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RESEARCH ARTICLE

The Journey of a Norwegian T-shirt: A Case Study of Fibre Material in the Clothing System

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Abstract

Current EU textile policy efforts largely focus on post-consumer waste collection and end-of-life management while pre-consumer losses remain insufficiently addressed. In addition, many textile life cycle assessments (LCAs) and material flow studies apply single-lifecycle boundaries with conventional allocation approaches and consumer-country perspectives. This limits the understanding of the potential for fibre retention across consecutive lifecycles and global value chains.

This study quantifies fibre flows and environmental performance of a cotton t-shirt across two consecutive lifecycles (loops) by combining material flow model with LCA for five impact categories (global warming, freshwater eutrophication and ecotoxicity, water consumption and land use). The model represents manufacturing in Bangladesh and use and end-of-life management in Norway as EU-relevant benchmark context.

Results show that, under current conditions, a maximum of 17% of the initial fibre input could be mechanically recycled and reutilized into a new T-shirt. It is also revealed that fibre losses occur predominantly in upstream operations: an estimated 44% of material was lost during the manufacturing stages. Scenarios analysis demonstrated that recycling pre-consumer waste could increase material recovery to up to 44%, while improving process efficiency (reducing waste generation) in yarn, wet processing and apparel production could reduce the global warming by 10% and other impacts by 20-25%. These findings suggest that meeting EU circular textile ambitions requires prioritizing upstream material efficiency and pre-consumer waste management, supported by coordinated action across policymakers, brands and manufacturers along the value chain.

Keywords Textiles · Clothing Industry · Pre-consumer Waste · Recycling · Life Cycle Assessment · Material Flow Modelling · Eco-design · Design for Circularity · Waste Minimization · Manufacturing

1. Introduction

The fashion industry operates within a global and still largely linear value chain. In 2022, Asia was the world's leading producing region of textiles and clothing, representing around 71%, while Europe's share was only 21% (World Trade Organization, 2022). Europe is the world's largest importer of apparel (CBI, Government of Netherlands, 2024), and EU citizens on average consumed 19 kg/capita of clothing and household textiles in 2022. As a result the textile sector is the EU's third highest contributor to water and land use impacts and the fifth largest contributor to greenhouse gas (GHG) emissions and raw material use (European Environment Agency, 2025b). In the EU alone, 6.94 million tonnes (16 kg/capita) of clothing and footwear waste were

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generated in 2022 (European Environment Agency, 2025a), of which only 1% of textile materials are recycled into new garments while 73% are incinerated or landfilled (Ellen MacArthur Foundation, 2017). In contrast, under the Ecodesign for Sustainable Products Regulation (ESPR), the EU requires textile products placed on the EU market to be recyclable and largely made of recyclable fibres by 2030 (European Commission, 2024). Some member states have already set concrete targets, for example, the Netherlands requires 50% of the textiles to be recycled by 2030, with at least 33% directed to fibre-fibre recycling (Ellen MacArthur Foundation, 2024). Meeting these ambitions on a short timeline requires pinpointing waste hotspots across the global value chain and deploying targeted strategies.

To examine the role of recycling in enabling material circularity and implications for upcoming EU policies, this study selects Norway as a representative case. Norway's implementation of EU waste and product regulations through the European Economic Area (EEA), its high consumption of garments and well-developed waste management infrastructure, mirrors the practices in many Western European countries. The textile consumption in Norway doubled from 50 000 (12 kg/capita) to 100 000 tonnes (18 kg/capita) between 1988 and 2022, with around half of these products (by value) imported from Asian countries, mainly China, Bangladesh, India and Vietnam (Simas & Arega, 2025). Moreover, in 2022, approximately 60% of the used textiles (51 000 tonnes) were discarded as mixed household waste, while the remainder was collected separately, primarily by charitable organizations (Mora-Sojo et al., 2023; Simas & Arega, 2025). Of these separately collected textiles only 1-3% remained in Norway. The majority is exported for further processing, where final end-of-life (EoL) treatment may involve reuse, recycling, incineration or landfilling. Unfortunately, the actual fate of exported textiles remains highly uncertain (Simas & Arega, 2025). This study adopts these empirical estimates, as these shares constitute a critical parameter for assessing material recovery potential.

Furthermore, this study uses the cotton t-shirt as a case. It provides a useful benchmark for material recovery performance, as it is a relatively simple garment to recycle. The recycling performance decreases when garment complexity increases, due to the use of added details such as zippers, buttons or prints.

Research on textile circularity has largely focused on post-consumer waste in Europe, examining how different EoL scenarios influence material flows and environmental performance of a clothing system using combined material flow analysis (MFA) and life cycle assessment (LCA) (Dahlbo et al., 2021; Koligkioni et al., 2018; Mora-Sojo et al., 2023; Schmidt et al., 2016). One key limitation of these studies is that they do not capture the entire textile value chain. In most cases, the system boundaries begin once ready-made garments have already arrived in consumer countries and end when discarded garments are exported for further processing. As a consequence, little is known about the fibre flows during upstream production stages, before garments reach the consumer market, even though evidence from manufacturing contexts indicates that pre-consumer waste and excess inventory are substantial (Akter et al., 2022). Similarly, the treatment of the discarded garments after export remains largely untouched in current LCA studies. As a result, the true potential for fibre recovery across the entire system remains unidentified and unquantified. This has large implications for policy making. Current policy discussions still emphasize post-consumer collection and end-of-life treatment inside Europe, as the evidence base for prioritizing interventions outside Europe is lacking.

Most existing LCA studies on clothing are confined to a single lifecycle. This hinders an in-depth assessment of circular strategies that involve repeated material use across consecutive lifecycles. Nevertheless, single lifecycle studies provide detailed life cycle inventories, identify impact hotspots across the value chain and suggest impact mitigation pathways. For example, Sandin et al., (2019) identify wet processing and yarn production as the most impact-intensive stages for a cotton t-shirt, while nearly half of the t-shirt's impact can be reduced if it is used twice as long before disposal.

A major methodological challenge in LCA is the selection of allocation approaches for product systems with recycling process in it, particularly the choice between the cut-off and substitution approach. Under the cut-off approach, recycling is modelled as an upstream process with the assumption that materials entering recycling process carry no embedded burdens (Sandin & Peters, 2018; Sun et al., 2024). In contrast, the substitution approach expands the system boundary to include credits for avoided primary material production associated with the use of recycled output. However, this approach does not incentivize the use of recycled material in the upstream production (Battery Pass consortium, 2023). While the EU seeks both high recyclability and high recycled content in products, neither approach fully combines the burden of discarded garments from the previous lifecycle with the benefits of using recycled inputs at the production stage.

To tackle these gaps, this study addresses the following research questions: (1) What is the maximum share of recycled fibre that can be recovered from a cotton t-shirt and how are the fibre losses distributed between pre- and post-consumer stages? (2) Can a two-loop (multicycling) system be used to evaluate the environmental effects of fibre recovery while avoiding conventional allocation assumptions? (3) How do the material recovery and environmental impacts change when varying the key parameters (e.g. collection rate, process losses and energy source)?

Based on study's results, we will identify measures that most effectively improve fibre recovery and environmental performance in the textile value chain and their implications for key actors (policymakers, brands and manufacturers) in the EU.

2. Methodology

This study was structured in three steps. First, the fibre flows were analyzed across the value chain of a t-shirt and its subsequent journey into a second t-shirt. Second, an LCA was carried out to estimate the potential environmental benefits that the recycling product system could achieve. Finally, four scenarios, higher separate collection, reducing and recycling preconsumer waste and a greener energy mix, were developed to explore the implications of potential policy interventions in textile waste management. This section outlines the overall analytical framework, while section 3 presents a detailed description of the subprocesses, parameter values and assumptions used in different scenarios.

2.1. Scope

A product system was developed in which t-shirt fibre material circulated through two consecutive lifecycles (two loops). In this system, the first t-shirt was produced entirely from primary cotton. After being discarded, it was separately collected, sorted and mechanically recycled, with the recovered fibre subsequently used in the production of a new t-shirt in the second loop. Each t-shirt was assumed to weigh 110 g and be white without any prints or trimmings, ensuring consistency across lifecycles.

The spatial boundary covered the global supply chain through which t-shirts are produced, consumed and treated at EoL as summarized in Figure 1. All production stages were modelled in Bangladesh, reflecting both its leading role as a global exporter of t-shirts (OEC, 2023) and the availability of quantitative studies detailing material flows across manufacturing stages.

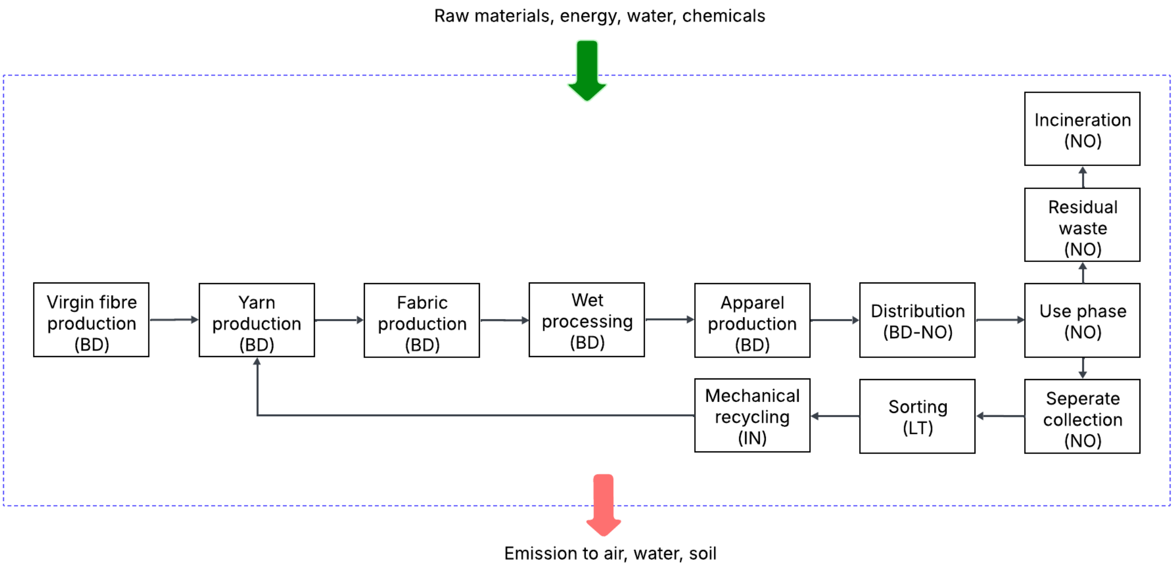


Figure 1. System boundary of the study including the processes involved in the product system and their respective geographical locations. BD= Bangladesh, NO= Norway, LT= Lithuania, IN= India. Consumer transport related to retail purchases is excluded.

The use phase and waste management processes were modelled for Norway, where discarded t-shirts entered residual waste and separate collection streams. After pre-sorting in Norway, the t-shirt was assumed to be exported to Lithuania for detailed sorting, consistent with current practices where most collected textiles in Norway are sent to Eastern European countries such as Poland, Lithuania, Estonia, and Bulgaria (Watson et al., 2020). Lithuania was selected because detailed material flows and lifecycle inventory (LCI) data are available from a sorting facility in Vilnius, Lithuania (Nørup et al., 2019). From there, the recyclable fraction of the t-shirt was assumed to be exported to India for mechanical recycling, reflecting current trade patterns (Nørup et al., 2019). This product system here does not mirror any specific existing supply chain, but it reflects the global trade patterns in the textile industry for Norway and the EU.

In addition to secondary data, the analysis was complemented by the lead author's professional experience in textile manufacturing and sourcing operation. These insights were used to interpret the factory-level implications of the results.

Numerous studies have already established that reuse offers the most significant environmental benefits compared to other end-of-life (EoL) options (Dahlbo et al., 2017; Koligkioni et al., 2018; Schmidt et al., 2016). However, reuse is facing practical limitations. A substantial share of separately collected textiles cannot be resold within Europe because of poor quality and limited demand for second-hand clothes. Instead they are incinerated, landfilled or exported to Asian and African countries (European Environment Agency, 2024; Šajn, 2022). This volume of poor-quality textiles is expected to grow following the EU's requirement for separate textile collection by 2025 (European Environment Agency, 2024). Against this backdrop, the reuse of discarded clothing is intentionally excluded from the scope of this study, instead, it focuses on assessing the potential benefits that recycling can bring to the system.

2.2. Fibre flows in the system

The reference product was a white, short-sleeve cotton t-shirt weighing 110 g (size Medium with light weight fabric) and consumed in Norway. Following Brunner & Rechberger, (2004), it was assumed that all the processes in the supply chain are balanced: the total mass of inflows into any process equals the total mass of outflows plus the stock changes within the process. However, the stock changes were set to zero due to the uncertainty and lack of data on clothing accumulation. Table 1 summarizes the parameters and data sources used for quantifying the flows. Quantification begins from the t-shirt mass (110 g) and propagates through the upstream processes (rows above the use phase) and downstream processes (rows below the use phase) using process-specific waste percentages.

Material recovery was calculated as the share of the fibre recovered through mechanical recycling at the end of the first life cycle relative to the initial fibre input required to produce one t-shirt, as shown in Eq. 1.

$$\textit{Material recovery (\%)} = \frac{m_{\textit{recovered fibre at end of loop}}}{m_{\textit{initial fibre input}}} \times 100 \qquad (1)$$

Table 1. Summary of parameters and their values used in system quantification.

Process	Parameter considered	Parameter value	Reference
Yarn production	Process loss%	25%	(Akter et al., 2022; Alam et al., 2023)
Fabric production	Process loss%	2%	Same as above
Wet processing	Process loss%	12%	Same as above
Apparel production	Process loss%	13%	Same as above
Distribution	Process loss%	1%	(Sandin et al., 2019)
Use phase	Wt. of the t-shirt	110 g	(Sandin et al., 2019)
Separate collection & pre-sorting	Collection rate% & Reject rate%	40%, 1.2%	(Mora-Sojo et al., 2023; Watson et al., 2020)
Sorting	Reject rate%	6.1%	(Nørup et al., 2019)
Mechanical recycling	Process loss%	20%	(Schmidt et al., 2016)

2.3. Life cycle assessment

The LCA was performed in accordance with ISO 14040/14044 (ISO, 2006) comprising four main phases. The goal and scope definition defines the scope, system boundary as described in section 2.1, the functional unit and the impact categories. The inventory analysis (LCI) identifies the material and energy inputs and outputs across processes within the system boundary. Section 3 provides a brief description of unit processes along with modelling assumptions and data sources. Life cycle impact assessment (LCIA) and interpretation are presented in the results and discussion section.

In this study, we have set the functional unit as ‘two consecutive lifecyles of a t-shirt’. This cumulative approach allows both burdens associated with recycling in the first loop and benefits of integration of recycled materials in the second loop to be captured within the same analytical framework. It avoids relying on allocation assumptions. By contrast, in a conventional single-lifecycle LCAs, recycling is typically handled in a way that separate the burdens of discarded waste from the benefits of recycled material use. Therefore, the cumulative approach provides a more transparent representation of material circularity and resource efficiency across multiple lifecycles.

LCA was performed in ‘SimaPro’ using ‘Ecoinvent 3.10’ datasets. LCIA was conducted using ReCipe 2016 Midpoint (H) method (version 1.09) and results are reported using characterization factors only, without external normalization or weighting. Five midpoint impact categories were assessed to provide a broad view of the environmental burdens.

- global warming potential (kg CO_2-eq.),
- freshwater eutrophication (kg P-eq.),
- freshwater ecotoxicity (kg 1,4-DCB),
- land use (m^2a crop-eq.), and
- water consumption (m^3).

The impact categories were selected for their direct relevance to cotton cultivation, fertilizer application, and energy and resource usage in the t-shirt (textile) manufacturing processes (Sandin & Peters, 2018).

To facilitate comparison across impact categories with different units and magnitudes, the results presented in Figure 3 were internally normalized. For each impact category, absolute life cycle impact results were scaled relative to the maximum value across the assessed scenarios which was set to 100%.

3. Model description and scenario development

3.1. Production and distribution

The production begins with cotton seed cultivation and harvesting, followed by ginning and bailing. Yarn production involves opening the bales from harvesting, carding and combing to remove the short fibres and impurities to produce high quality yarn. T-shirts are made from knitted fabric, produced on circular knitting machines that interloop yarns to create fabric. Wet processing includes pre-treatment, dyeing and finishing. Apparel production involves cutting finished fabric into different body parts, sewing these parts into garments, and then ironing and packaging the finished t-shirt.

Material losses occur at every stage: damaged or quality-rejected yarn and fabrics, short fibres in spinning and knitting, faulty and unevenly dyed fabric in wet processing and fabric offcuts in garment cutting. Fibre inputs at the process-level were parameterized using data from Alam et al., (2023) and Akter et al., (2022) while the energy and auxiliary inputs were derived from Sandin et al., (2019). The electricity usage in production was modelled using Bangladesh’s national grid mix, which is predominantly fossil-based (natural gas, oil and coal). After production, garments were assumed to be shipped from Bangladesh to Norway by boat.

3.2. Use and end-of-life stages

Based on Sandin et al., (2019), a t-shirt was assumed to be used 30 times before disposal, with washing after every second uses (Granello et al., 2015; Gwozdz et al., 2013). Consumer transport to and from retail stores was excluded.

At EoL, the modelling residual included the collection and transport to incineration facilities based on Mora-Sojo et al., (2023). For modelling of the separate collection, a transport distance of 150 km by lorry from the collection point to the pre-sorting facilities, an electricity use of 70 kWh per tonne of pre-sorted textiles and a garment rejection rate of 1.2% as waste were used (Schmidt et al., 2016; Watson et al., 2020).

After pre-sorting, t-shirt were sent to a large-scale sorting centre in Lithuania, where they were segregated into reusable, recyclable and waste categories. According to Nørup et al., (2019), in this kind of sorting centre 6% of sorted garments was waste, with the remainder (94%) suitable for reuse or recycling. For this study, all reusable items were assumed to be recyclable.

Finally, garments were exported to India for mechanical recycling. Here garments are shredded into small pieces, and further processed into loose recycled fibres using a rotating drum (Schmidt et al., 2016). Mechanical recycling represents the most mature and commercially deployed fibre-to-fibre recycling pathway for cotton garments, whereas chemical recycling is mainly used for synthetic fibres or mixtures of synthetic and natural fibre. Chemical recycling is still at a pilot stage (Dahlbom & Martvall, 2025), which leads to unavailable and uncertain life cycle inventory data (Sandin & Peters, 2018). Detailed modelling of the individual processes is included in the Appendix.

3.3. Scenario development

Single intervention scenarios were developed from the baseline two loop product system, applying the principle of ‘ceteris paribus’, where one system parameter is altered while others remain constant (Hausman, 2008). Each scenario represented a plausible intervention in the textile waste management and industry practices, to make the textile value chain more sustainable and circular. Table 2 summarizes the key parameters used in each scenario.

- **Baseline**: The previously described two-loop, circular product system forms the baseline scenario.
- **Higher separate collection (HSC)**: In line with the EU Waste Framework Directive mandating separate collection of textile waste by January 1, 2025 (European commission, 2023), this scenario assumed a 90% collection rate. The remaining 10% still entered into residual waste stream due to contamination, e.g. dirty items, undergarments that recyclers do not accept (Norsk Tekstilgjenvinning, 2024).

Table 2. Key parameters and assumptions used in the scenario analysis.

Scenarios	Separate collection rate (%)	Pre-consumer process loss%	Pre-consumer waste recycling	Electricity mix used in production
Baseline	40%	Yarn production - 25%, Wet processing - 12%, Apparel production - 13%	No	Bangladesh national grid mix
Higher separate collection (HSC)	90%	Same as Baseline	Same as Baseline	Same as baseline
Pre-consumer waste minimization (PCWM)	Same as Baseline	Yarn production - 13%, Wet processing - 5%, Apparel production - 10%	Same as Baseline	Same as baseline
Pre-consumer waste recycling (PCWR)	Same as Baseline	Same as Baseline	Yes	Same as baseline
Green energy (GE)	Same as Baseline	Same as Baseline	Same as Baseline	Prospective low-carbon mix: 30% renewables (solar/wind/hydro) + 10% nuclear

- **Pre-consumer waste minimization (PCWM):** This scenario addressed the ESPR's objectives on resource efficiency and waste prevention (European Commission, 2024). It also reflected the best-practice efficiency observed in factories by Alam et al., (2023). In this scenario, process losses were reduced to 13% in yarn production, 5% in wet processing, and 10% in apparel production.
- **Pre-consumer waste recycling (PCWR)**: To achieve the ESPR's objective of increasing recycled content in textile products, this scenario increases the availability of recycled fibres. It assumed that production waste in Bangladesh is recycled rather than landfilled, reflecting recent initiatives to promote local recycling infrastructure. Such initiatives includes providing financial incentives for using locally recycled fibres in the production to reduce dependency on imported cotton, and building recycling infrastructure in collaboration with local and international partners such as Recover (Recover™, 2023), and the United Nations Industrial Development Organization (UNIDO) (SWITCH2CE, 2023) .
- **Green energy (GE)**: This scenario explores the effect of partial decarbonization of electricity use in manufacturing stages by replacing the current fossil-dominated Bangladesh grid with a electricity mix comprising 30% renewable sources (solar, wind, hydropower) and 10% nuclear. The selected electricity mix represents a long-term, policy and investment-driven pathway for a technically and environmentally sustainable energy system (Das et al., (2020)). The GE scenario also reflects some clothing brand's direct investments in renewable energy projects aimed at reducing scope-3 emissions.

3.4. Analyzing uncertainty

Although the PCWM scenario represents a best-practice setting based on observed ranges of process loss reported by Alam et al., (2023), we also conducted a deterministic bounding sensitivity analysis applying minimum and maximum values for the key parameters in the baseline scenario, as shown in Table 3. We assessed their effect on the estimated fibre recovery and environmental impacts relative to baseline scenario. Two bounding cases were evaluated: a low-loss case, where all selected loss parameters were set to their literature-based lower bounds, and a high-loss case, where all selected loss parameters were set to their upper bounds. This approach covers the extremes of the parameter ranges and thus may overstate combined variability. A probabilistic uncertainty analysis (e.g. Monte Carlo simulation) was not undertaken because empirical evidence on the underlying probability distributions and correlations among process-loss parameters is limited. Adopting arbitrary distributions would introduce additional uncertainty.

Table 3. Baseline scenario parameter values, and lower and upper bounds in the sensitivity analysis.

Process	Parameter input	Baseline	Lowest bound	Highest bound	Reference
Yarn production	Process loss%	25%	16%	35%	(Rahman & Uddin, 2022) & (Çelik et al., 2022)
Fabric production	Process loss%	2%	2%	5%	(Akter et al., 2022)
Wet processing	Process loss%	12%	5%	15%	(Alam et al., 2023)
Apparel production	Process loss%	13%	10%	20%	(Alam et al., 2023)
Separate collection & pre-sorting	Reject rate%	1.2%	1.2%	8%	(Millward-Hopkins et al., 2023)
Mechanical recycling	Process loss%	20%	5%	50%	(Esteve-Turrillas & de la Guardia, 2017) & (Anas et al., 2025)

4. Results

4.1. Magnitude of fibre flows

Figure 2 illustrates the flows of fibrous material in different forms (fibre, yarn, fabric, ready and discarded garments) in a circular system. In the first loop production began with 197 g of primary cotton fibre entering yarn production. Material losses occurred at every stage, with slightly over half of the pre-consumer waste in yarn production (49 g), and nearly a quarter in both wet processing (17 g) and apparel production (17 g). Losses in fabric production were minimal (3 g). Altogether, the pre-consumer wastes totalled 86 g, representing 44% of the initial raw material and 52% of the total waste across the value chain. Thus, a finished t-shirt embodies only 56% of the original cotton fibre input.

Once the t-shirt was put on the Norway market, a small portion (1 g) remained unsold at retail store. After the use phase, total post-consumer waste amounted to 78 g. Of this post-consumer waste, about 66 g entered the residual waste stream and was destined for incineration, 8 g was lost during recycling operations and the remaining 4 g was rejected as unsuitable for recycling during pre-sorting in Norway and subsequent sorting in Lithuania. By the end of the first life cycle, mechanical recycling recovered merely 33 g of fibre- equivalent to 17% of the initial input.

In the second loop, 33g of recycled fibre recovered from the first lifecycle was spun together with 165 g of primary fibre to meet the quality requirement, yielding the same total fibre input (197 g) for t-shirt production. The subsequent stages and associated material flows and losses mirrored those in the first loop. While the system diagram (Figure 2) suggests that additional loops are possible, mechanical recycling shortens the fibre length and reduces its quality, creating uncertainty about how many loops cotton fibres can realistically undergo. For this reason, the analysis is limited to the first two loops when evaluating both material flows and environmental impacts.

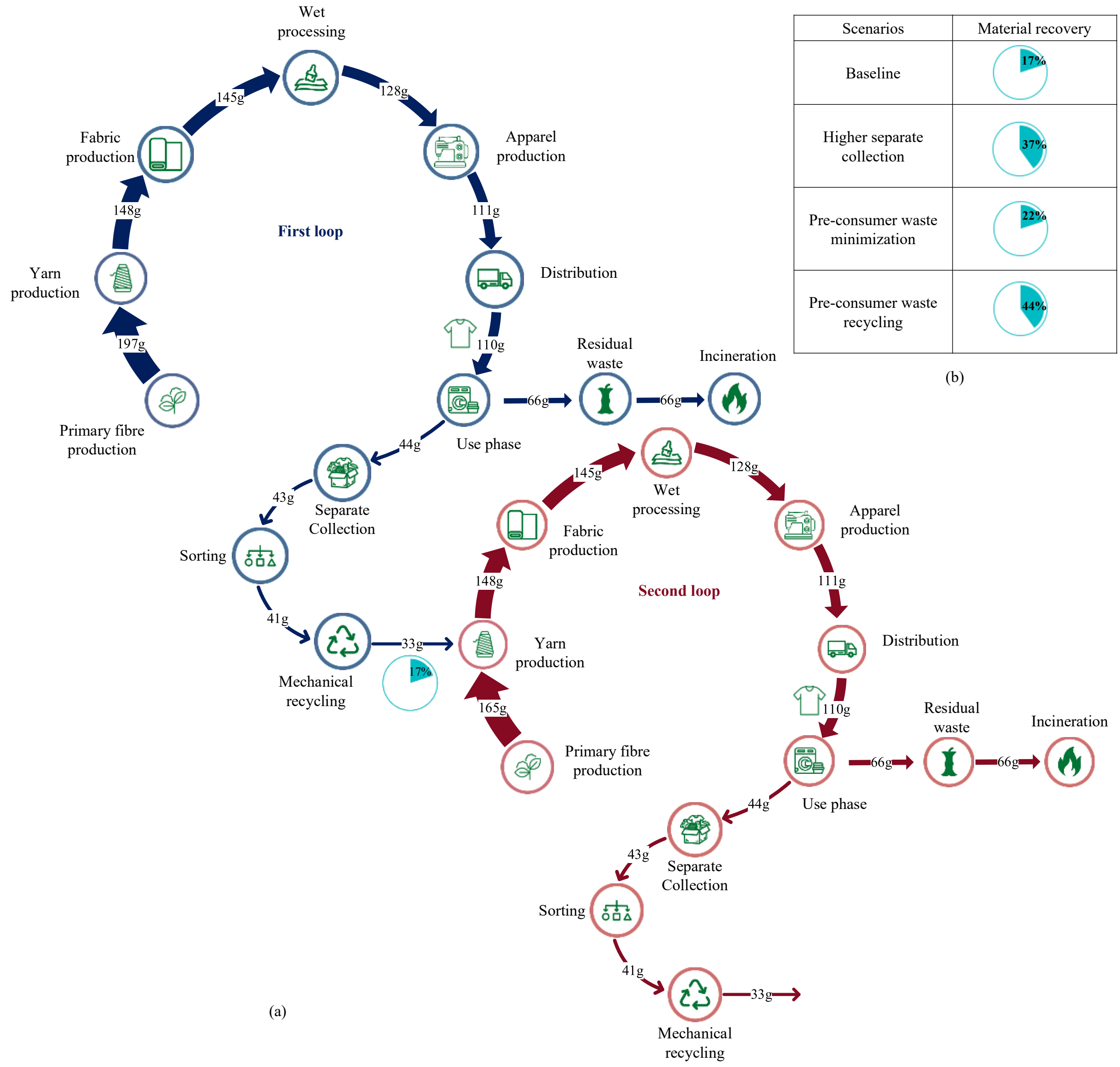


Figure 2. (a) Fibre flows across the supply chain in product system. Blue circles and arrows represent processes and flows in the first lifecycle, while red circles and arrows indicate the second lifecycle. (b) Material recovery (%) at the end of the first loop across the scenarios.

4.2. Life cycle assessment

Figure 3 presents each lifecycle stage's contribution to the environmental impacts for t-shirts across two consecutive loops.

For the baseline system, the cumulative (first loop + second loop) global warming potential (GWP) was 6.68 kg CO2-eq. Across the two loops the manufacturing processes that convert cotton fibre into a finished t-shirt (yarn, fabric, wet processing and apparel production) accounted for more than half of the total GWP (56%). Among the manufacturing stages, wet processing was the largest contributor (27%, see Appendix A-12), followed by primary fibre production (cultivation, harvesting and ginning) which contributed around 22% of total GWP. The use phase, consisting of laundry activities, is the third highest impact-causing operation. Energy use in the form of electricity, heat and natural gas was the dominant driver of GWP across the lifecycle stages. (See Appendix A-13 for background process contribution). For the other impact categories- freshwater eutrophication, ecotoxicity, land use and water consumption- fibre production was the dominant stage, contributing 76% of eutrophication impact and over 90% of the remaining impacts. Downstream operations (collection, sorting, recycling and incineration) contributed marginally: less than 3% of GPW and less than 1% for other categories.

Out of the total cumulative GWP of 6.68 kg CO_2-eq, the t-shirt from the first loop accounted for 3.50 kg CO2-eq. Comparing the two loops, the second loop showed lower impacts across all categories due to the reduced input of primary cotton. Reductions were modest for GWP (about 4%) but larger for the other categories (about 12% for eutrophication and 15% for freshwater ecotoxicity, land use and water consumption). This pattern reflects the high share of impacts attributed to primary fibre production in these impact categories.

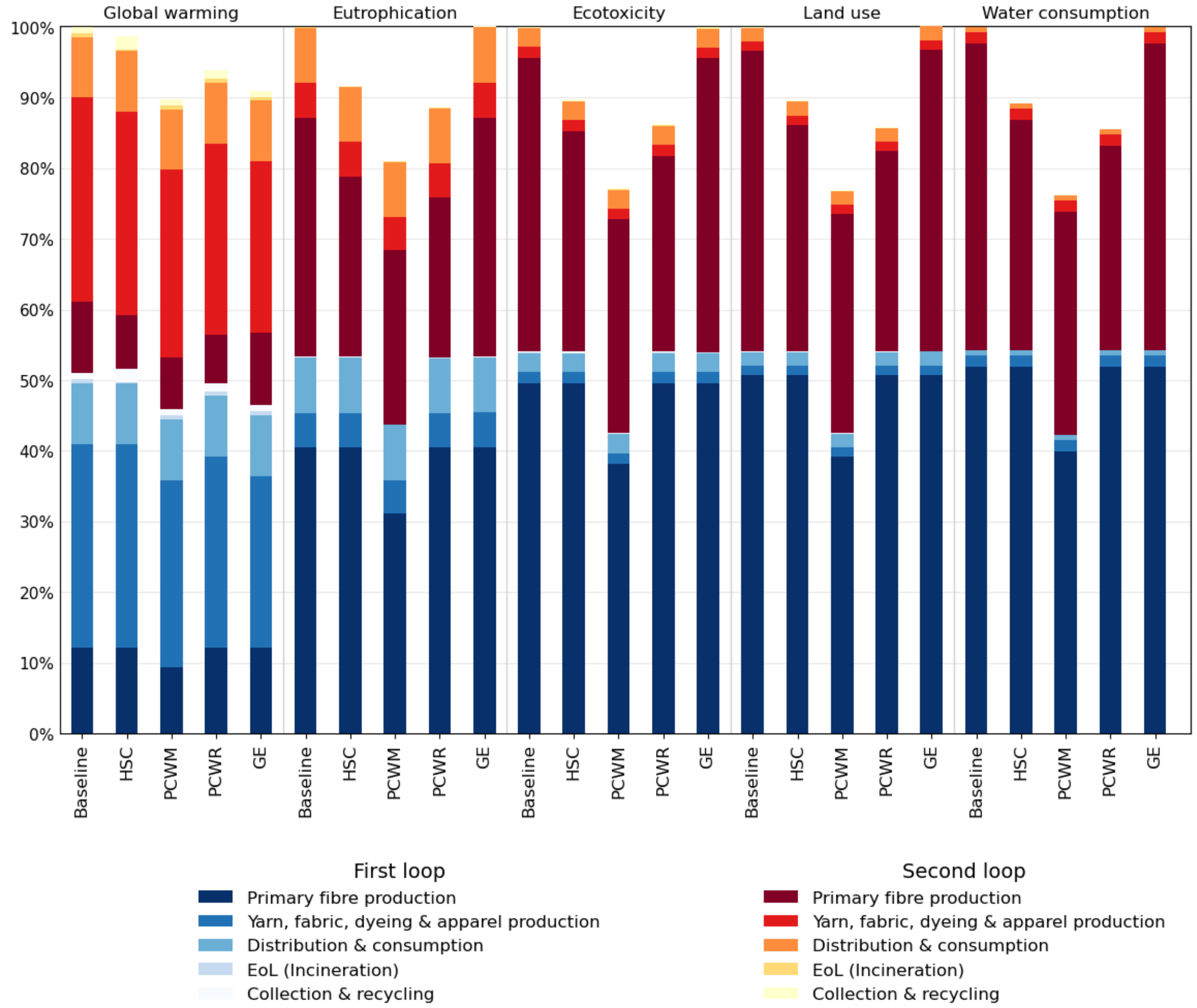


Figure 3. LCA result for t-shirts across two consecutive loops for each scenario, normalized to the highest value within each impact category. HSC= Higher separate collection, PCWM= Pre-consumer waste minimization, PCWR= Pre-consumer waste recycling, GE= Green energy.

4.3. Scenario comparison (Recovery-impact relationship)

The scenario results show a consistent relationship between fibre recovery and environmental performance: scenarios that increase recovered fibre and reduce primary fibre demand also deliver larger environmental improvements.

Relative to baseline recovery of 17% (33 g recovered from 197 g input), the HSC scenario increased recovery to 37% (73 g), which translated into an approximately 2% reduction in GWP and around 10% reductions in other impact categories. In the PCWM scenario, recycled fibre remained 33 g, but the primary fibre input was reduced by 23% (to 152 g), increasing the recovery rate to 22%. This upstream efficiency improvement led to the largest environmental gains, about 10% lower GWP and 20-25% reductions in other categories. As less fibre was required, less material was processed and less waste was landfilled across both loops. The PCWR scenario achieved the highest material recovery of 44% (87 g) by diverting production stage waste from landfill to recycling. Consequently it delivered environmental improvements between HSC and PCWM. Unlike the fibre-focused scenarios (HSC, PCWM, PCWR), the (GE) scenario did not alter the fibre recovery percentage but reduced GWP by 9% through its low-carbon electricity mix in the production phases. However, due to the dominance of primary fibre production in the other impact categories, this scenario did not result in measurable benefits beyond GWP.

5. Discussion

5.1. Understanding hypothetical product systems and validation

This study analyzed the effect of the European textile industry strategies by benchmarking the current product system against various sustainable textile policy interventions. The baseline system and accompanying scenarios were modelled to assess the maximum achievable potential of fibre-to-fibre recycling. These systems are referred to as ‘hypothetical’ because, in practice, closed-loop recycling operates alongside other circular strategies such as reuse, resale, repair, or cascade recycling. Therefore, real-world fibre-to-fibre recovery from the product system is likely to be lower than the 17% estimated in the baseline scenario, because garments diverted to these alternative pathways are not available for recycling. The scenarios do not predict when the modelled recovery levels will be achieved, rather, the short-, medium-, and long- term horizons used in this discussion indicate the type of enabling changes required.

The product-level fibre flows from this study indicate that production-stage losses could be substantially higher than previously reported in global material flow assessments. In our baseline model, approximately 44% of the initial fibre input is lost during production. This contrasts with only 12% production loss reported by the Ellen MacArthur Foundation (2017), suggesting the underestimation of pre-consumer waste in global material flow models. One likely reason is the assumption of lower process losses in production stages based on different data sources. Global material flow assessments typically rely on national accounts, official statistical surveys, and industry reports which may not capture the specific operational losses of a specific product line in a specific factory. To address this limitation, our estimates draw on recent factory-based empirical studies (Akter et al., 2022; Alam et al., 2023) covering a large number of manufacturing facilities and explicitly quantifying process losses. This makes our estimates more representative of operational realities and therefore yields higher estimates of pre-consumer waste.

A similar discrepancy emerges for the distribution of waste across the life cycle. In this study, the total waste amounts to 164 g, of which pre-consumer waste represents 52% and postconsumer waste 48% (baseline scenario). This differs from the European Environment Agency's (2024) estimate that 82% of the total textile waste is post-consumer waste in EU. This difference likely reflects system-boundary choices in how textile waste is quantified, particularly whether production losses occurring outside Europe are included and whether realistic production waste rates are captured in the European reporting system.

Direct comparison of the results with other LCIA studies is difficult, as this analysis follows a t-shirt through two loops in a circular system. However, results from first loop in the baseline system can be compared with previous estimates of around 3 kg CO_2-eq per lifecycle (Moazzem et al., 2021; Sandin et al., 2019), which are slightly lower than in this study. The higher values here again reflect consideration of higher process losses, differences in electricity mix and EoL treatment of pre-consumer waste. Importantly, the dominant contribution of cotton cultivation to the environmental impacts in this study is consistent with earlier findings: cotton fibre production accounted for the highest shares of land use (96%) and water depletion (73%) impacts (Moazzem et al., 2021; Sandin et al., 2019).

Beyond the t-shirt case study, this conceptual multi-cycling (multi-loop) approach shifts the evaluation from 'impacts of one product life' to 'impacts per unit of service over repeated material use'. This perspective makes it explicit that the value of pre- and post-consumer waste recycling lies not in the recycling process itself, but in the displacement of primary material in subsequent production. In single-lifecycle LCAs, this mechanism is typically represented through allocation conventions that can be difficult to interpret for policy and industrial decision-making. The multi-cycling approach provides a clearer and more transparent way to communicate burdens and benefits across time. The multi-cycling framing also makes technical constraints (e.g. fibre length degradation in mechanical recycling) more visible, because the achievable benefit depend on whether recovered fibres can realistically re-enter the same product loop. It enables indicators such as 'cumulative primary fibre displacement over N loops' or 'material retention per unit of service' which are directly relevant for monitoring progress towards circularity targets.

5.2. Scenario insights and policy implications

5.2.1. *Higher Separate Collection (HSC)*

In this scenario, material recovery increases to 37%, about 20% above the current system (Baseline). This positive correlation between separate collection rates and material recovery is supported by existing studies (Dahlbo et al., 2017; McKinsey & Company, 2022) confirming that collection systems are a key level for circularity. Realizing these gains requires more than collection containers. For municipal authorities and charitable organizations, priority actions include improving capture rates and reducing contamination (e.g. clearer sorting guidance, dedicated stream for non-accepted items), appropriate scaling of sorting capacity, and developing financing mechanism to manage the increased amount of collected waste (European Environment Agency, 2024).

Medium-term structural needs relate primarily to sorting and downstream market organization. Investment in automated and effective sorting is needed to avoid 'leakage' of low-quality collected textiles. This is particularly important because today large volumes of second-hand clothing collected by charitable organizations or sorters in Europe are exported as mixed bale. These bales often contain poor-quality garments that cannot be resold and end up in landfills or waterbodies in recipient countries (Marc, 2023; The Independent, 2022).

For brands, a longer-term lever is to strengthen extended producer responsibility (EPR) schemes by linking producers fees to the share of their products found in residual waste (as identified through waste audits), thus creating a direct incentive for design choices and takeback performance.

5.2.2. *Pre-consumer waste minimization (PCWM)*

The key outcome is a 22% reduction in primary fibre demand and associated lower amounts of material processed, which translates into highest environmental benefits across impact categories.

Studies by Alam et al. (2023); Moazzem, Wang, et al. (2021) indicate that major source of process losses includes marker inefficiency during fabric cutting, uneven dyeing and faulty fabric in wet processing. The industry practice also often involves deliberate overproduction to buffer against shipment volume shortfall due to these inefficiencies and quality nonconformance, which in turn generates excess inventory. Actionable measures can therefore focus first on reducing operational losses. Manufacturers can improve marker planning, strengthen wet-processing quality control and implement tighter process monitoring to reduce rework and reject rates. Brands can accelerate the process by requiring routine reporting of material input, process loss and leftover inventory and then integrating these indicators into supplier scorecards and purchasing decisions alongside existing compliance and quality metrics. Incentives such as preferential order placement or financial rewards for suppliers demonstrating improved efficiency or investing in waste-reducing technologies would further strengthen the transition to pre-consumer waste minimization. As operational losses decline and output becomes more predictable, the perceived need for deliberate overproduction falls as well.

5.2.3. Pre-consumer waste recycling (PCWR) The pre-consumer waste recycling scenario achieved the highest material recovery with 44% of fibres retained. A key insight is that recovering pre-consumer waste can increase fibre availability for closed-loop recycling, even when post-consumer collection constraints persist. In addition, compared to post-consumer waste, pre-consumer waste is relatively clean (Juanga-Labayen et al., 2022), making it more suitable for fibre-to-fibre recycling and enabling higher-quality secondary fibres (Arafat & Uddin, 2022). This underlines the importance of pre-consumer recycling as a cornerstone for circularity in the textile sector.

Despite this potential, pre-consumer waste remains weakly governed in many producing countries. At present, garment factories are not legally required to sort and recycle their fabric or apparel cutting waste (Maria, 2021). A substantial share of pre-consumer waste currently is channeled through the informal 'grey market' where traceability is limited and labor conditions are often exploitative and hazardous including low wages, child labor, poor hygiene and sanitation with documented health impacts (Akter et al., 2022; The Centre for Child Rights and Business, 2024).

At the product design stage, the ESPR pushes brands toward ecodesign, specially design for recycling. Brands can meet this expectation by embedding circular design guidance and life cycle thinking into design processes to avoid unnecessary fibre blends and complex trims. Designing garments that are easier to recycle not only reduces EoL constraints, but also improves the recyclability of pre-consumer waste, thereby supporting waste reduction across the value chain.

Medium-term structural change requires policy and market alignment. In parallel, the EU can complement brand-level measures through government-to-government partnerships that link circular textile policy with climate commitments and help finance upstream formal recycling systems. While the EU's ESPR aims to make brands responsible for their products over the value chain with sufficient recycling capacity and with minimal incineration and landfilling, it does not explicitly target pre-consumer waste. Incorporating reporting requirements for production-stage waste, traceability expectations and recovery performance indicators into delegated acts could improve accountability and enable monitoring of upstream circularity. Over time, reducing reliance on informal markets will depend on investment in domestic recycling capacity and governance mechanisms in the production countries.

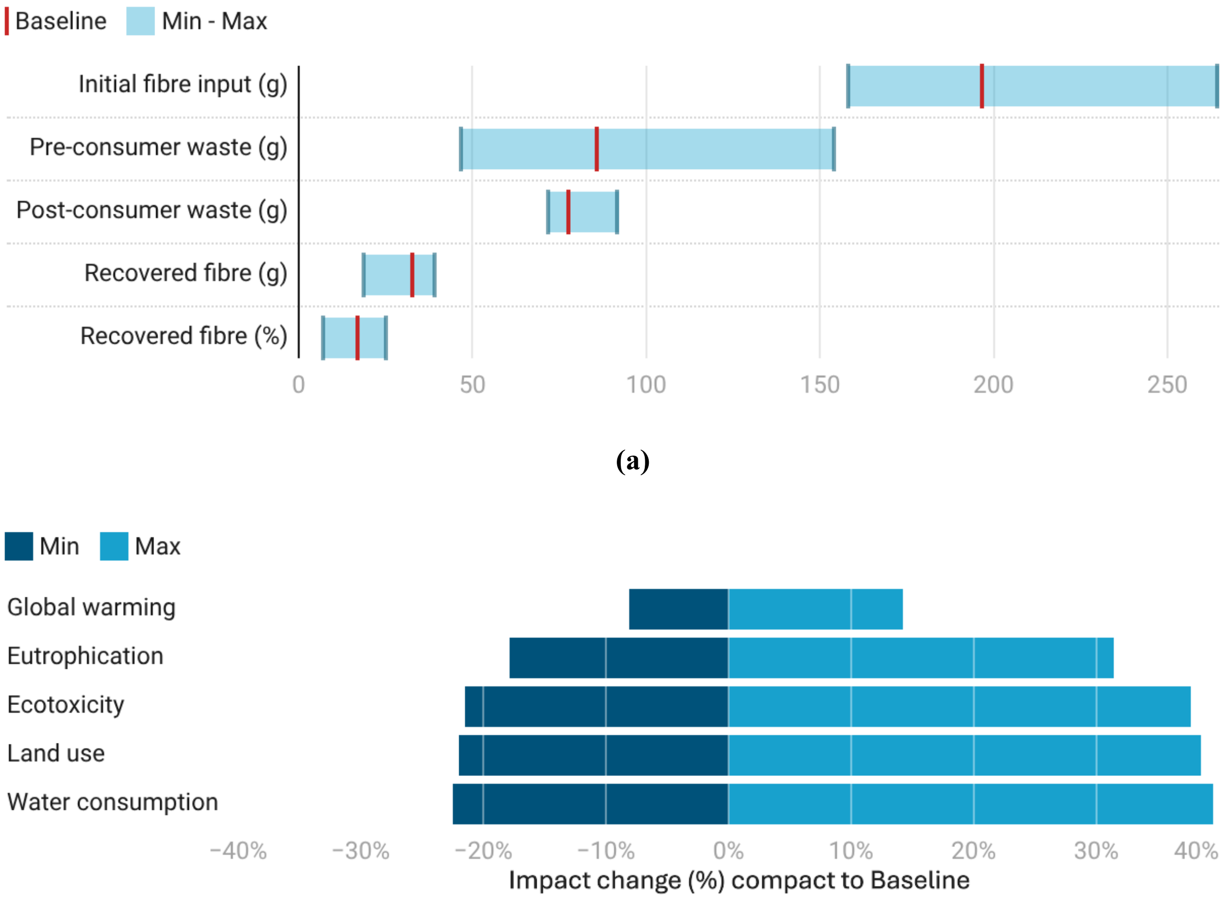
5.2.4. Green energy (GE) A 9% improvement in GWP in the green energy scenario indicates the importance of cleaner energy in the textile supply chain. In our LCA modelling, the assumed mix with 30% renewable electricity share represents a step change from the current 2% of renewables in the Bangladeshi mix and the observed 9% reduction in GWP suggests that higher renewable penetration would further reduce climate impacts.

In the medium-term, brands can support renewable uptake by co-investing the cost difference between fossil-based and renewable electricity, while manufacturers can reduce electricity demand through efficiency measures in operations. This climate mitigation pathway is also increasingly recognized by fashion brands and manufacturers. For example, H&M together with Bestseller, agreed at COP28 to invest in a 500 MW offshore wind project in Bangladesh to expand renewable energy availability in a key manufacturing hub (Global Fashion Agenda, 2024). In the medium to long term, meaningful decarbonization depends on national grid transitions in major manufacturing countries. This remains challenging because most garment production is concentrated in Asia, where fossil-based electricity still dominates. At present, renewables account for less than 2% of electricity generation in Bangladesh, compared with 49% in India, 44% in Vietnam, and 38% in China (Dinita Setyawati et al., 2024; ICED, NITI, 2025; Muyi Yang & Shiyao Zhang, 2024). Countries with low renewable energy penetration may therefore risk losing competitiveness as global brands increasingly prioritize low-carbon and sustainable sourcing, highlighting the business as well as environmental relevance of energy transition.

5.3. Sensitivity analysis

The sensitivity analysis as shown in Figure 4 indicates that the magnitude of fibre flows and environmental impacts vary notably. In particular, the required initial fibre input varies from 158 g to 265 g and pre-consumer waste from 47 g to 92 g, which are most sensitive to variations in upstream loss rates. The post-consumer waste and recovered fibre changes less because it is constrained by the fixed product mass entering the use phase.

For environmental impacts, uncertainty leads to much larger variation (-22% to +40%) in impact categories dominated by cotton cultivation, such as freshwater eutrophication/ ecotoxicity, land use and waste consumption, than in climate change (-8% to +14%) when compared to the Baseline.



(a)

(b)

Figure 4. Sensitivity analysis of (a) fibre flows and (b) environmental impact showing the range (min-max) of results compared to baseline.

5.4. Limitation and future work

The analysis assumed that production conditions, including process losses, energy and material inputs, remain same across both loops. Current literature provides no evidence that garments made with recycled fibres demand different process parameters than those produced with primary fibres. Further investigation of the second-loop lifecycle inventory could alter the results by reducing or increasing the estimated impacts.

A 1:1 replacement ratio between recycled and primary fibres was applied. This assumption is less realistic for mechanically recycled cotton (Sandin & Peters, 2018). Cotton fibres shorten during cutting and shredding, reducing fibre quality (Schmidt et al., 2016). Evidence suggests that yarn blends containing 30% recycled fibre can still meet quality standards (Arafat & Uddin, 2022). The second loop of the baseline and PCWM scenario fit within this range. However, scenarios (HSC and PCWR) that estimated 37-44% recovery go beyond current technical limits. For modelling purposes, all recovered fibres were treated as reusable in second loop, implicitly assuming future improvements in recycling and spinning technologies. Without such advances, much of the excess recovered fibre would likely be downcycled into lower-value applications rather than reintroduced in closed-loop t-shirt production.

The model also assumed mass balance, with no stock accumulation across processes. This is a reasonable approximation in production, where material accumulation is minimal. However, during the use phase, evidence shows that households in many developed countries accumulate clothing over time (Dahlbo et al., 2021; Mora-Sojo et al., 2023; Watson et al., 2020). Excluding this stock effect may lead to an overestimation of textiles entering waste streams. The effect of garment lifetime should be studied in detail to incorporate the increase of garments in wardrobe (stock change). Dynamic material flow analysis modelling for textile products can be particularly useful in this regard, and currently, no study has modelled textile flows using dynamic MFA.

To account for both recycled content at the production input and recovery at EoL in LCA, the circular footprint formula (CFF) has been proposed by the EU's Product Environmental Footprint methodology (Ekvall et al., 2020). However, applying the CFF requires additional parameters such as the change in material quality between life cycle stages and allocation of material recycling and energy recovery. Future research could apply CFF to a similar case to incorporate fibre-quality degradation explicitly and compare outcomes with the multi-loop approach to assessing sensitivity to allocation and quality factors.

6. Conclusion

Using Norway as a representative EU case, this study combined fibre flow mapping with multi-cycle LCA to evaluate how much material circularity fibre-to-fibre recycling can deliver over two consecutive t-shirt lifecycles. The analysis shows that, under current conditions, only about 17% of the initial fibre input could be mechanically recovered and reintroduced into a subsequent t-shirt, even in a context with comparatively robust waste management.

The key insight from the fibre flow model is that losses do not occur solely after the use phase: pre-consumer and post-consumer waste contribute in roughly equal measure. Thus, circularity strategies focusing only on post-consumer collection and recycling overlook a major source of fibre loss. This constrains the availability of recycled fibres needed to meet the recycled-content goals set by the Ecodesign for sustainable products regulation.

The multi-cycle LCA framing enables evaluation and communication of environmental impacts over repeated material use, rather than a single product life, without relying on allocation conventions. LCA results confirm that recovered fibre leads to improving environmental performance of the product system, with the largest gains in categories dominated by fibre cultivation (water use, land occupation and freshwater impacts).

Scenario analysis further indicates that fibre recovery gains and environmental impact reductions within the textile value chain system remain limited unless upstream material inefficiencies are addressed. Minimization and recycling of pre-consumer waste deliver the largest gains in fibre retention and environmental performance, whereas higher separate collection of discarded textiles and cleaner electricity provides more modest improvements. These scenario results should be interpreted as model-based, best-case scenario under defined assumptions (idealized routing of discarded garments) and therefore represent an upper bound on recycling-based circularity rather than current real-world performance.

Taken together, the study's main contribution to sustainable, circular value chains is to demonstrate quantitatively that addressing pre-consumer waste is a decisive, yet often under-accounted, lever for improving textile circularity in practice. Building on these findings, the feasible options for accelerating progress in shorter term include manufacturers improving material efficiency and establishing traceable handling of production waste, while brands integrate material-loss metrics into sourcing decisions and embed life-cycle thinking in the design phase. In the medium term, progress depends on investment in recycling infrastructure and cleaner energy, supported by climate-aligned cooperation and cofinancing between the EU and producer countries. At the policy level, EU policymakers can broaden the perspective to explicitly include pre-consumer waste, strengthen measurement of pre-consumer waste generated both within and outside the EU, and support industry actions that reduce production losses and expand recycling options. Mandatory separate collection coupled with performance-based producer responsibility can complement these upstream measures.

Overall, if policy and business efforts remain concentrated on post-consumer streams, the EU risks missing its circular textile goals even with higher separate collection rates and robust downstream waste management.

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Declarations

Competing Interests The authors declare no competing interests.

AI Use During the preparation of this work, the main author used ChatGPT for editing texts to improve clarity and correct grammatical errors. After using the tool, the authors carefully reviewed and edited the content and take full responsibility for the published article.

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Appendix

Modelling details

The following tables provide life cycle inventory used in the modelling of different unit processes across the value chain.

Table A1. Modelling of 1 kg fibre production

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Fibre	1	kg	Fibre, cotton {GLO}| market for	

Table A2. Modelling of 1 kg yarn production

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Electricity	4	kWh	Electricity, medium voltage {BD}| market for	(Sandin et al., 2019)
Acrylic acid	0.00016	kg	Acrylic acid {RoW}| market for	Used for lubricant (Sandin et al., 2019)
Polyacrylamide	0.00032	kg	Polyacrylamide {GLO}| market for	
Water	0.00112	kg	Water, ultrapure {RoW}| market for	
Waste	0.33	kg	treatment of waste yarn and waste textile, unsanitary landfill {IN}	(Alam et al., 2023)

Table A3. Modelling of 1 kg fabric production

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Electricity	0.5	kWh	Electricity, medium voltage {BD}| market for	(Sandin et al., 2019)
Acrylic acid	0.008	kg	Acrylic acid {RoW}| market for	Used for lubricant (Sandin et al., 2019)
Polyacrylamide	0.016	kg	Polyacrylamide {GLO}| market for	
Water	0.056	kg	Water, ultrapure {RoW}| market for	
Transport	0.255	tkm	Transport, freight, lorry, unspecified {GLO}| market for	250 km (Assumption)
Waste	0.02	kg	treatment of waste yarn and waste textile, unsanitary landfill {IN}	(Alam et al., 2023)

Table A4. Modelling of 1 kg wet processing

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Water	60	kg	tap water production, underground water with chemical treatment {RoW}	(Sandin et al., 2019)
Acrylic acid	0.0002	kg	Acrylic acid {RoW}| market for	Used for Per oxide stabilizer (Sandin et al., 2019)
Magnesium oxide	0.00001	kg	Magnesium oxide {GLO}| market for	
Phosphoric acid	0.0002	kg	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for	
Water, ultrapure	0.00159	kg	Water, ultrapure {RoW}| market for	
Diethanolamine	0.0009	kg	Diethanolamine {GLO}| market for	Used for softener (Sandin et al., 2019)
Stearic acid	0.006	kg	Stearic acid {GLO}| market for	
Water, ultrapure	0.0231	kg	Water, ultrapure {RoW}| market for	
Fluorescent whitening	0.06	kg	Fluorescent whitening agent, distyrylbiphenyl type {GLO}| market for	(Sandin et al., 2019)
Formic acid	0.01	kg	Formic acid {RoW}| market for	(Sandin et al., 2019)
Hydrogen peroxide	0.07	kg	Hydrogen peroxide, without water, in 50% solution state {RoW}| market for	(Sandin et al., 2019)
Acrylic acid	0.008	kg	Acrylic acid {RoW}| market for	Used for lubricant (Sandin et al., 2019)
Polyacrylamide	0.016	kg	Polyacrylamide {GLO}| market for	
Water	0.056	kg	Water, ultrapure {RoW}| market for	
Sodium hydroxide	0.025	kg	Sodium hydroxide, without water, in 50% solution state {RoW}| market for	(Sandin et al., 2019)
Sulphuric acid	0.02	kg	Sulfuric acid {RoW}| market for	(Sandin et al., 2019)
Heat	38	MJ	heat production, light fuel oil, at boiler 10kW, non-modulating {RoW}	(Sandin et al., 2019)
Detergent	0.05	kg	Acrylic acid {RoW}| market for	(Sandin et al., 2019)
Electricity	1.5	kWh	Electricity, medium voltage {BD}| market for	(Sandin et al., 2019)
Transport	0.284	tkm	Transport, freight, lorry, unspecified {GLO}| market for	250 km (Assumption)
Waste water	0.045	m3	Wastewater from textile production {GLO}| market for	(Sandin et al., 2019)
Waste	0.136	kg	treatment of waste yarn and waste textile, unsanitary landfill {IN}	(Alam et al., 2023)

Table A5. Modelling of 1 kg apparel production

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Water	0.18	kg	tap water production, underground water with chemical treatment {RoW}	(Sandin et al., 2019)
Sewing thread	0.0035	kg	Fibre, polyester {GLO}| market for	(Sandin et al., 2019)
Confectioning template	0.05	kg	Kraft paper {RoW}| market for	(Sandin et al., 2019)
Packaging film	0.02	kg	Packaging film, low density polyethylene {GLO}| market for	(Sandin et al., 2019)
Corrugated board box	0.06	kg	Corrugated board box {RoW}| market for	(Sandin et al., 2019)
Electricity	2.711	kWh	Electricity, medium voltage {BD}| market for	(Sandin et al., 2019)
Heat	3.6	MJ	heat production, natural gas, at boiler modulating <100kW {RoW}	(Sandin et al., 2019)
Waste	0.15	kg	treatment of waste yarn and waste textile, unsanitary landfill {IN}	(Alam et al., 2023)

Table A6. Modelling of 1 kg t-shirt distribution

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Transport	0.253	tkm	Transport, freight, lorry, unspecified {RoW}| market for	Factory at Gazipur - Chattogram port: 250 km (Google Map)
Transport	15.9	tkm	Transport, freight, sea, container ship {GLO}| market for	Chattogram port - Oslo port: 15775 km (Sea-Distance.org)
Transport	0.0808	tkm	Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| market for	Oslo port - Distribution center: 80 km (Assumption)
Transport	0.0303	tkm	Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| market for	Distribution center - retail store: 30 km (Assumption)
Waste	0.01	kg	treatment of municipal solid waste, municipal incineration {NO}	(Sandin et al., 2019)

Table A7. Modelling of use phase of 1 kg t-shirt

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Washing, drying and finishing	15	kg	Washing, drying and finishing laundry {GLO}| market for	(Sandin et al., 2019)

Table A8. Modelling of incineration of 1 kg t-shirt

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Transport	0.014	tkm	Municipal waste collection service by 21 metric ton lorry {GLO}| market for	14 km for waste collection (Mora-Sojo et al., 2023)
Transport	0.05	tkm	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| market for	50 km to incineration plant (Mora-Sojo et al., 2023)
Incineration	1	kg	treatment of municipal solid waste, municipal incineration {NO}	

Table A9. Modelling of separate collection and pre-sorting of 1 kg t-shirt

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Transport	0.15	tkm	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}| market for	150 km to pre-sorting plant (Mora-Sojo et al., 2023)
Electricity	0.07	kWh	Electricity, low voltage {NO}| market for	(Mora-Sojo et al., 2023)
Waste	0.012	kg	treatment of municipal solid waste, municipal incineration {NO}	(Mora-Sojo et al., 2023)

Table A9. Modelling of sorting of 1 kg t-shirt

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Electricity	0.0161	kWh	Electricity, low voltage {LT}| market for	(Nørup et al., 2019)
Heat	0.0259	MJ	Heat, central or small-scale, natural gas {RER}| market for	(Nørup et al., 2019)
Wire	0.0007	Kg	Wire drawing, steel {RER}	(Nørup et al., 2019)
Tap water	0.00011	Kg	Tap water {RER}| market for	(Nørup et al., 2019)
Transport	0.577	tkm	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}| market for	Oslo - Nynäshamn port: 539 km (Google Map)
Transport	0.294	tkm	Transport, freight, sea, ferry {GLO}| market for	Nynäshamn port- Ventspils port: 275 km (Google Map)
Transport	0.471	tkm	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}| market for	Ventspils port - Vilnius: 440 km (Google Map)
Waste	0.07	kg	treatment of municipal solid waste, municipal incineration {RoW}	(Nørup et al., 2019)

Table A10. Modelling of mechanical recycling of 1 kg sorted t-shirt

Item	Amount	Unit	Dataset (Ecoinvent 3.10, Cut-off)	Comments & source
Electricity	0.1	kWh	Electricity, medium voltage {INSouthern grid}| market for	(Schmidt et al., 2016)
Transport	0.311	tkm	Transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}| market for	Vilnius - Ventspils port: 311 km (Google Map)
Transport	13.3	tkm	Transport, freight, sea, container ship {GLO}| market for	Ventspils port - Mumbai port: 311 km (Google Map)
Transport	1.51	tkm	Transport, freight, lorry, unspecified {RoW}| market for	Mumbai port - Recycling plant at Panipat: 1512 km (Google Map)
Transport	1.46	tkm	Transport, freight, lorry, unspecified {RoW}| market for	Recycling plant at Panipat - Yarn factory at Gazipur: 1820 km (Google Map)
Waste	0.2	kg	treatment of waste yarn and waste textile, unsanitary landfill {IN}	(Schmidt et al., 2016)

Table A11. Modelling of electricity mix for green energy scenarios

Share of electricity source	Original	Green energy scenario	Dataset (Ecoinvent 3.10, Cut-off)
Electricity from Indian grid	10%	10.0%	Electricity, high voltage {BD}| electricity, high voltage, import from IN-Eastern grid
Electricity from coal	3%	3.0%	Electricity, high voltage {RoW}| electricity production, hard coal
Electricity from hydro	1%	18.0%	Electricity, high voltage {RoW}| electricity production, hydro, run-of-river
Electricity from gas (combined cycle plant)	13%	6.0%	Electricity, high voltage {RoW}| electricity production, natural gas, combined cycle power plant
Electricity from gas (conventional plant)	59%	27.0%	Electricity, high voltage {RoW}| electricity production, natural gas, conventional power plant
Electricity from oil	14%	14.0%	Electricity, high voltage {RoW}| electricity production, oil
Electricity from wind	0.01%	4.5%	Electricity, high voltage {RoW}| electricity production, wind, 13MW turbine, onshore
Electricity from nuclear		10.0%	Electricity, high voltage {RoW}| electricity production, nuclear, pressure water reactor
Electricity from solar		7.5%	Electricity, low voltage {RoW}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si

Table A12. LCIA results of t-shirts from first and second loop for baseline scenario

	Global warming (kg CO2 eq)		Freshwater eutrophication (kg P eq)		Freshwater ecotoxicity (kg 1,4-DCB)		Land use (m2a crop eq)		Water consumption (m3)	
Lifecycle stages	**First loop**	**Second loop**	**First loop**	**Second loop**	**First loop**	**Second loop**	**First loop**	**Second loop**	**First loop**	**Second loop**
Primary fibre production	8.36E-01	7.00E-01	6.68E-04	5.59E-04	4.74E-02	3.97E-02	1.14E+00	9.58E-01	8.74E-01	7.32E-01
Yarn production	5.69E-01	5.69E-01	1.16E-05	1.16E-05	1.98E-04	1.98E-04	3.71E-03	3.71E-03	1.02E-03	1.02E-03
Fabric production	1.17E-01	1.17E-01	3.57E-06	3.57E-06	6.22E-05	6.22E-05	1.12E-03	1.12E-03	2.60E-04	2.60E-04
Wet processing	9.50E-01	9.50E-01	5.79E-05	5.79E-05	1.08E-03	1.08E-03	6.50E-03	6.50E-03	2.50E-02	2.50E-02
Apparel production	3.38E-01	3.38E-01	8.39E-06	8.39E-06	1.50E-04	1.50E-04	1.88E-02	1.88E-02	8.26E-04	8.26E-04
Distribution	3.11E-02	3.11E-02	5.32E-07	5.32E-07	6.95E-05	6.95E-05	1.07E-03	1.07E-03	6.32E-03	6.32E-03
Use phase	5.59E-01	5.59E-01	1.28E-04	1.28E-04	2.48E-03	2.48E-03	4.28E-02	4.28E-02	5.91E-03	5.91E-03
EoL (Incineration)	3.78E-02	3.78E-02	4.46E-07	4.46E-07	7.76E-05	7.76E-05	1.34E-04	1.34E-04	7.74E-05	7.74E-05
Separate collection & pre-sorting	1.93E-03	1.93E-03	2.21E-08	2.21E-08	4.71E-06	4.71E-06	6.97E-05	6.97E-05	9.19E-05	9.19E-05
Sorting	1.39E-02	1.39E-02	1.30E-07	1.30E-07	2.80E-05	2.80E-05	4.38E-04	4.38E-04	2.89E-05	2.89E-05
Mechanical recycling	4.31E-02	4.31E-02	9.00E-07	9.00E-07	6.38E-05	6.38E-05	1.35E-03	1.35E-03	7.67E-05	7.67E-05
Total	3.50E+00	3.36E+00	8.80E-04	7.71E-04	5.16E-02	4.39E-02	1.22E+00	1.03E+00	9.13E-01	7.71E-01

Table A13. Contribution of background processes to impacts for baseline scenario

	Global warming (kg CO2 eq)		Freshwater eutrophication (kg P eq)		Freshwater ecotoxicity (kg 1,4-DCB)		Land use (m2a crop eq)		Water consumption (m3)	
Background processes	**First loop**	**Second loop**	**First loop**	**Second loop**	**First loop**	**Second loop**	**First loop**	**Second loop**	**First loop**	**Second loop**
Electricity	5.43E-01	5.43E-01								
Heat	3.84E-01	3.84E-01								
Natural gas	2.10E-01	2.07E-01								
Cotton production	3.69E-01	3.09E-01	6.39E-04	5.35E-04	4.65E-02	3.90E-02	1.12E+00	9.35E-01	-6.22E-01	-5.21E-01
Landfilling	1.45E-01	1.45E-01								
Whitening agent	1.14E-01	1.14E-01								
Wastewater from textile production			1.31E-04	1.31E-04						
Spoil from mining			5.74E-05	5.39E-05						
Irrigation									1.46E+00	1.23E+00
Others	1.73E+00	1.66E+00	5.23E-05	5.11E-05	5.07E-03	4.94E-03	1.03E-01	9.87E-02	7.19E-02	6.67E-02
Total	3.50E+00	3.36E+00	8.80E-04	7.71E-04	5.16E-02	4.39E-02	1.22E+00	1.03E+00	9.13E-01	7.71E-01