticides are relatively minor across most categories.

3.2.2. Spinning process

The spinning process is also a key stage in the life cycle of the homewear set, where fibers are turned into yarn, forming the basis for the final textile product. Although crucial for knit production, spinning is the third-largest contributor to the overall environmental impact in textile manufacturing. This stage is energy-intensive, requiring significant electricity to power the machinery, which increases its environmental footprint.

Fig. 7 illustrates the percentage contributions of key input categories - electricity, paraffin use, and textile waste treatment - during the spinning process. These inputs play a significant role in shaping the environmental impacts of the homewear set, highlighting the energy-intensive nature of spinning and the importance of material and waste management in reducing the overall environmental footprint.

In the spinning process, electricity is the main contributor to most environmental impact categories. It accounts for 93.8 % of climate change impacts, highlighting the significant greenhouse gas emissions from energy-intensive operations. Electricity also contributes 94.9 % to freshwater ecotoxicity. Its reliance on fossil fuels is evident, with electricity representing 98.7 % of the impact in non-renewable energy resources (fossil). It contributes 98.0 % to freshwater eutrophication, land use, and water consumption, showcasing its broad environmental footprint. The only exception is ozone layer depletion, where electricity's contribution is relatively low (15.4 %), as other sources are more responsible for emissions in this category.

Textile waste treatment, mainly through municipal incineration, shows varied contributions across environmental categories. It is the largest contributor to ozone layer depletion, responsible for 84.6 % of the impact, due to the significant emissions from waste incineration. It contributes between 1 % and 6 % to climate change, freshwater ecotoxicity, and land use, indicating a moderate but notable impact. However, its contribution to non-renewable energy resources, freshwater eutrophication, and water consumption is minimal, remaining below 2 %.

Paraffin use has the smallest environmental impact across all categories, contributing less than 0.2 % to climate change, freshwater ecotoxicity, and non-renewable energy resources. It does not contribute to ozone layer depletion, highlighting its negligible role in these environmental impacts.

In summary, electricity consumption dominates most environmental categories in the spinning process. Transitioning to renewable energy

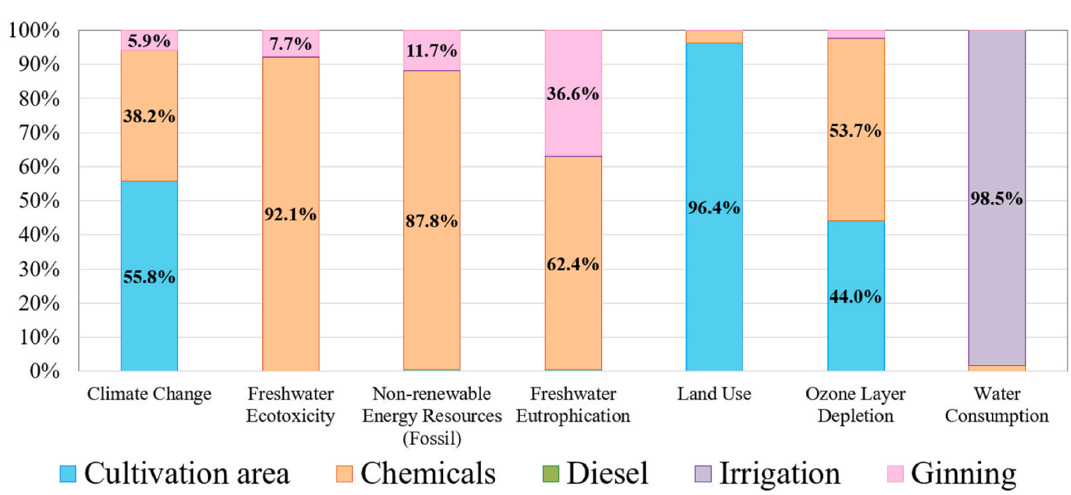

Fig. 5. Percentage contribution of each cotton production stage (Cultivation, Chemicals, Diesel, Irrigation, and Ginning) to the environmental impacts of the Impetus homewear set.

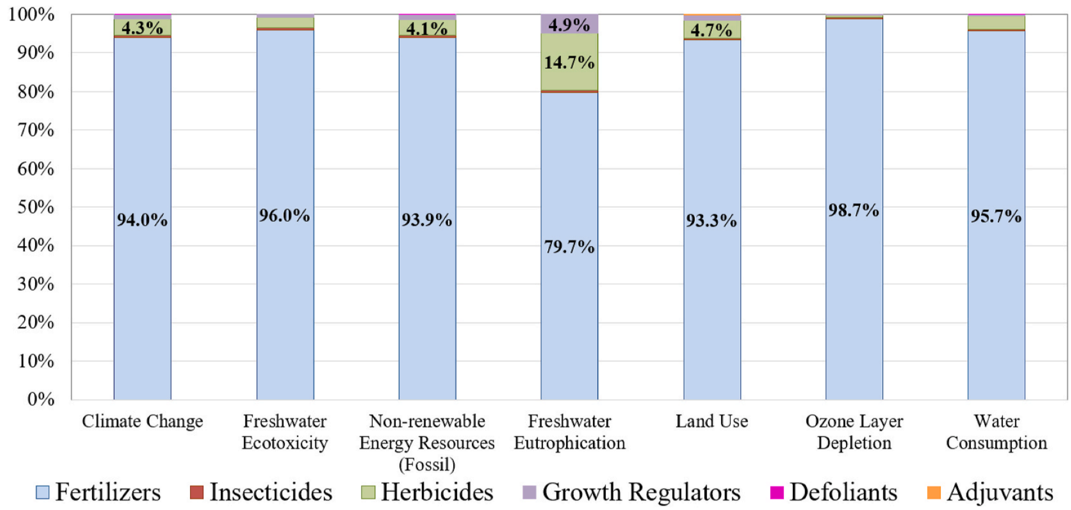

Fig. 6. – Percentage contribution of various chemicals used in cotton cultivation (fertilizers, insecticides, herbicides, growth regulators, defoliants, and adjuvants) to the environmental impacts of the Impetus homewear set.

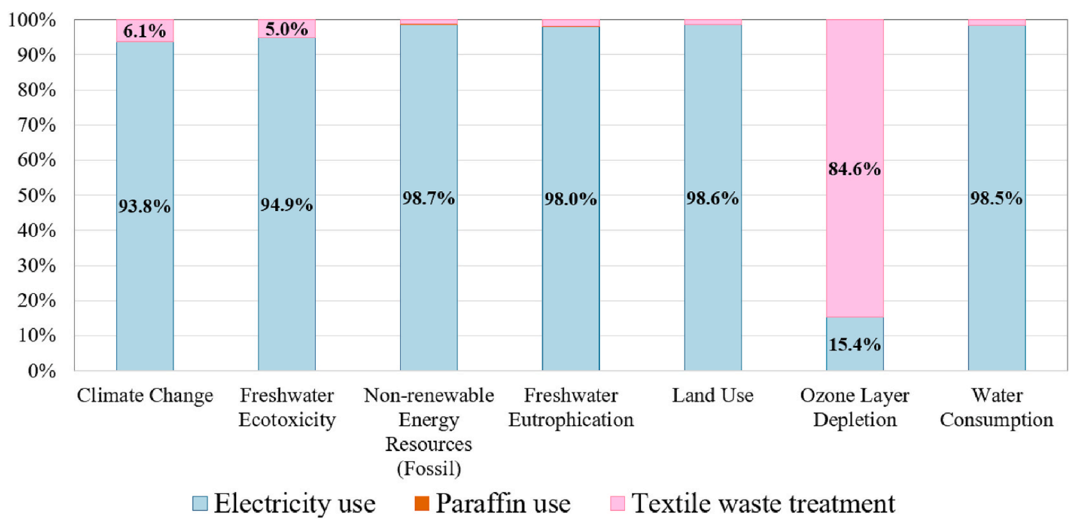

Fig. 7. Percentage contributions of input categories (Electricity, Paraffin Use, and Textile Waste Treatment) to the environmental impacts of the Impetus homewear set during the spinning process.

sources and enhancing energy efficiency could significantly lower these impacts.

3.2.3. *Knit finishing processes*

The knit finishing processes are major contributors to the environmental impacts of the homewear set, primarily due to their high water, energy, and chemical consumption. These stages are essential for improving the knit's texture, softness, durability, and appearance, using techniques like chemical washing and heat treatment to achieve the desired properties.

Fig. 8 provides a detailed breakdown of the environmental impacts associated with the knit finishing processes of the homewear set. It illustrates the percentage contribution of various input categories - electricity, natural gas, water, chemicals, and wastewater - towards the overall environmental footprint. This analysis highlights the significant role each input plays in driving environmental impacts across different categories, emphasizing the areas where improvements can be made to reduce the environmental burden of the finishing processes.

Electricity significantly impacts climate change (14.6 %) and non-renewable energy resources (11.3 %), primarily due to the carbon intensity of fossil fuels. Natural gas, used for heat and steam, accounts for 49.9 % of non-renewable energy resources and 12.1 % of climate change.

Water consumption is another major contributor, representing 49.2 % of total water use.

Chemicals are the primary environmental concern in the finishing processes, contributing significantly to various impact categories. They account for 99.5 % of land use, 86.0 % of freshwater ecotoxicity, and notably impact ozone layer depletion (92.7 %), climate change (72.3 %), and freshwater eutrophication (65.2 %).

Chemicals contribute 45.0 % to total water consumption, while direct water use in the process accounts for 49.2 %. Water consumption includes both direct use at each process stage and indirect use such as for raw material preparation. With no dyeing involved, the overall water demand is lower, making the water used for chemicals processing comparable to direct process water use. The extensive use of chemicals in textile processing leads to resource depletion, pollution, and ecosystem degradation.

Wastewater generated contributes to Freshwater Eutrophication (20.4 %). The analysis highlights the significant environmental impact of chemicals, energy, and water in the finishing processes of the homewear set. Reducing the use of chemicals, energy, and water can

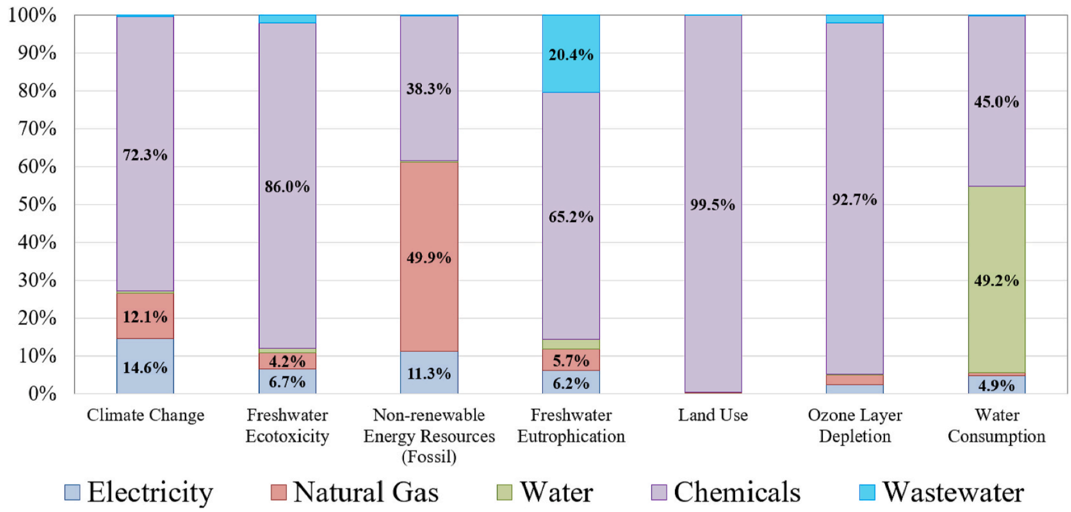

Fig. 8. Percentage contributions of input categories (electricity, natural gas, water, chemicals, and wastewater) in the knit finishing processes to the environmental impacts of the homewear set incorporating regenerative cotton and recycled cellulosic fibers.

greatly minimize the environmental footprint of these processes.

Fig. 9 provides a detailed breakdown of the percentage contributions to the environmental impacts of the chemicals used in the finishing processes of the homewear set. It illustrates the percentage contribution of different chemical categories, including surfactants, softeners, and other auxiliaries, towards key environmental issues such as climate change, freshwater eutrophication, and chemical use. This analysis underscores the significant role that chemical inputs play in driving environmental degradation in textile processing, highlighting the need for targeted actions to mitigate their effects.

The softening agent is the largest contributor to climate change, accounting for 74.5 %, followed by the knit softener at 20.1 %. For freshwater ecotoxicity, the softening agent leads with 78.7 %, while the knit softener contributes 16.3 %. In terms of non-renewable energy resources (fossil), the knit softener has the highest impact at 56.2 %, with the softening agent at 29.7 %, both largely dependent on fossil fuels.

The softening agent leads in freshwater eutrophication (53.6 %) and water consumption (77.5 %), with the knit softener at 36.0 % and 17.0 %, respectively. It also dominates in land use (99.0 %) and ozone layer depletion (97.0 %), due to resource-heavy materials and chemicals like chlorine. Overall, the softening agent and knit softener are the biggest contributors to environmental impacts. Reducing their use or finding sustainable alternatives could significantly lower the footprint of the homewear set.

3.2.4. Cutting process

The cutting process in the production of the homewear set is essential for shaping and preparing knit for garment assembly. While it does not rely heavily on raw materials or chemicals, it still generates environmental impacts due to the use of resources and energy. Key resources include electricity, compressed air, paper, plastic, and solid waste, each contributing to various impact categories. Fig. 10 shows the percentage contributions of these inputs to the environmental impacts, providing a clear overview of their effects during the cutting process.

In the cutting process, paper is the largest contributor to climate change, accounting for 42.2 %, followed by solid waste at 30.9 %. Electricity and plastic contribute less. For freshwater ecotoxicity, solid waste is the main contributor at 53.5 %. Compressed air and paper also contribute, with paper's impact stemming from chemical treatments used in its production. In terms of non-renewable energy resources (fossil), paper again stands out as the largest contributor at 56.1 %, reflecting its heavy reliance on fossil fuels. Electricity and plastic also depend on fossil energy in their production processes. For freshwater eutrophication, paper is the largest contributor at 90.0 %, highlighting the significant impact of paper production, particularly from fertilizers and chemicals, on water quality. For land use, paper is the main

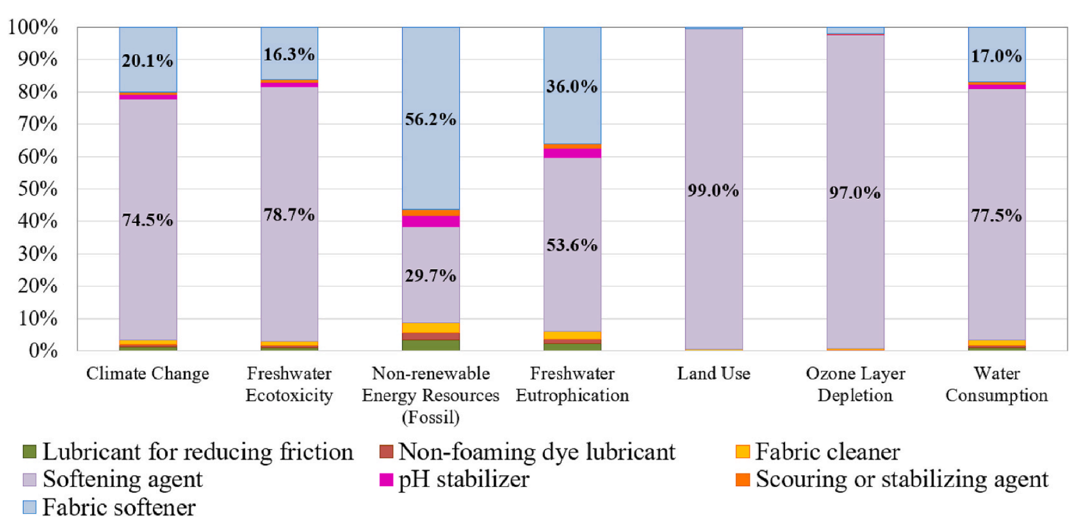

Fig. 9. Percentage contributions of various chemicals used in the knit finishing processes of the homewear set across different environmental impact categories.

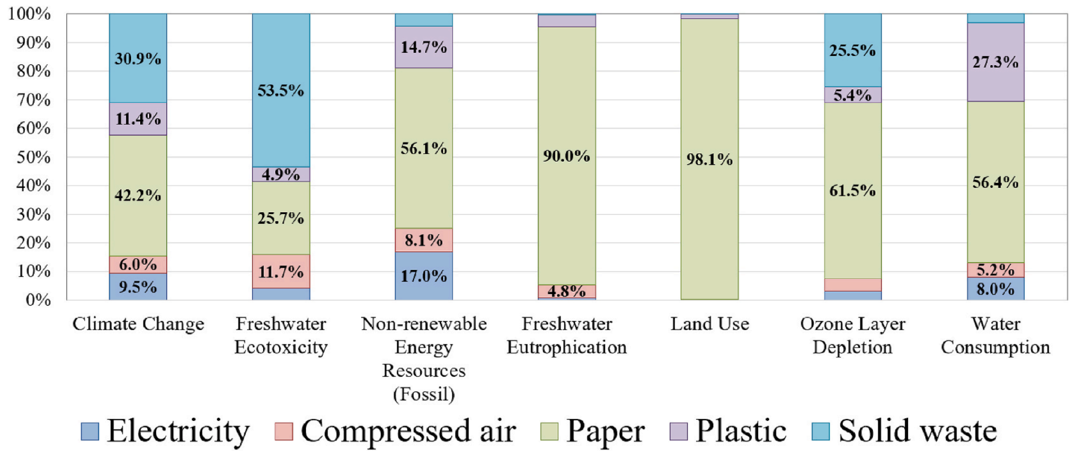

Fig. 10. Percentage contributions of input categories (Electricity, Compressed Air, Paper, Plastic, and Solid Waste) to the environmental impacts of the homewear set during the cutting process.

contributor at 98.1 %, due to the land required to grow materials like wood pulp, which impacts land availability and biodiversity. For ozone layer depletion, paper is the biggest contributor at 61.5 %, primarily due to chemicals such as chlorine bleach used in its production. Solid waste also contributes significantly at 25.5 %, from materials that release ozone-depleting substances. In water consumption, paper leads with 56.4 %, reflecting the high water use in its production, particularly during pulp processing and bleaching. Plastic contributes 27.3 %, showing that its production also requires considerable water.

Overall, the perforated paper used to ensure suction and fixation of knits - essential for proper blade operation - is the main contributor to environmental impacts in the cutting process, particularly in land use, freshwater eutrophication, and ozone layer depletion. Solid waste also has a significant impact, especially in climate change and freshwater ecotoxicity. Reducing paper use and finding sustainable alternatives to plastic can help lower the environmental footprint. Potential alternatives include reusing permeable mesh remnants, using paper with lower grammage, or producing functional knits from cutting waste to replace the paper.

3.3. Comparative assessment of homewear sets: regenerative and recycled vs. conventional cotton

Table 2 presents a comparative assessment of the environmental impacts associated with the homewear set produced by the Portuguese textile company, using regenerative cotton and recycled cellulosic fibers, versus a comparable product manufactured from 100 % conventional cotton with globally sourced dyed knit. The regenerative cotton was cultivated on a farm adopting regenerative agricultural practices, where the annual carbon footprint was quantified, accounting for carbon sequestration by both soil and native vegetation. To reflect the influence of these practices, the environmental performance of the regenerative and recycled cotton homewear set is evaluated under two distinct scenarios: one that excludes and another that includes the carbon offsetting potential resulting from sequestration during cotton cultivation.

The comparative LCA shows that the homewear set produced by the Portuguese manufacturer, using regenerative cotton and recycled cellulosic fibres, consistently presents lower environmental impacts across all assessed categories compared to a similar product made from conventional cotton. These findings are consistent with results reported in the literature (Munasinghe et al., 2021; Sandin and Peters, 2018; Vitale et al., 2025). These reductions stem from multiple factors: the incorporation of post-industrial cellulosic textile waste, supporting circularity; the use of cotton grown under regenerative agricultural practices; the elimination of the dyeing stage; a simplified and more localized value chain; enhanced energy efficiency; and optimized production processes.

Focusing on the climate change impact, the regenerative cotton and recycled cellulosic fiber homewear set presents a GWP of 5.50 kg CO_2 eq/FU when carbon sequestration is not considered - representing a 53.9 % reduction relative to the conventional cotton set (11.95 kg CO_2 eq/FU). When carbon offsetting from soil and vegetation sequestration during cotton cultivation is included, the impact further decreases to 2.21 kg CO_2 eq/FU, corresponding to an 81.5 % reduction. The application of carbon offsetting leads to a 60.0 % reduction in the climate change impact of the regenerative and recycled set compared to the non-offset scenario. This aligns with Pires et al. (2024), who showed that accounting for biogenic carbon storage and emission timing can significantly reduce climate impacts of cotton-based products.

In the freshwater ecotoxicity category, the homewear set produced by the Portuguese manufacturer using regenerative cotton and recycled cellulosic fibres exhibits an impact of 0.22 kg 1,4-DCB eq/FU, representing a 74.1 % reduction compared to the conventional product (0.84

Table 2
Potential environmental impacts of homewear sets (functional unit, FU) made with regenerative cotton and recycled pre-consumer cellulose waste versus conventional cotton, considering scenarios with and without carbon sequestration.

Environmental impact category	Similar homewear set	Regenerative & Recycled Set		% Reduction	
		Without offsetting	With offsetting	Without offsetting	With offsetting
Climate Change, kg CO_2 eq/FU	11.95	5.50	2.21	53.9 %	81.5 %
Freshwater Ecotoxicity, kg 1,4-DCB eq/FU	0.84	0.22	0.22	74.1 %	74.1 %
NRER (Fossil), kg oil eq/FU	3.31	1.78	1.78	47.0 %	46.3 %
Freshwater Eutrophication, kg P eq/FU	7.84×10^{-3}	1.47×10^{-3}	1.47×10^{-3}	81.2 %	81.2 %
Land use, m^2·a crop eq/FU	6.90	1.85	1.85	73.2 %	73.2 %
Ozone Layer Depletion, kg CFC-11 eq/FU	9.08×10^{-5}	1.37×10^{-5}	1.37×10^{-5}	84.9 %	84.9 %
Water Consumption, m^3/FU	4.66	1.54	1.54	66.9 %	66.9 %

NRER = Non-renewable Energy Resources (Fossil).

kg 1,4-DCB eq/FU). In the non-renewable energy resources (fossil) category, its impact is 1.78 kg oil eq, markedly lower than that of the conventional counterpart (3.31 kg oil eq/FU). Regarding freshwater eutrophication, the regenerative and recycled set demonstrates a substantial improvement, with an impact of 1.47×10^{-3} kg P eq/FU, corresponding to an 81.2 % reduction relative to the conventional product (7.84×10^{-3} kg P eq/FU).

Land use impact is also significantly reduced, with the regenerative and recycled set requiring 1.85 m^2·a crop eq compared to 6.90 m^2·a crop eq for the conventional option. For ozone layer depletion, the impact is 1.37×10^{-5} kg CFC-11 eq/FU - 84.9 % lower than that of the comparable product (9.08×10^{-5} kg CFC-11 eq/FU). Finally, in terms of water consumption, the regenerative cotton and recycled cellulosic fibre homewear set uses 1.54 m^3/FU, reflecting a 66.9 % reduction when compared to the conventional product's consumption of 4.66 m^3/FU.

The reductions in environmental impacts observed for the homewear set produced by the Portuguese manufacturer using regenerative cotton and recycled cellulosic fibres can be attributed to a range of sustainable practices integrated throughout its production. The use of cotton sourced from regenerative agriculture contributes to a decreased carbon footprint by enhancing carbon sequestration during cultivation. The notably lower water consumption associated with this homewear set reflects the adoption of water-efficient production techniques. Reductions in freshwater ecotoxicity and eutrophication primarily result from the elimination of dyeing processes and the implementation of regenerative agricultural practices, which reduce the use of chemical inputs.

Incorporating 30 % pre-consumer cellulose waste into the product composition decreases energy demand and reliance on virgin materials, thereby contributing to lower land use and abiotic resource depletion. Furthermore, the use of renewable energy sources within the manufacturing process supports the overall reduction of environmental impacts. The observed decrease in ozone depletion potential is also consistent with the sustainable characteristics of the production system.

Despite these improvements, opportunities remain to further reduce fossil energy consumption and minimize ecotoxicity impacts. Continued process optimization, alongside the exploration of alternative materials and expanded use of renewable energy, could further enhance the environmental performance of the homewear set produced by the Portuguese manufacturer.

3.4. Sensitivity analysis

To investigate potential environmental improvements, a sensitivity analysis was performed by substituting the energy sources employed in the foreground processes - those directly controlled by the manufacturer of the regenerative and recycled cotton homewear set - with renewable alternatives. Four energy configurations were analyzed and compared (Table 3).

- **Baseline scenario:** Represents the current energy mix utilized by the homewear set manufacturer, comprising:
  o Grid electricity (78.2 %).
    oOn-site photovoltaic generation (21.8 %, from the UPAC).
    oBiomass (wood pellets) — currently used in the ironing stage.
    oNatural gas — used in the knit finishing process, which remains dependent on this energy source.
- **Scenario 1 (Solar electricity + biomass):** Grid electricity is fully replaced by solar power, and natural gas is substituted with hardwood chip biomass.
- **Scenario 2 (Hydroelectricity + biomass):** Grid electricity is replaced by hydroelectric power, and natural gas is substituted with hardwood chip biomass.
- **Scenario 3 (Wind electricity + biomass):** Grid electricity is replaced by wind power, and natural gas is substituted with hardwood chip biomass.

Table 3
Potential environmental impacts of the baseline and alternative energy scenarios, based on the electricity and thermal energy sources used in the foreground processes for the manufacture of the homewear set (FU).

Environmental impact category	Baseline Scenario	Scenario 1	Scenario 2	Scenario 3
Climate Change, kg CO_2 eq/FU	5.50	5.20	5.30	5.14
Freshwater Ecotoxicity, kg 1,4-DCB eq/FU	0.22	0.231	0.218	0.224
NRER (Fossil), kg oil eq/FU	1.78	1.37	1.39	1.36
Freshwater Eutrophication, kg P eq/FU	1.47×10^{-3}	1.52×10^{-3}	1.51×10^{-3}	1.48×10^{-3}
Land use, m^2·a crop eq/FU	1.85	2.544	2.520	2.517
Ozone Layer Depletion, kg CFC-11 eq/FU	1.37×10^{-5}	1.425×10^{-5}	1.429×10^{-5}	1.421×10^{-5}
Water Consumption, m^3/FU	1.54	1.539	1.564	1.536

In all scenarios, the use of wood pellets for steam generation during the ironing stage remains unchanged. These alternative configurations were designed to evaluate the environmental benefits of increasing renewable energy integration, particularly by extending biomass use to the knit finishing stage currently reliant on natural gas.

The sensitivity analysis demonstrated that all renewable energy scenarios contributed to reductions in climate change impacts relative to the baseline, with decreases ranging from 3.6 % to 6.7 %. The scenario combining wind electricity and biomass (Scenario 3) achieved the greatest reduction. Substantial decreases in fossil resource depletion were observed across all alternatives, ranging from 21.9 % to 23.6 %. Conversely, freshwater ecotoxicity and eutrophication showed slight increases of up to 5.0 % and 3.4 %, respectively. Land use impacts increased by over 36.1 % in all renewable scenarios, reflecting the additional land requirements associated with renewable energy infrastructure and the cultivation of bioenergy crops (Clarke et al., 2019). Ozone layer depletion rose marginally by approximately 3.7 %–4.3 %, while water consumption remained essentially unchanged.

Overall, substituting grid electricity and natural gas with renewable electricity and biomass presents clear benefits in mitigating climate change and reducing fossil resource depletion. However, these benefits come with trade-offs, including increased land use and minor elevations in other environmental impact categories. Among the alternatives assessed, the combination of wind electricity and biomass demonstrated the most favorable balance, achieving the greatest reductions in both climate change impacts and fossil energy consumption.

Given these results, companies seeking to lower their environmental footprint can consider integrating renewable energy sources such as wind and solar power into their energy strategies. Adoption pathways include power purchase agreements (PPAs) with renewable energy providers, direct investments in renewable projects, and installation of on-site generation systems where feasible. Additionally, procurement of renewable energy certificates (e.g., Guarantees of Origin) allows companies to indirectly support renewable energy production. Incorporating wind and solar energy enables companies to significantly reduce greenhouse gas emissions, decrease reliance on fossil fuels, and align their operations with global sustainability and climate targets.

3.5. Recommendations for value chain improvements in sustainable textile manufacturing

Based on the LCA of the homewear set incorporating regenerative cotton and recycled cellulosic fibers, several targeted recommendations have been identified to reduce environmental impacts across the value chain. These recommendations focus on enhancing sustainability through operational improvements and strategic decision-making.

3.5.1. Cultivation

The Portuguese textile company should continue sourcing cotton from sustainable farming systems, with a strategic focus on further optimizing operations. Key priorities include enhancing energy efficiency, minimizing material and water use, and reducing reliance on chemical inputs. Supporting regenerative practices - such as cover cropping and reduced tillage - can deliver additional environmental benefits by improving soil health, increasing carbon sequestration, and enhancing biodiversity.

3.5.2. Spinning

Given the high energy demand of the spinning phase, Portuguese textile company is encouraged to collaborate with its yarn suppliers to transition toward low-carbon energy sources. Investment in on-site renewable energy systems (e.g., photovoltaic panels), coupled with sourcing electricity from certified green suppliers, would significantly reduce the carbon footprint. In parallel, energy efficiency measures should be expanded to lower overall energy consumption.

3.5.3. Knit finishing

Environmental performance in knit finishing processes can be improved by adopting chemicals with higher fixation rates and sourcing them from renewable or recycled feedstocks. Integrating renewable energy sources - such as biomass or biomethane - can reduce dependence on fossil fuels like natural gas. Additionally, process optimization, including more efficient use of chemical baths and heat recovery systems, should be explored to further reduce inputs and emissions.

3.5.4. Cutting

The environmental burden of the cutting stage is driven largely by the consumption of single-use paper. To mitigate this impact, paper could be partially or fully replaced with reusable mesh substrates of equivalent performance, and closed-loop approaches could be implemented whereby cutting off-cuts are re-integrated into new knit production. Additional reductions in environmental impact may be achieved by substituting conventional plastic components with bio-based or recycled alternatives, optimizing energy efficiency within cutting operations, and strengthening on-site waste segregation and recovery protocols.

3.5.5. Packaging

Although less impactful than earlier stages, the packaging phase presents meaningful opportunities for environmental improvement. Material selection should prioritize recyclability, biodegradability, and minimal use of resources. Redesigning packaging to reduce material use - while maintaining product protection and logistics efficiency - can lower both environmental and economic costs. Using recycled cardboard and paper, or substituting problematic materials like plastic film, aligns with circular economy principles and enhances sustainability across the product lifecycle.

3.6. Implications for policy, industry innovation, and consumer engagement

The LCA results of the homewear set incorporating regenerative cotton and recycled cellulosic fibers reveal critical hotspots in cotton cultivation, spinning, and finishing—offering valuable insights for broader regulatory, industrial, and consumer-focused strategies.

3.6.1. Policy and regulatory relevance

The study underscores the importance of supporting agricultural policies that incentivize regenerative practices, such as carbon farming and efficient water use. The findings can inform regulatory frameworks aiming to promote sustainable sourcing under the EU Strategy for Sustainable and Circular Textiles (European Commission, 2022a) and related initiatives focused on product environmental performance and traceability.

3.6.2. Driving innovation in the textile sector

The results encourage investment in sustainable innovation across the textile supply chain. These include adopting low-impact energy systems, developing bio-based chemicals, and fostering supply chain collaborations that prioritize transparency and resource efficiency. Companies like Impetus can act as catalysts by integrating these practices and sharing best practices across the sector.

3.6.3. Consumer engagement and market dynamics

With a 53.9 % reduction in climate change impact and significant reductions in water use (66.9 %) compared to conventional cotton products, the homewear set incorporating regenerative cotton and recycled cellulosic fibers exemplifies how sustainability and performance can co-exist. Transparent communication of these environmental benefits - supported by robust, third-party certifications - can foster consumer trust and align purchasing decisions with sustainability goals.

3.6.4. Digital Product Passport and traceability

The forthcoming implementation of the Digital Product Passport (Legardeur and Ospital, 2024) under the Eco-design for Sustainable Products Regulation (European Commission, 2024) presents a key opportunity to enhance transparency and traceability across textile value chains. The DPP will provide standardized, verifiable information about the environmental performance and material composition of textile products, accessible throughout their lifecycle.

For companies like Impetus, integrating environmental data - such as LCA results, fiber origin, chemical use, and end-of-life recommendations - into the DPP framework can support regulatory compliance, enable circular business models, and reinforce consumer trust. Moreover, it can facilitate sustainable procurement decisions by retailers and public institutions and encourage better sorting, reuse, and recycling at the product's end of life.

3.6.5. Evaluating sustainable fiber options

While regenerative cotton presents compelling advantages - especially in soil regeneration and carbon sequestration - it is essential to weigh these benefits against other sustainable alternatives.

- Recycled Cotton: Avoids the environmental burdens of cultivation and can dramatically reduce water and GHG impacts. However, limitations in fiber quality often necessitate blending, affecting durability and product design.
- Organic Cotton: Reduces chemical use and enhances ecosystem health but may have trade-offs in land and water use, depending on local yield performance and farming practices.

Each option carries context-dependent benefits and limitations. A systems-level approach that combines regenerative, recycled, and organic fibers - tailored to regional capabilities and product-specific needs - can optimize the environmental outcomes and resilience of textile value chains.

4. Conclusions

This study applied the LCA methodology to evaluate the environmental performance of a homewear set produced from a yarn blend containing 30 % pre-consumer cellulosic textile waste and 70 % cotton cultivated using regenerative agricultural practices. Results were benchmarked against a functionally equivalent product made entirely of conventional cotton and dyed using traditional methods.

The findings demonstrate clear environmental benefits of combining regenerative cotton with recycled textile inputs. Compared to the conventional alternative, the regenerative–recycled set achieved reductions across all assessed impact categories. Climate change impacts decreased by 53.9 %, reaching 81.5 % when accounting for carbon sequestration in cotton cultivation. Water consumption was reduced by over two-thirds (from 4.7 m^3/FU to 1.5 m^3/FU), while land use impacts also decreased. These improvements were mainly attributed to regenerative farming practices, the incorporation of post-industrial textile waste, elimination of the dyeing process, and partial reliance on renewable electricity.

Despite these gains, cotton cultivation remained the most environmentally burdensome life cycle stage, contributing 32.0 % to climate change, 92.5 % to water consumption, and 33.9 % to land occupation. While regenerative agriculture mitigates some of these impacts through carbon sequestration, irrigation demands and land use pressures continue to pose significant challenges. Other life cycle stages, including knitting, spinning, and finishing, also contribute notably to the environmental footprint due to electricity demand, chemical inputs, and fossil fuel consumption. The cutting stage impacts land use, eutrophication, and water consumption, mainly due to paper usage.

Sensitivity analysis confirmed the potential benefits of substituting conventional grid electricity and natural gas with renewable sources such as wind power and biomass. All renewable energy scenarios evaluated resulted in significant reductions in climate change impacts and fossil resource depletion. However, these improvements come with trade-offs, including increased land use and slight rises in freshwater ecotoxicity and eutrophication. Among the scenarios evaluated, the combination of wind electricity and biomass emerged as the most effective strategy for minimizing climate change impacts while reducing fossil energy dependence. These results underscore the importance of carefully balancing trade-offs in the transition to renewable energy and highlight the need for integrated, systems-level approaches to enhance sustainability in textile production.

Several limitations of this study should be acknowledged. First, the system boundaries excluded the use and end-of-life stages, which can significantly influence overall environmental impacts. Second, only a subset of impact categories was assessed, while others – such as human toxicity, biodiversity loss, and microplastics release – were not considered, and their inclusion could provide further insights. Finally, the analysis focused solely on environmental aspects; complementary assessments, such as social life cycle assessment (S-LCA) and life cycle costing (LCC), are needed to capture the full spectrum of sustainability dimensions.

Overall, substituting conventional cotton with regenerative cotton and recycled fibers proved to be an effective strategy to reduce greenhouse gas emissions, water consumption, and resource intensity in textile production without compromising product quality. Avoiding chemical-intensive dyeing and integrating renewable energy sources further enhance sustainability performance. Nevertheless, certain categories – particularly land use and ecotoxicity – highlight remaining opportunities for improvement through lower-impact chemical inputs and optimized resource management. Policy measures that support sustainable farming practices, incentivize cleaner industrial operations, and promote transparent communication of environmental benefits can accelerate progress and engage consumers.

Future research should extend system boundaries to include end-of-life scenarios, assess a broader range of environmental categories, and integrate social and economic assessments alongside LCA. Such work would provide a more comprehensive evaluation of regenerative and circular textile systems, supporting informed decision-making by industry stakeholders, policymakers, and consumers.

CRediT authorship contribution statement

Teresa M. Mata: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Inês Ruge:** Writing – original draft, Validation, Investigation, Data curation. **Hernâni Dias:** Validation, Project administration, Funding acquisition, Data curation. **Isabel Batista:** Validation, Project administration, Funding acquisition, Data curation. **Tércio Pinto:** Validation, Project administration, Funding acquisition, Data curation. **Ricardo Figueiredo:** Validation, Project administration, Funding acquisition, Data curation. **Alberto Figueiredo:** Validation, Project administration, Funding acquisition, Data curation. **António A. Martins:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146738.

Data availability

Data will be made available on request.

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