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Research Paper

Combining Material Flow Analysis and Life Cycle Assessment to explore integrated textile waste management systems: current and future scenarios in Lombardy region (Italy)

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ABSTRACT

Rising textile consumption, low level of circularity in the textile sector, and recent European legislative developments, have increased attention on textile waste management. While several studies have assessed the environmental impacts of individual textile waste treatment processes, analyses of integrated textile waste management systems remain limited. To address this gap and support decision making, this study combines Material Flow Analysis and Life Cycle Assessment to evaluate strategies for managing post–consumer textile waste, with a case study from an Italian region. Six scenarios were analysed, exploring the effects of restricting exports of textiles outside Europe, increasing the share of renewable electricity, improving separate collection rates, and implementing chemical recycling. A Material Recovery Score was also introduced to capture the trade-offs between material recovery and environmental impacts. Results confirm that preparing textiles for reuse delivers relevant environmental benefits, due to avoided impacts from virgin production, while restricting exports for reuse increases overall impacts. Future scenarios, characterised by higher separate collection rate and by the introduction of chemical recycling, achieve the highest Material Recovery Scores but also show higher environmental impacts, driven by energy demand and solvent use of chemical recycling processes. The adoption of more renewable electricity mixes results in slightly higher overall impacts in some categories, such as Climate Change, while categories like Resource Use (minerals and metals) show the opposite pattern. Overall, these findings emphasize the need to improve chemical recycling performance and prioritise effective reuse to minimise the environmental impacts of the waste management system, offering valuable guidance to policymakers and industry stakeholders.

1. Introduction

Textile waste management has recently attracted increasing attention, mainly due to rising consumption and the limited capacity for sorting and recycling (Deckers et al., 2024). Globally, textile production and consumption are steadily growing, also because of fast fashion explosion, resulting in higher waste generation and associated environmental impacts (Ellen MacArthur Foundation, 2017). Focusing on Europe, landfilling and incineration have been the predominant methods for textile waste treatment (Napolano et al., 2025). However, the European Union (EU) has set the goal to improve the environmental performances and the circularity of the textile sector (European Commission, 2022). A key step toward this objective is the Revised Waste Framework Directive (European Parliament, 2025), which establishes for Member States to implement post-consumer textile waste (PCTW) separate collection by January 1, 2025, and Extended Producer Responsibility schemes for textiles. Increasing PCTW volumes are going to be separately collected, and there is the need to support the design of future waste management systems.

Quantitative analytical tools such as Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) are widely used to support the development of waste management systems and to identify effective pathways towards circularity. MFA enables a systematic description of the material flows of a system, while LCA provides a global estimate of its potential environmental impacts. Christensen et al. (2020) stated that LCA is expected to play a role in waste management understanding and

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improving existing waste management systems, comparing alternative technologies, and developing both new technologies and policies. For instance, Amadei et al. (2024) combined MFA and LCA to map the impacts of the EU plastic value chain, including waste management, Rigamonti et al. (2013) to improve the municipal solid waste management system at the regional level while Turner et al. (2016) at the municipal level.

Focusing specifically on PCTW, Napolano et al. (2025) developed an MFA, founding that in EU in 2019 approximately 11 Mt of textile products were discarded, with about 80% destined for incineration or landfill, and they forecasted that the total discarded textiles in 2035 could be more than 15 Mt. Regarding waste management options, LCA studies confirm the soundness of the waste hierarchy. For instance, Solis et al. (2024a), evaluating different technologies, concluded that preparation for reuse is the most beneficial management pathway, and the environmental benefits of reuse have been confirmed also by Zamani et al. (2015). In the field of recycling, Moazzem et al. (2021) highlighted that open-loop fabric recycling achieved lower environmental impacts than fibre recycling into yarn, open-loop fibre recycling, and monomeric or polymeric chemical recycling. MFA and LCA were applied by Morell-Delgado et al. (2024) about PCTW management in Catalonia (Spain), without the impacts assessment of future scenarios. In Dahlbo et al. (2017) also alternative scenarios of PCTW management in Finland have been evaluated, but the life cycle inventory (LCI) of chemical recycling lack of details. Koligkioni et al. (2018) combined MFA and LCA, but only reuse in different geographical areas was considered, without any recycling treatment. The most complete study about this topic is Solis et al. (2024b), where different strategies such as the increase of separate collection, the availability of advanced recycling technologies and a ban on textile exports have been assessed for the EU context.

The present study aims to go more into depth in the analysis of PCTW management systems, focusing on four issues that were overlooked in past studies. First, rather than analysing single treatment options, this study evaluates integrated textile waste management systems, considering the full range of available pathways. Second, this work considered into depth the influence on LCA results of Substitution Factors (SFs), representing the displacement of virgin materials by reuse and recycling (Abagnato et al., 2024; Sandin & Peters, 2018). Third, updated LCIs about fibre and monomeric chemical recycling processes are proposed, explicitly including a de-dyeing step. Indeed, dye removal represents a key stage before recycling, since dye residues can cause instability in recycling processes and lead to inconsistent colour in recycled materials, thus reducing the market value, as confirmed by several studies (Gorreta et al., 2025; Määttänen et al., 2019; Mu & Yang, 2022; Munasinghe Arachchilage et al., 2025; Periyasamy & Harlin, 2025). However, this issue seems overlooked in previous LCA studies. Fourth, the influence of a more renewable electricity mix is considered both in the waste treatments and in the virgin processes replaced by material or energy recovery, as suggested by Bisinella et al. (2024).

These issues are investigated combining MFA and LCA with a case study from Lombardy region (Italy), selected due to the availability of primary data on PCTW management. To the best of the authors' knowledge, this is the first study applying MFA and LCA to a comprehensive PCTW management system in Italy, one of the leading textile-producing countries in Europe. However, the proposed approach is suitable also for other geographic areas, and the recommendations emerging from this study could be useful also for future developments of PCTW management in other regions or countries, to face the increasing volumes of separately collected PCTW given by the EU mandatory separate collection. Through the comparison of different scenarios, this study aims to answer three research questions to support decision making: (i) from a life cycle impact perspective, is it preferable to limit export for reuse in favour of recycling within Europe?; (ii) What is the influence on LCA results of a more renewable electricity mix in both waste treatment and virgin production processes?; (iii) What is the effect of introducing chemical recycling processes on the LCA results of the overall waste management system?

This approach aims to provide decision support and policy recommendations for authorities responsible for waste management and for operators in the PCTW management sector.

2. Materials and methods

First, scenarios were identified with the involvement of the stakeholders (officers working about the waste management policies of Lombardy region). The scenarios were identified to capture a range of possible future developments (Section 2.1). Then, PCTW composition was estimated based on trade data, and the same composition was considered for all scenarios, to ensure their comparability in the LCA (Section 2.1 and S1 in Supplementary Materials Section 1 (SM1)). According to each scenario, the MFA was developed to represent the waste flows, starting from the PCTW generation until the final disposal or the recovery of materials or energy. MFA were obtained with a combination of primary data from the Regional Environmental Agency and data from literature sources and databases (Section 2.1 and SM2). Then, for each scenario the LCA was developed (Section 2.2), combining data for the life cycle inventory from several sources (Section 2.2.2 and SM5, SM6). In the LCA, Substitution Factors (SF) were estimated to account for the virgin production displacement (Section 2.2.4). In the end, a Material Recovery Score to represent the quantity, the quality and the compliance with the waste hierarchy was estimated for each scenario, to show the trade-offs between potential environmental impacts and material recovery (Section 2.3 and SM9).

2.1. Scenarios definition and material Flow analysis

Six scenarios were identified (Table 1). In Scenario 1 (S1), which represents the current situation, textiles discarded by citizens in mixed municipal waste were sent to waste-to-energy plants in Lombardy, except for a very low fraction sent to landfill (0.2% of mixed waste, according to the Regional Environmental Agency). It was assumed that PCTW is 7% of residual waste, according to Deckers et al. (2024) and to information from waste-to-energy plants holders in Lombardy. The quantity of separately collected PCTW and the sorting locations were retrieved from the Regional Environmental Agency data (year 2021), about European Waste Codes 200110 and 200111 (municipal separate collection of textile products). The share of separately collected PCTW sent to each treatment option (reuse, recycling, energy recovery, landfill) was estimated from data provided by a sorting plant in Italy, and from Nørup et al. (2019a), Huygens et al. (2023), Napolano et al. (2025) and (European Environmental Agency, 2025a, b, c) (details in SMs). The countries where textiles were exported for reuse and recycling after the sorting step were estimated using the United Nations Comtrade Database. The ratio between closed- and open-loop recycling was taken from European Commission: Joint Research Centre et al. (2025). In open-loop recycling, cleaning wipes and insulation materials were obtained from textile waste. It was assumed, since no information was found, that 50% of the open-loop recycling was used to produce wipes, and 50% to produce insulation materials. For closed-loop recycling, a mechanical fibre recycling process was considered, where both spinnable fibres and fibres for the manufacturing of insulation materials are obtained from textiles (Duhoux et al., 2021). Before recycling, the removal and disposal of non-textile materials (leather, metals, plastics and rubber from footwear) was included. Finally, it was assumed that a fraction of the textiles exported for reuse out of Europe was not suitable for reuse and was disposed with a mix of sanitary landfill and uncontrolled disposal (UNEP, 2024): this fraction was estimated as 5.5% from Odonkor (2024), who carried out surveys among second-hand (SH) textiles importers in Ghana, and it was then subjected to sensitivity analysis.

The scenario "no export out of EU" (S2) represents a situation where, with the current sorting and recycling technologies, PCTW flows are entirely managed in the EU, without export for sorting, reuse or

Table 1

Scenarios' definition (OLR = open-loop recycling; CLR = closed-loop recycling; PV = photovoltaic). * The modelling of the more renewable electricity mix is reported in Section 2.2.5 and in Supplementary Materials (Section SM4) for each country involved in the study.

Scenario	% separate collection	Treatment technologies and recovered materials	Electricity mix	Textile waste management
S1: current scenario	29.5%	• Manual sorting • OLR (fibres and fabrics) • Mechanical CLR (spinnable fibres)	Data year 2021	Most of the separately collected TW are addressed to reuse
S2: no export out of Europe	29.5%	• Manual sorting • OLR (fibres and fabrics) • Mechanical CLR (spinnable fibres)	Data year 2021	Reuse decreases while recycling increases
S3: future baseline renewables	29.5%	• Manual sorting • OLR (fibres and fabrics) • Mechanical CLR (spinnable fibres)	50% from PV sources, 50% in proportion to the country mix in 2021 *	Same management as S1 but without uncontrolled disposal out of Europe
S4: future best technology fossil	54.3%	• Manual + automatic sorting • OLR (fibres and fabrics) • Mechanical CLR of wool (spinnable fibres) • Chemical recycling of polyester (monomers) • Chemical recycling of cotton and viscose (cellulose fibres pulp) • Alkaline/enzymatic hydrolysis of polycotton (monomers and cellulose pulp/PET flakes and glucose)	Data year 2021	Increasing of recycling thanks to new technologies. Reuse remains stable.
S5: future best technology renewables	54.3%	Same as S4	Same as S3	Same as S4
S6: future best technology renewables Lombardy	54.3%	Same as S4 and S5	Same as S3	Strong decrease in reuse and consequent increase in recycling

recycling. Textiles that were exported from the EU for reuse and recycling in S1 are all sent to open- and closed-loop recycling in Europe in S2. This scenario explores the effects of possible future restrictions on PCTW and second-hand (SH) textiles exports from the EU, or the effects of the refusal to import these streams by extra-EU countries.

In the “future baseline renewables” scenario (S3), an electricity mix with a larger share of renewables was considered compared to the electricity mix used in S1 and S2 (see Section 2.2.5 and SM4). This more renewable electricity mix was considered both in countries where waste treatments take place and where virgin production is located. In S3, the MFA was very similar to S1 except that landfill disposal in Lombardy and uncontrolled disposal outside Europe were excluded, replaced respectively by energy recovery and sanitary landfill S4 (“future best technology fossil” scenario), S5 (“future best technology renewables” scenario), and S6 (“future best technology renewables Lombardy” scenario) consider the effects of a high separate collection rate, given by EU policy of mandatory separate collection. This rate was estimated assuming that some textile products were separately collected at 80%, according to McKinsey (2022), while other types of products (cleaning articles) are entirely disposed in residual waste (see SM1, SM2). A combination of manual and automated sorting was assumed (Nellström et al., 2022): the first is for sorting of textiles for reuse, while the latter for recycling. It was assumed that closed-loop recycling means (mechanical) fibre recycling for wool, (chemical) monomeric recycling for polyester, and (chemical) fibre recycling for cotton and viscose. For blended cotton-polyester textiles both alkaline hydrolysis and enzymatic hydrolysis separation processes were considered and compared. In S4 the electricity mix is the current one, while S5 and S6 include all the aforementioned technologies, but with a more renewable electricity mix (Section 2.2.5). In S4 and S5, the absence of landfill in Lombardy and of uncontrolled disposal out of Europe were considered, as in S3. In S6 also the ban of PCTW and SH textiles exports is considered, with a waste management system entirely located in the regional boundaries, both for sorting, recycling, and energy recovery, while the reuse takes place only in Italy.

For comparability, all scenarios have the same PCTW composition. This was estimated according to the methodology developed by Napolano et al. (2025). Data about the yearly production, import and export of textile products (apparel, footwear, home textiles and technical textiles) were retrieved from the Eurostat Prodcom Database. Italy was taken as the reference, since the focus of this work is an Italian region. This methodology allowed to estimate the textiles composition according to the type of products. Then, a fibre composition was associated to each category of products (Napolano et al., 2025; Huygens et al., 2023), allowing the estimation of the composition of the total waste (see SM1).

2.2. *Life Cycle Assessment*

2.2.1. *Goal and scope*

The goal of the study is to support informed policy making in the regional waste management sector by quantifying the potential environmental impacts of the current waste management system of the PCTW generated in Lombardy and estimating the potential impacts of alternative scenarios. The target audience of the study are public officers working in the field of waste management in Lombardy (Italy) and operators of the textile waste management.

The functional unit is the management of 1 tonne of PCTW generated in Lombardy. Waste is assumed to be burden-free (Ekvall et al., 2007). The system boundaries include collection, sorting, preparation for reuse, open- and closed-loop recycling, energy recovery and disposal (Fig. 1). Transports are always considered (SMs Excel).

Since waste management systems are multifunctional, this was addressed by applying system expansion by substitution (European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2010). For reuse and recycling, the impacts of virgin production were subtracted, while energy recovery avoided the impacts of the average consumption mix of heat and electricity. These choices have been made according to the ILCD Handbook (European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2010): when large changes are not expected as a consequence of a choice, it is suggested to consider the substitution of the average market mix. This study is focused only on PCTW, which is less than 10% of the total mixed municipal waste in Lombardy. For this reason, it was assumed that a slightly higher or lower amount of PCTW addressed to energy recovery does not imply large changes in the background system. On the other hand, it was assumed that reuse and recycling can cause large changes, providing second-hand textiles and secondary raw materials that can replace virgin production, since these processes are put in place to affect the global production of textiles and fibres.

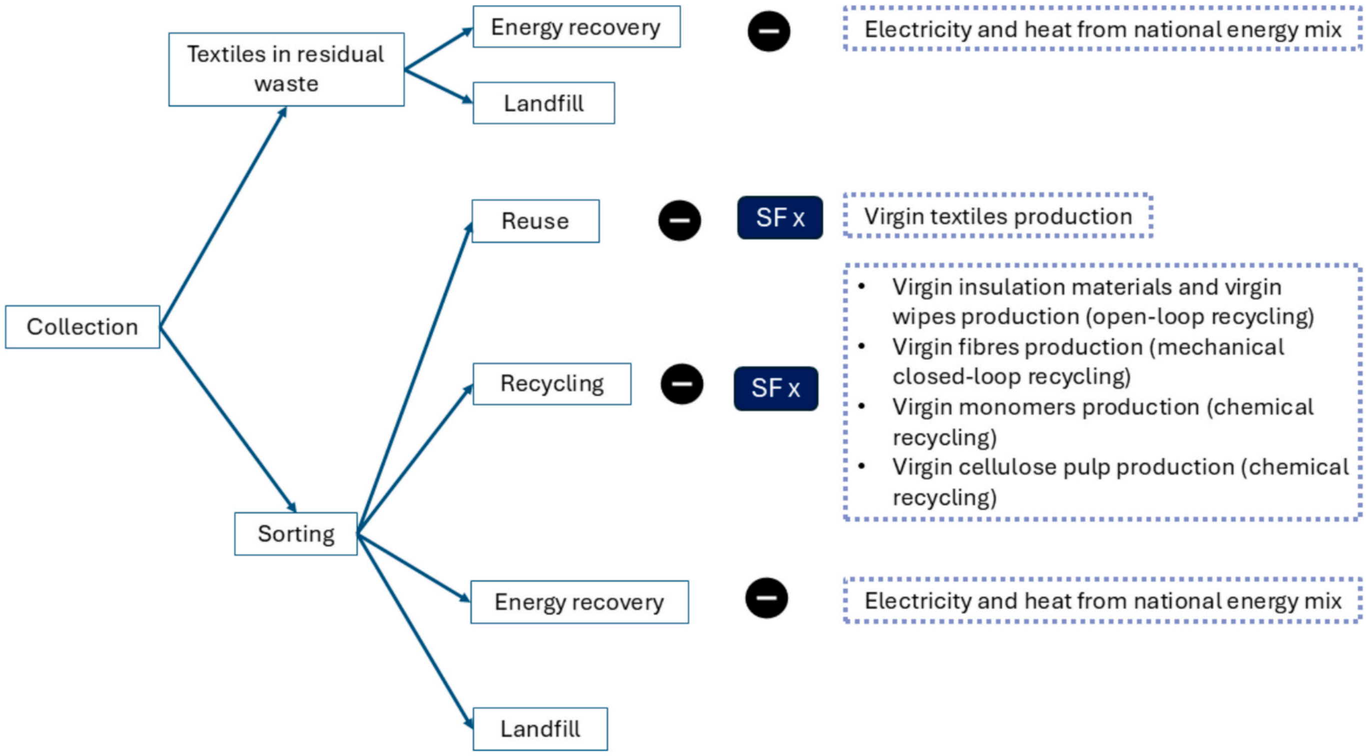


Fig. 1. System boundaries with system expansion by substitution (SF = substitution factor).

2.2.2. *Life Cycle Inventory*

Several sources were used for the Life Cycle Inventory phase (SM5, SM6, SMs Excel): (i) sorting was modelled according to Nørup et al. (2019) and Solis et al. (2024a); (ii) open-loop recycling according to Schmidt et al. (2016); (iii) closed-loop mechanical fibre recycling according to Duhoux et al. (2021) and Bianco et al. (2022); (iv) chemical recycling of polyester and of cotton according to Schmidt et al. (2016); (v) alkaline hydrolysis of polycotton according to Peters et al. (2019); (vi) enzymatic hydrolysis of polycotton according to Subramanian et al. (2020); (vii) the virgin production of textiles and fibres replaced by second-hand textiles and recycled materials have been modelled according to Notarnicola et al. (2011), Sandin et al. (2019), Wiedemann et al. (2020), Bianco et al. (2023), Schmidt et al. (2016), Zhang et al. (2021), and Duhoux et al. (2021). Some closed-loop recycling processes have been slightly modified compared with the original publications (see SM5). In particular, in the monomer recycling of polyester and in fibre recycling of cotton and viscose into cellulose pulp, a de-dyeing step was added, and in enzymatic hydrolysis, the recirculation of reactants used in the pretreatment and the enzymes recovery was also considered.

Virgin production processes for cotton were assumed to happen in India, while the other fibres and materials in China. India was chosen for cotton because of the availability of datasets referred to this country in the ecoinvent database and because India is the first country for cultivated area and the second for cotton production, according to the International Cotton Advisory Committee database. About wool, primary data were collected by Wiedemann et al. (2020) considering sheep fleece production in Australia and wool fabric production in China, reflecting the global market trends (International Wool Textile Organisation, 2026). About synthetics and man-made fibres, virgin production was assumed in China because it is the first producer and European trade partner according to the European Man Made Fibres Association.

End-of-life processes have been modelled from ecoinvent database (SMs Excel). The electricity and the heat recovered from waste incineration were calculated considering the lower heating value (LHV) of the waste, the electric or thermal efficiency of the waste-to-energy plant and the efficiency of the electricity distribution grid and of the district heating system. For energy recovery in Italy, ecoinvent datasets were integrated with data from three of the major Italian waste-to-energy plants.

2.2.3. *Software, database, and impact assessment method*

The data to model the life cycle impacts of each step were retrieved from "Cut-off" ecoinvent 3.11 datasets and processed in SimaPro v10.2.0.1. Ecoinvent datasets were selected to best represent the different technologies, considering the geography that best fit for each situation. The Environmental Footprint 3.1 was adopted as Life Cycle Impact Assessment method. The optional normalisation and weighting steps were carried out to obtain single score impacts for each scenario. The normalisation and weighting steps were carried out according to Environmental Footprint 3.1 method.

2.2.4. *Estimate of substitution factors*

A substitution factor (SF) was introduced to estimate the quality of the materials recovered from reuse and recycling (Rigamonti et al., 2020) by representing to which extent a second-hand textile or a recycled material replaces a virgin one. For fibre CLR, after a review of the existing literature, it was decided to use an initial value of 0.2. This value represents the share of recycled fibres that can be used to be re-spun together with virgin fibres in order to obtain a new yarn and then a new fabric for a new product. Fidan et al. (2021) stated that in the textile company they analysed, the maximum recycled cotton content in denim weaving was 20%, while Arafat & Uddin (2022) stated that yarn containing only up to 10% post-consumer recycled cotton is suitable for knit fabric. No data were found regarding the share of recycled staple fibres from mechanical tearing of polyester or polycotton garment that can be mixed with virgin fibres to manufacture new fabrics. Solis et al., (2024a) reported SF for fibre recycling, but it seems that those values represent the share of recycled fibres obtained from the treatment of 1 tonne of waste, and not the quality of the recycled fibres in comparison to the virgin fibres. Also open-loop recycling into insulation materials usually requires mixing recycled fibres with virgin materials, which are used as binder or to ensure mechanical performance and manufacturability. The share of recycled and virgin materials can vary according to the situation. For instance, Majumder et al. (2023) obtained thermo-acoustic insulation materials with 40% recycled wool fibres, 40% old jute bags and 20% virgin polyester binder; Hegyi et al. (2022) tested insulation mattresses with 43% recycled polyester fibres, 36% recycled plastics and 21% virgin cellulosic fibres; Samardzioska et al. (2023) tested insulation panels with 93% recycled textiles and 7% virgin polyester binder. Given these values, in the present study it was assumed that a reasonable value for the SF of textile fibres obtained from OLR and addressed to insulation panels manufacturing is 0.8, considering that 20% of virgin material is still needed. On the other hand, for OLR into cleaning wipes the SF was assumed to be 1, since it was expected that virgin and secondary wipes have the same functionality (Schmidt et al., 2016). For the chemical monomeric and polymeric recycling processes considered in the future scenarios, the SF is 1, since the monomers obtained from the depolymerisation of synthetic textiles, the amorphous PET granules and the glucose syrup obtained from enzymatic process, have the same quality as the replaced materials. Cotton and viscose pulping allows to obtain a cellulosic pulp which is usually characterised by shorter fibres and shorter polymer length than virgin pulp for textile production (Peterson et al., 2022). However, in this work, according to Schmidt et al. (2016), the 1:1 substitution of virgin sulphate pulp was considered, assuming that the recovered pulp could be used in different sectors. However, since it is difficult to clearly estimate a proper value for the SFs, as it depends on several factors, these parameters have been subjected to a sensitivity analysis. In this study SF was estimated according to technical factors, but SFs can consider also economical and market aspects. For instance, SF represent also the penetration of the recycled materials in the market: the sensitivity analysis with a lower SF gives insights about the impacts of the PCTW management system when there is less demand of recycled materials.

When textiles are sent to reuse, the replacement of virgin textiles was considered. In this case, the SF represent how much a second-hand textile replaces the purchase of a new one and if its lifespan is lower than the new one. The SF for reuse is calculated as the product of two terms: the first term is referred to the purchase habits (Nichilo et al., 2025), while the second to the lifespan of the second-hand textiles. The SF for reuse is variable according to the location, since it depends on socio-economic aspects (Koligkioni et al., 2018), and it is currently assessed with surveys among costumers. Published behavioural surveys regarding second-hand (SH) textiles were considered to estimate the SF in the different locations where reuse happens (Farrant et al., 2010; Laitala & Klepp, 2021; Nørup et al., 2019b; Bakowska et al., 2025; Vinted Climate Change Impact Report, 2021). According to this approach, SF was 27% in Italy, 33% in East Europe, and 28% out of Europe (see SM5.10). Then, a sensitivity analysis was carried out on these values. Also in this case, SF variation represents both a variation in the demand of SH textiles and in their quality (lifespan, which is also due to personal behaviour and cultural aspects).

2.2.5. *Electricity and heat mixes modelling*

This work included the modelling of future electricity mixes with a larger share of renewables, to assess how much this aspect affects the LCA results. The electricity mix modification affected both waste treatments and virgin production. In particular, the following LCA modelling aspects in the context of the present work are influenced: (i) the burdens of sorting and recycling processes; (ii) the credits from energy recovery, since it was avoided the production from the average national mix; (iii) the credits from reuse and recycling, since the virgin production was displaced. The analysed system includes processes in different areas of the world: India both for virgin production and recycling; China for virgin production; European countries (Italy, Germany, France, Lithuania, Bulgaria, Slovakia) for sorting and recycling; Tunisia for sorting. In scenarios with the current electricity mix (S1, S2 and S4) the ecoinvent datasets about electricity market mixes of the different countries were used, with data referred to 2021. For heat, the average market mix displaced by energy recovery (only where also heat was recovered) was estimated from the International Energy Agency Data Browser for each country (see SM4).

For future renewables scenarios (S3, S5, S6), it was assumed that 50% of the electricity generation came from photovoltaic (PV) sources, while the remaining 50% was considered equal to the current electricity mix of the different countries according to ecoinvent database (see SM4 and SMs Excel). This choice is a simplified assumption to represent a higher penetration of renewable sources in the electricity mix of different countries. However, according to the forecasts from the Renewable Energy Progress Tracker by the International Energy Agency and Tracker (2026), PV represent around 75% of the net additions in global renewable electricity generation in the future. Since this study is not focused on the analysis of decarbonisation pathways of electricity generation, setting the 50% of electricity generation from PV was deemed sufficient to understand how the penetration of the most relevant renewable electricity source affects the LCA result of the PCTW management system. Future studies, specifically focused on prospective LCA analyses, need to assess more into depth the decarbonisation effects on waste management systems with the use of more complex tools and methods such as PREMISE (Sacchi et al., 2022).

Only the electricity mixes of the countries involved in the system were modified (China, India, Italy, Germany, France, Lithuania, Bulgaria, Slovakia, Tunisia). The average residential heating mix for future scenarios in Europe was instead modelled according to Neuwahl et al. (2024) (see SM4). The electricity mix was modified in the ecoinvent datasets that in the future scenarios were used to model the foreground system (both waste management processes and virgin production processes). The list of the datasets where the electricity mix was modified is available in the Excel SMs.

2.2.6. *Analysis with a different point of substitution*

In a second step of the work, a different point of substitution was considered, always following the system expansion by substitution approach (see SM10). Indeed, the substitution approach can be further expanded to account also for impacts on the emissions of subsequent products (Ekvall et al., 2025). In case of reuse, after sorting, also the use phase and the end-of-life in the country where the textile product was exported for reuse were considered. For recycling, the impacts of the recycling process, the manufacturing, the use and end-of-life of the product obtained from recycling are included. The use phase was modelled according to European Commission: Joint Research Centre et al. (2014). When subtracting the virgin impacts, the whole lifecycle of the virgin products was considered (raw materials production, textiles manufacturing, use phase, end-of-life). This approach was followed to show the influence of SF. Indeed, when SF is 1 the subtraction of the entire virgin lifecycle impacts means that only the impacts of virgin materials production are subtracted, since the impacts of the use phase and of end-of-life are the same for the virgin and the recycled materials. Instead, when SF is lower than 1, also the contributions of the other lifecycle phases are included (see SM10).

2.3. *Material recovery score*

Since MFA represents the entire waste flows and LCA estimate the potential environmental impacts of waste management, it was chosen to identify a unique score for each scenario to describe the recovered materials. This Material Recovery Score (MRS) captures not only the amount and the quality of the recovered materials, which are considered also in MFA and LCA, but also the compliance with the waste hierarchy. MRS helps to aggregate in a single indicator how much each scenario allows the recovery of materials, and could be useful for the communication of the results to policy makers. Indeed, points were assigned to the recovered products and materials in each scenario according to three different aspects: (i) the compliance with the waste hierarchy; (ii) the quality of the recovered materials respect to the virgin; (iii) the point of substitution in the textile production.

According to the waste hierarchy, higher points were assigned to materials recovered for reuse than for recycling (see SM9). The quality of the recovered materials was represented through the SF. The point of substitution was identified at the level of: (i) product; (ii) fabric; (iii) yarn; (iv) fibre; (v) polymer; (vi) monomer; (vii) raw materials.

The different options in the three aspects (waste hierarchy compliance, quality, and point of substitution) were ranked and to each option points were assigned and then normalised dividing by the maximum points in the scale. A normalised score was obtained for each recovered material (see SM9 for more details about scores and normalisation). In the end, the MRS for each scenario was obtained according to equation (1):

$$ScenarioMaterialRecoveryScore = \sum_{i=1}^{n} \frac{massrecoveredmaterial_i}{masstotalwasteinput} \bullet normalisedmaterialscore_i \tag{1}$$

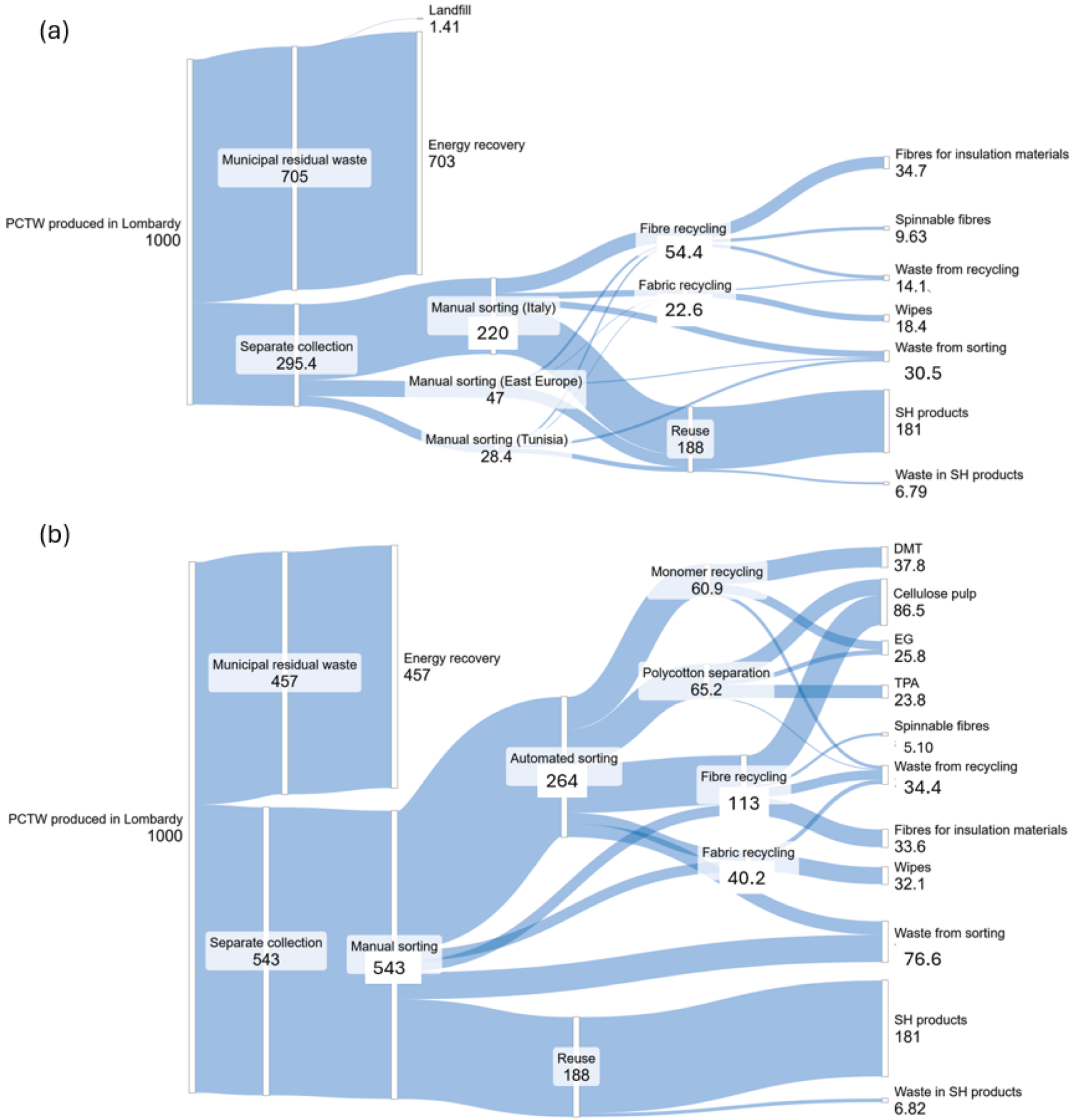


Fig. 2. Material Flow Analysis of scenario 1 "current situation" (a) and of scenario 4 "future best technology fossil" and 5 "future best technology renewables" (b). Data are referred to the functional unit of managing 1000 kg of waste in input to the waste management system (SH = second-hand). Diagrams have been created with the use of SankeyMATIC.

3. Results

3.1. Material flow analysis results

Fig. 2 shows the MFA of PCTW generated in Lombardy for three of the analysed scenarios, namely "current situation" (S1) and "future best technology" (S4 and S5). From the analysis of the primary data provided by the Regional Environmental Agency, in 2021, the separately collected PCTW in Lombardy were 37.5 kt, while the estimated PCTW in residual waste were 89.4 kt, with a total PCTW generation of 126.9 kt in 2021. Then, the results were scaled on the management of 1 t of waste to show the MFA of each scenario. In the SMs (SM2 and SMs Excel), the MFA results for all the scenarios are reported.

In the current scenario S1, most PCTW is deposited by citizens into mixed municipal waste, which is almost entirely sent to energy recovery in the waste-to-energy plants of the region. The separate collection rate is 29.5%. Three main sorting hubs were identified: Italy (Lombardy and Campania regions), Eastern Europe (Bulgaria, Lithuania, Slovakia) and Tunisia. Most separately collected PCTW is sent to reuse: SH products represent 61.3% of the separate collection. They are followed by fibres for insulation materials (11.8% of separate collection), wipes for cleaning (6.24%) and spinnable fibres (3.26%). The textiles discarded after sorting, recycling and those non-suitable for reuse in the second-hand exports represent together 17.4% of the separate collection.

In the "no export out of Europe" scenario (S2) the separate collection rate remained the same. The main differences with S1 are the absence of sorting in Tunisia, and the decrease of PCTW sent to reuse, that in S2 are 24.0% of the separate collection. On the other hand, more fibres for insulation materials, wipes and spinnable fibres were obtained (respectively 30.6%, 16% and 8.58% of separately collected PCTW).

S3 ("future baseline renewables") has the same MFA of S1, with the only difference being the elimination of landfill in Lombardy for PCTW in mixed municipal waste, and of uncontrolled waste disposal out of Europe, replaced by sanitary landfill.

The "future best technology fossil" and "future best technology renewables" scenarios (S4 and S5) show a strong increase in separate collection (54.3% of the total PCTW). The textiles sent for reuse remain the same as S3 and the higher flow of collected PCTW is sent to recycling. With the availability of new recycling technology, the recovered polyester monomers represent 16.1% of the separate collection, and cellulose pulp 15.9%. On the other hand, spinnable fibres from mechanical recycling are only the 0.94% of the separate collection, since in these scenarios only wool was sent to this treatment. Open-loop recycling products (fibres for insulation materials and wipes) represent together 12.1% of the separate collection.

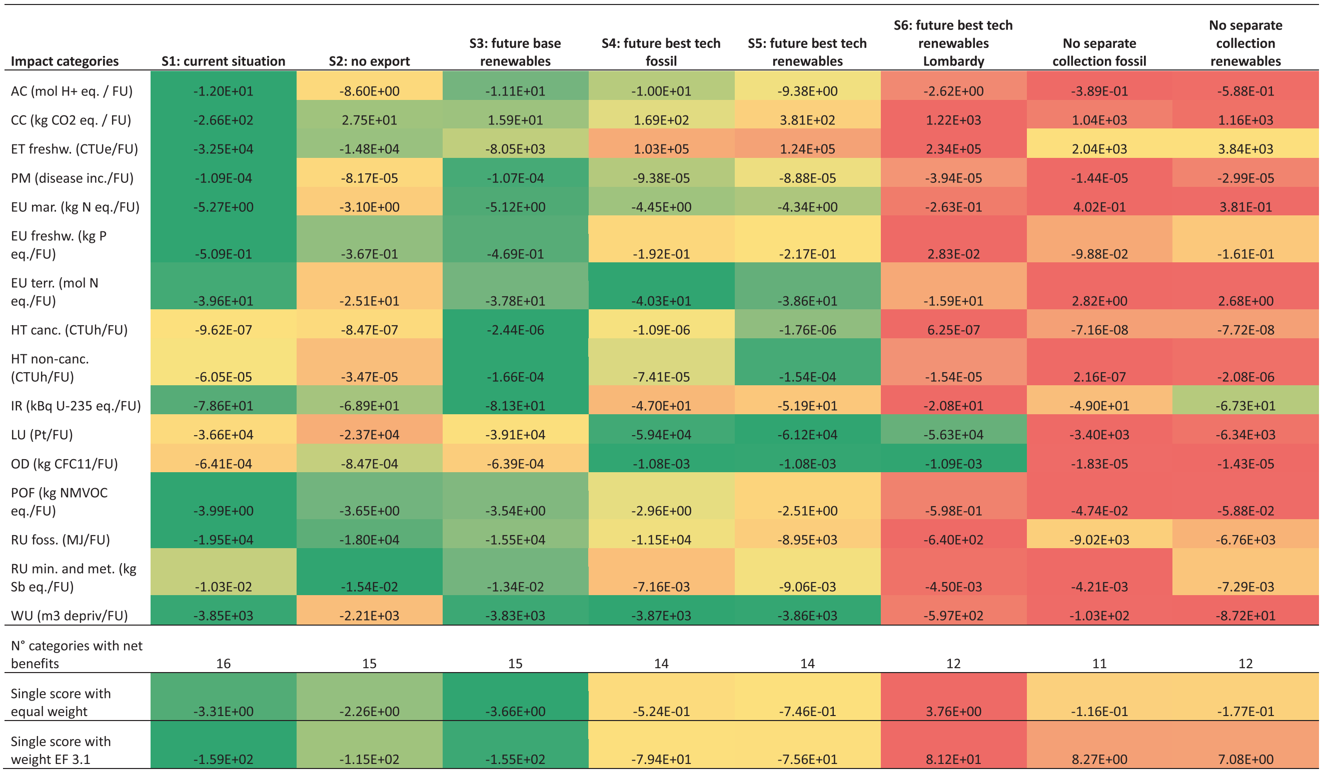
The materials recovered from recycling are even more in S6 ("future best technology renewables Lombardy"), where it was assumed that all the PCTW collected in Lombardy are managed inside the regional boundaries. Recovered monomers are 28.4% of separate collection, cellulose pulp 28.1%, and spinnable wool fibres 1.66%. Reuse strongly decreased (4.77% of separate collection) while open-loop recycling applications were 12.8%.

3.2. The combination of MFA and LCA results

The integration of MFA and LCA provides a comprehensive view of textile waste management by linking material flows with environmental impacts. All scenarios show net benefits in several impact categories

Table 2

LCA results for all scenarios. AC = Acidification; CC = Climate Change; ET freshw. = Ecotoxicity freshwater; PM = Particulate Matter; EU mar. = Eutrophication marine; EU terr. = Eutrophication terrestrial; HT canc. = Human Toxicity carcinogenic; HT non-canc. = Human Toxicity non-carcinogenic; IR = Ionising Radiation; LU = Land Use; OD = Ozone Depletion; POF = Photochemical Ozone Formation; RU foss. = Resource Use fossil; RU min. met. = Resource Use minerals and metals; WU = Water Use. The Single score with equal weight is the score obtained after normalisation as a sum of all the normalised impacts (meaning that to each category the same weight was assigned). For each impact category, the cells background shows the ranking of the scenarios, from the worst scenarios in red to the best scenarios in green.



Impact categories	S1: current situation	S2: no export	S3: future base renewables	S4: future best tech fossil	S5: future best tech renewables	S6: future best tech renewables Lombardy	No separate collection fossil	No separate collection renewables
AC (mol H+ eq. / FU)	-1.20E+01	-8.60E+00	-1.11E+01	-1.00E+01	-9.38E+00	-2.62E+00	-3.89E-01	-5.88E-01
CC (kg CO2 eq. / FU)	-2.66E+02	2.75E+01	1.59E+01	1.69E+02	3.81E+02	1.22E+03	1.04E+03	1.16E+03
ET freshw. (CTUe/FU)	-3.25E+04	-1.48E+04	-8.05E+03	1.03E+05	1.24E+05	2.34E+05	2.04E+03	3.84E+03
PM (disease inc./FU)	-1.09E-04	-8.17E-05	-1.07E-04	-9.38E-05	-8.88E-05	-3.94E-05	-1.44E-05	-2.99E-05
EU mar. (kg N eq./FU)	-5.27E+00	-3.10E+00	-5.12E+00	-4.45E+00	-4.34E+00	-2.63E-01	4.02E-01	3.81E-01
EU freshw. (kg P eq./FU)	-5.09E-01	-3.67E-01	-4.69E-01	-1.92E-01	-2.17E-01	2.83E-02	-9.88E-02	-1.61E-01
EU terr. (mol N eq./FU)	-3.96E+01	-2.51E+01	-3.78E+01	-4.03E+01	-3.86E+01	-1.59E+01	2.82E+00	2.68E+00
HT canc. (CTUh/FU)	-9.62E-07	-8.47E-07	-2.44E-06	-1.09E-06	-1.76E-06	6.25E-07	-7.16E-08	-7.72E-08
HT non-canc. (CTUh/FU)	-6.05E-05	-3.47E-05	-1.66E-04	-7.41E-05	-1.54E-04	-1.54E-05	2.16E-07	-2.08E-06
IR (kBq U-235 eq./FU)	-7.86E+01	-6.89E+01	-8.13E+01	-4.70E+01	-5.19E+01	-2.08E+01	-4.90E+01	-6.73E+01
LU (Pt/FU)	-3.66E+04	-2.37E+04	-3.91E+04	-5.94E+04	-6.12E+04	-5.63E+04	-3.40E+03	-6.34E+03
OD (kg CFC11/FU)	-6.41E-04	-8.47E-04	-6.39E-04	-1.08E-03	-1.08E-03	-1.09E-03	-1.83E-05	-1.43E-05
POF (kg NMVOC eq./FU)	-3.99E+00	-3.65E+00	-3.54E+00	-2.96E+00	-2.51E+00	-5.98E-01	-4.74E-02	-5.88E-02
RU foss. (MJ/FU)	-1.95E+04	-1.80E+04	-1.55E+04	-1.15E+04	-8.95E+03	-6.40E+02	-9.02E+03	-6.76E+03
RU min. and met. (kg Sb eq./FU)	-1.03E-02	-1.54E-02	-1.34E-02	-7.16E-03	-9.06E-03	-4.50E-03	-4.21E-03	-7.29E-03
WU (m3 depriv/FU)	-3.85E+03	-2.21E+03	-3.83E+03	-3.87E+03	-3.86E+03	-5.97E+02	-1.03E+02	-8.72E+01
N° categories with net benefits	16	15	15	14	14	12	11	12
Single score with equal weight	-3.31E+00	-2.26E+00	-3.66E+00	-5.24E-01	-7.46E-01	3.76E+00	-1.16E-01	-1.77E-01
Single score with weight EF 3.1	-1.59E+02	-1.15E+02	-1.55E+02	-7.94E+01	-7.56E+01	8.12E+01	8.27E+00	7.08E+00

(Table 2) thanks to avoided virgin production from reuse and recycling, though the magnitude varies by scenario (Fig. 3). Reuse, mechanical fibre recycling, and open–loop recycling generally yield net benefits because their burdens are lower than the avoided impacts, whereas chemical recycling results in net burdens across most categories.

Although preparation for reuse accounts for less than 20% of total waste in all scenarios, it delivers a major share of environmental credits. For instance, in S2, reuse represents only 7% of input waste but it contributes 52% of Acidification credits, 66% of Water Use credits, and 97% of non–carcinogenic Human Toxicity credits. Credits arise mainly from avoided wool, cotton, and viscose production (Acidification, Land Use, Water Use), avoided dyeing (carcinogenic Human Toxicity, Ecotoxicity), and avoided energy use in virgin textile manufacturing (Climate Change).

Textiles not separately collected (70.5% of PCTW in S1–S3; 45.7% in S4–S6) generate Climate Change burdens due to incineration of synthetics, while energy recovery provides credits in other impact categories (Resource Use, Ionising Radiation, Freshwater Eutrophication, Particulate Matter).

Closed–loop mechanical fibre recycling and open–loop recycling (fibres and fabrics) represent less than 10% of waste in most scenarios (except for 20% in S2) but contribute notable credits, especially in Ozone Depletion and Resource Use, mainly from avoided polyester production.

Chemical monomer recycling of polyester, cotton and viscose pulping, and polycotton chemical separation (18% of waste in S4 and S5) shows burdens that typically outweigh benefits. In Ecotoxicity, polyester chemical recycling contributes 96% of burdens (S4), largely due to dimethyl sulfoxide (DMSO) used in polyester de–dyeing. Other burdens stem from acid use (H_2SO_4 in cotton pulping and polycotton alkaline

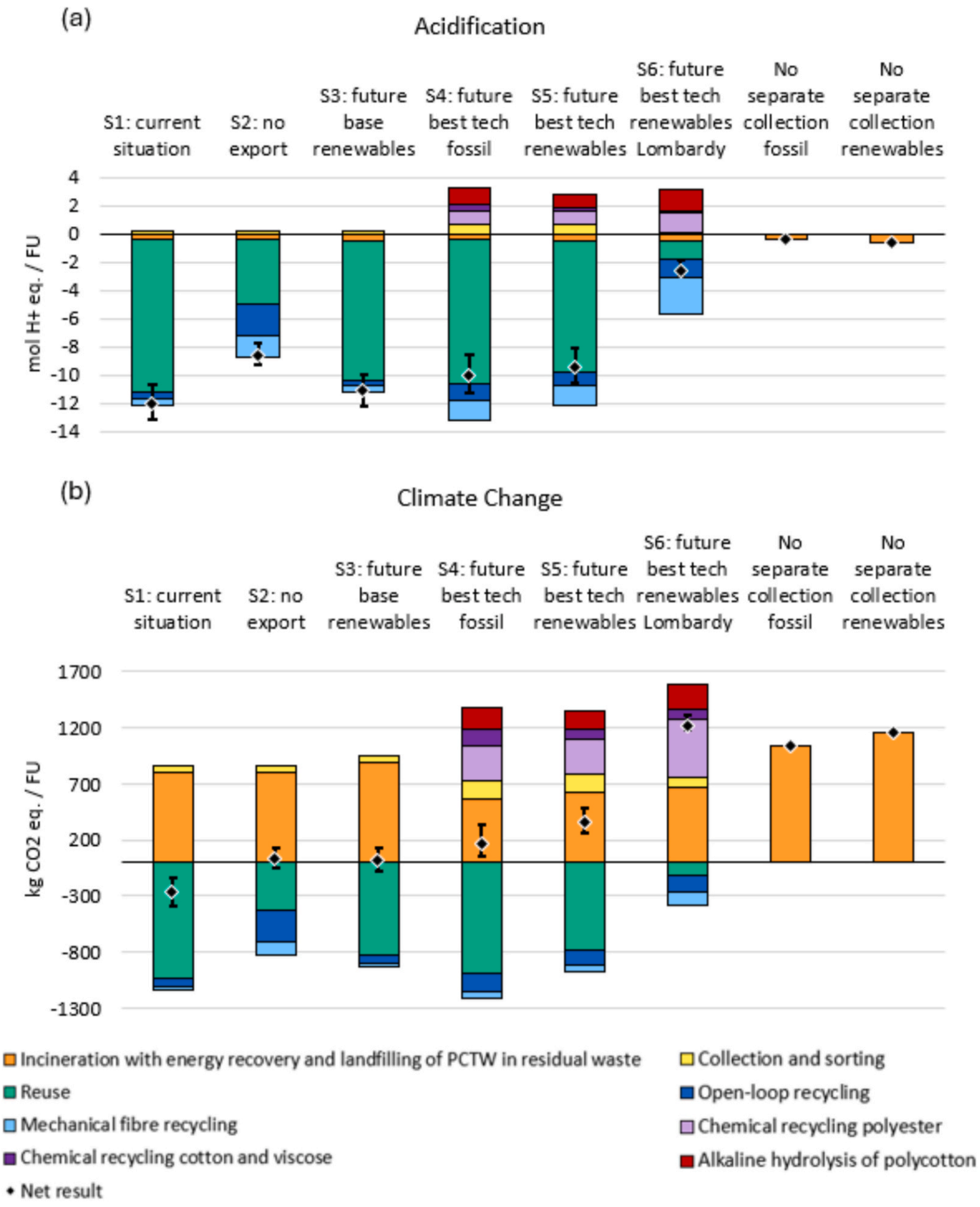


Fig. 3. Life Cycle Assessment results in Acidification (a) and Climate Change (b) for the 6 analysed scenarios and for two additional scenarios where all textiles are sent to energy recovery in Lombardy. The error bars represent the variation of the results with the increase or the decrease in all Substitution Factors (of reuse and recycling) by 10%. The Substitution Factors already set equal to 1 were not increased in the sensitivity analysis (secondary wipes from open-loop recycling and materials from chemical recycling).

Table 3

Single score impacts (with equal weights, obtained with the normalisation factors of EF 3.1 method) and Material Recovery Score (MRS) for each scenario. The ranking according to single score impacts and to Material Recovery Score are indicated into brackets. Last column indicates the % contributions of the materials recovered in each scenario to the overall MRS.

Scenario	Single score impacts (ranking)	MRS (ranking)	Contributions to MRS
S1 (current situation)	−3.31 (2°)	0.206 (3°)	Second-hand products (75%); fibres for insulation materials (14%); fabrics for wipes (9%); fibres for spinning (3%)
S2 (no export out of EU)	−2.26 (3°)	0.194 (4°)	Fibres for insulation materials (37%); second-hand products (31%); fabrics for wipes (24%); fibres for spinning (7%)
S3 (future baseline, renewables)	−3.66 (1°)	0.206 (3°)	Second-hand products (75%); fibres for insulation materials (14%); fabrics for wipes (9%); fibres for spinning (3%)
S4 (future best technology, fossil)	−0.52 (5°)	0.359 (1°)	Second-hand products (43%); cellulosic fibres from chemical pulping (21%); monomers (19%); fabrics for wipes (9%); fibres for insulation materials (8%); fibres for spinning (1%)
S5 (future best technology, renewables)	−0.75 (4°)	0.359 (1°)	
S6 (future best technology, renewables, Lombardy)	3.76 (6°)	0.343 (2°)	Cellulosic fibres from chemical pulping (39%); monomers (35%); fabrics for wipes (9%); fibres for insulation materials (9%); second-hand products (6%); fibres for spinning (1%)

hydrolysis has relevant impacts on Acidification), high heat demand (Climate Change), and chemicals production (Resource Use). Nonetheless, chemical recycling yields substantial Land Use credits (31% in S4–S5; 59% in S6), mainly from cellulose pulp and terephthalic acid (TPA) recovery. Alkaline hydrolysis performs better than enzymatic hydrolysis in all impact categories (see SM8).

Comparing scenarios, S1 (current) and S3 (future baseline renewables) perform best, driven by reuse credits. Reductions in reuse due to export restrictions increase impacts regardless of technology level. Indeed, S2 impacts exceed S1, and S6 impacts exceed S5. The impacts of two additional scenarios, where all PCTW are disposed by citizens in the residual waste and sent to energy recovery in Lombardy have been calculated, both with the current and the renewable electricity mix. These two scenarios generally show worse performance than S1–S5 and often better than S6 (Table 2; Fig. 3).

A higher PV electricity share reduces both burdens and credits in categories like Acidification and Climate Change, typically increasing overall impacts due to lower energy–related credits (Fig. 3). However, renewables scenarios perform better in Resource Use (minerals and metals) and carcinogenic Human Toxicity. When focusing on single scores after normalisation, renewable scenarios are slightly better than scenarios with the current mix, while after the weighting step the situation is the opposite, since the Climate Change category has a relevant weight factor in EF 3.1 method.

When also the second life of recovered materials was included in the analysis, considering a different point of substitution, the waste management system presented no more net benefits but the ranking between the scenarios did not change (see SM10). The credits from the avoided virgin lifecycle, indeed, are overcome by the burdens of the use phase of the products, since the SFs are quite low.

3.3. Material recovery score results

The MRS shows the best result in the future best technology scenarios (S4 and S5), where the separate collection is higher and reuse and recycling are combined. Also for MRS, the restrictions on exports for reuse lead to a worse result, such as for potential environmental impacts. Indeed, S6 performs worse than S4 and S5, while S2 worse than S1 and S3. Table 3 shows the results in single score LCA impacts together with the MRS of the scenarios. A trade–off between environmental impacts and material recovery is revealed: scenarios with higher impacts (S4, S5, S6) also achieve higher MRS.

3.4. Sensitivity analyses

The influence of separate collection rate, waste content in textiles sent to reuse, SFs, and chemical recycling design on LCA results was tested.

A threshold for separate collection rate was identified for the case study: it was found that, in the current situation, a rate lower than 23.5% (breakeven point) leads to net Climate Change burdens. About SH textile export, S1 showed higher impacts than S2 when the waste content in SH textiles exported outside the EU exceeded 10% for Human Toxicity (cancer), revealing the importance of setting controls to check their reusability (see SM7).

The sensitivity of results to SFs was tested by applying a ± 10% variation, and SFs for reuse showed a much stronger influence than those for recycling. For instance, a 10% increase in reuse SFs reduced the single score results by 60% in S4, 44% in S5, and 10% in S1, while scenarios with lower reuse rates (S2 and S6) were less affected. On the other hand, a crisis in SH market, with lower displacement of virgin production, causes a relevant increase in the overall impacts of PCTW management systems. Increasing SF for mechanical fibre recycling by 10% resulted in reductions below 3% in all scenarios (SM7), since recycling avoids less impacts than reuse and since PCTW sent to recycling are less than those sent to reuse. When all SFs were simultaneously increased by 10%, single-score impacts decreased by 11% in S1, 9% in S2, 10% in S3, 66% in S4, 48% in S5, and 2% in S6, but the ranking between the six scenarios remained the same.

Since chemical recycling showed high impacts contribution, the impacts of a process configuration where mechanical and chemical treatments are applied in series were assessed (for polyester, polycotton, cotton and viscose). First, spinnable fibres are recovered mechanically, while only non-spinnable ones are sent to chemical recycling, decreasing the amount of solvents and heat needed to treat the same amount of textile waste. This led to substantial impact reductions in S4, S5, and S6, with single score decreases of 261%, 182%, and 98%, respectively. Climate Change was among the most affected impact categories (Fig. 4), and the overall performance of S4 and S5 became comparable to that of the best-performing scenarios (S1 and S3). A further analysis on polyester monomer recycling is described in SM7, with the suggestion of lower demand of solvent for dyes removal (due to a higher recovery rate).

In the end, a breakeven analysis on chemical recycling efficiency was conducted by reducing LCI inputs and outputs by 10–90% to represent future industrial optimisation. Results indicate that chemical recycling

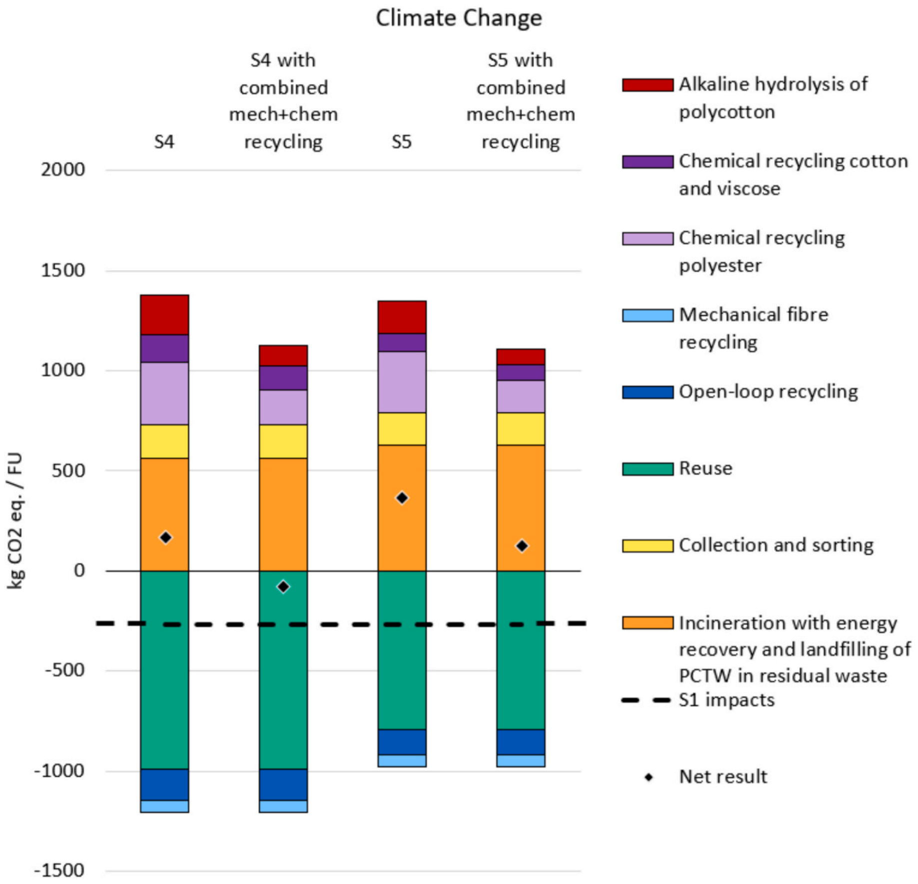


Fig. 4. Comparison of Climate Change impacts with the implementation of a mechanical step to recover spinnable fibres followed by the chemical process to recover fibres (cellulose pulp) or monomers (ethylene glycol, terephthalic acid and dimethyl-terephthalate). The improved scenarios are compared with the Climate Change impacts of the current situation (S1), that was the best scenario in this impact category.

still requires significant improvements: S4 outperformed S1 for Climate Change and Acidification only when process inputs were reduced by at least 50%, while S6 remained more impactful than S1 even under the most optimistic assumptions (Fig. 5). Areas of improvement can be identified in higher solvent and reactants recovery (to decrease the virgin demand of chemicals), by-products recovery (such as salts generated in alkaline hydrolysis, see SM5.8), recovery of removed dyes, and lower heat demand (given by proper industrial processes design).

4. Discussion and interpretation

By integrating MFA and LCA, this study shows that PCTW management performance is highly sensitive to how material flows are distributed among reuse, recycling, energy recovery, and disposal. Even small changes in MFA shares affect LCA results, confirming the importance of system configuration. This study represents the first attempt to capture PCTW flows in an Italian context with the use of primary data about the management of PCTW separately collected, providing a clear state-of-the-art overview to decision makers (see Table S20).

Reuse consistently emerges as the strategy with greatest impact–avoidance potential, aligning with previous research (Dahlbo et al., 2017; Schmidt et al., 2016; Solis et al., 2024a; Zamani et al., 2015). Given environmental credits from reuse, restrictions to the export of SH textiles are not beneficial, but it is crucial that only reusable items are exported. Reuse benefits are significantly influenced by SF. SF estimate the is challenging because behavioural patterns strongly influence whether SH products displace virgin purchases. In addition, rebound effects related to SH clothing consumption may occur (Mizrachi and Sharon, 2025) , even if they are out of the scope of the present study. Future studies should investigate these aspects and integrate them in LCA. Also, effects related to the social impacts should be addressed in the future.

Chemical recycling shows higher impacts than in earlier literature. This is probably due to a more complete LCI: process steps that in previous studies were often overlooked were considered here (de–dyeing, disposal of chemicals, and wastewater treatment after recycling). For instance, in Schmidt et al. (2016) dyes removal is not mentioned, and it is not stated how the unreacted polyester waste is managed, while in Dahlbo et al. (2017) the LCI includes only electricity and heat inputs. In Solis et al. (2024a) the LCI of polyester chemical recycling is not available due to non-disclosure agreement, but also in this case no indication is found about de-dyeing. The present study results, in this way, show the importance of considering or not some stages in the LCA of these processes (especially the dyes removal) for future LCA studies and for processes developments. Since the combination of mechanical and chemical treatments showed significant improvements in LCA results, it is recommended first to recover the spinnable fibres mechanically, and then to send to chemical recycling the non-spinnable fibres. Given the development of new textile recycling technologies, harmonised upscaling methodologies are needed to derive reliable inventories from laboratory scale data and to support the design of emerging recycling processes. At the same time, product–oriented LCAs are needed to evaluate whether textiles from emerging recycling technologies outperform virgin alternatives.

Comparability with other studies remains limited due to differing modelling assumptions and LCI sources. Moreover, since MFA and LCA are combined here, outcomes depend on both process–level inventories, separate collection rates and MFA flows, as well as regional conditions

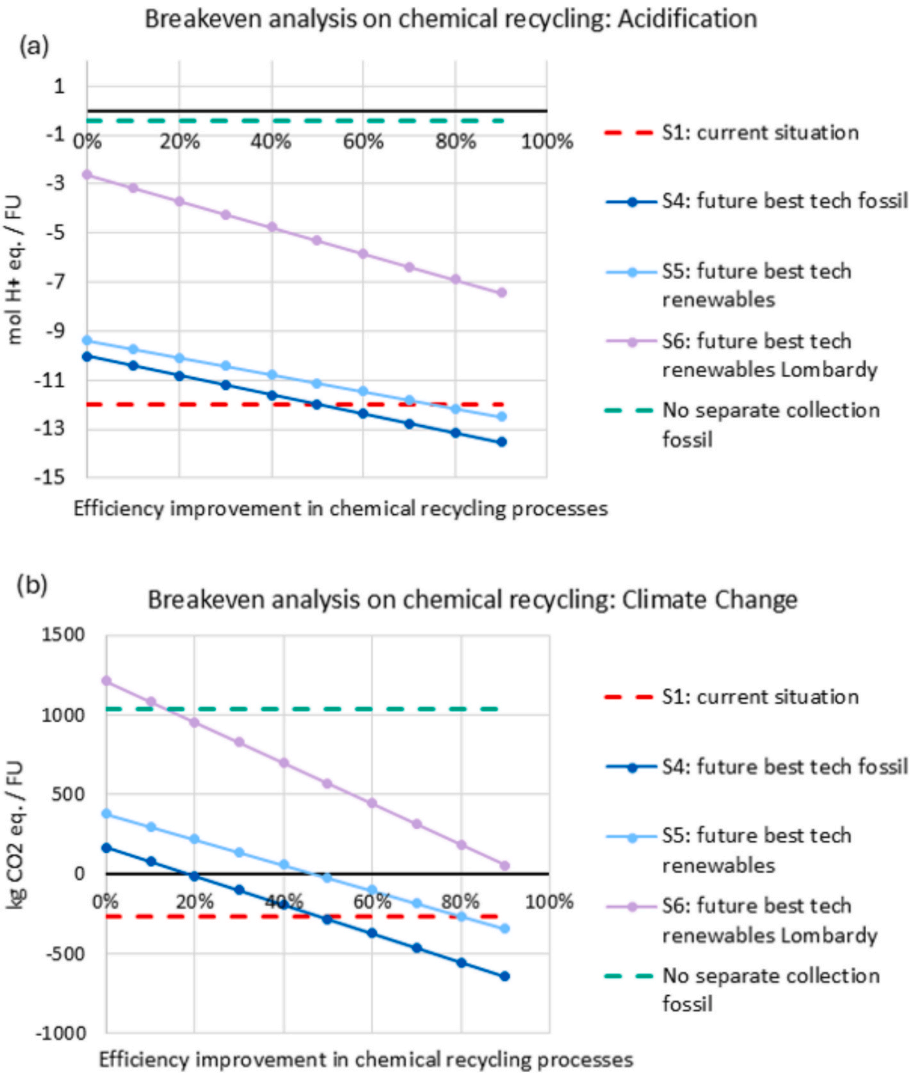


Fig. 5. Breakeven analysis about energy and materials demand in chemical recycling processes for Acidification (a) and Climate Change (b). The efficiency improvement on x axis represents the decrease in materials and energy demand in chemical recycling processes. For instance, if efficiency improvement is 10%, it means that the input of materials and energy in the life cycle inventory was decreased of 10% in comparison to the original values. The results are compared to the Acidification and Climate Change impacts of two benchmarks: the current situation (S1) and the situation where all the waste is sent to energy recovery in Lombardy with the current electricity mix ("No separate collection fossil").

and scenarios definition. However, some comparisons with Solis et al. (2024b) can be done: (i) in the present study the impacts of the current scenario are lower, mainly given by the very small fraction of PCTW sent to landfill in Lombardy; (ii) here the impacts of chemical recycling are higher, because of the differences in LCI sources and because of the consideration of a de-dyeing stage in the present study; (iii) mechanical recycling is usually better than chemical treatments, aligned with Solis et al. (2024a); (iv) alkaline hydrolysis of polycotton performs better than enzymatic separation, as in Solis et al. (2024a).

A key limitation is that the study is not a fully prospective LCA, since background processes do not systematically reflect future energy scenarios, nor were they aligned with Shared Socioeconomic Pathways by the Intergovernmental Panel on Climate Change (IPCC). For future research, the use of dedicated tools such as PREMISE (Sacchi et al., 2022) is therefore recommended. Despite this limitation, results suggest that scenarios with higher PV shares tend to show slightly higher impacts in some relevant categories (e.g. Climate Change) due to reduced credits from material recovery as the energy system decarbonises.

5. Conclusions

This study combined MFA and LCA to evaluate current and future textile waste management scenarios, with a case study about an Italian region (Lombardy). Combining the two methods enabled the assessment of scenarios where all treatment options coexist, reflecting real system conditions rather than isolated technologies.

Six scenarios were modelled to examine the effects of limiting exports, increasing renewable electricity shares, and introducing advanced recycling technologies. The findings, addressing three research questions, showed that: (i) restricting exports of second-hand textiles outside Europe worsens LCA results, as reuse credits from avoided virgin production are relevant; (ii) considering higher renewable electricity shares in waste treatments and in avoided virgin productions, leads to higher (e.g. Climate Change) or lower (e.g. minerals and metals Resource Use) overall LCA impacts according to the impact category (iii) the introduction of chemical recycling leads to a general increase of the whole PCTW management system impacts, due to energy-intensive operations and solvent use, with relevant impacts due to dyes removal steps.

However, combining mechanical and chemical recycling shows improvement potential if efficiency and process design are optimized.

The main recommendations for decision makers are: (i) within the current PCTW management system in Lombardy, a separate collection rate higher than 23.5% should be ensured to obtain net benefits of the PCTW management systems on Climate Change; (ii) controls addressed to check SH textiles reusability are needed, to ensure the environmental benefits of reuse; (iii) following the waste hierarchy and prioritise mechanical treatments before chemical recycling leads to lower overall impacts in PCTW management; (iv) subsidise chemical recycling research and development, to upscale processes lowering their environmental impacts.

Overall, system configuration strongly influences environmental performance. Future research should focus on improving chemical recycling efficiency, developing robust life cycle inventories and upscaling methods for emerging technologies, and assessing behavioural aspects and rebound effects linked to reuse, integrating these into LCA modelling.

CRediT authorship contribution statement

Samuele Abagnato: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Gregory Peters:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Mario Grosso:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Lucia Rigamonti:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Samuele Abagnato reports financial support was provided by Lombardy Region. If there are other authors, they 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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During the preparation of this work the author(s) used Artificial Intelligence tools (Chat GPT and Copilot) in order to rephrase some paragraphs to increase the readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2026.115589. Supplementary Materials include details about waste composition, Material Flow Analysis and Life Cycle Assessment assumptions.

Data availability

Data will be made available on request.

References

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

Amadei, A.M., Rigamonti, L., Tosches, D., Sala, S., 2024. Combining Mfa and Lca models to unveil the EU plastic value chain impacts. SSRN. https://doi.org/10.2139/ssrn.4930124.

Arafat, Y., Uddin, A.J., 2022. Recycled fibers from pre- and post-consumer textile waste as blend constituents in manufacturing 100% cotton yarns in ring spinning: a sustainable and eco-friendly approach. Heliyon 8 (11), e11275. https://doi.org/10.1016/j.heliyon.2022.e11275.

Bianco, I., Gerboni, R., Picerno, G., Blengini, G.A., 2022. Life Cycle Assessment (LCA) of MWool® recycled wool fibers. Resources 11 (5), 41. https://doi.org/10.3390/resources11050041.

Bianco, I., Picerno, G., Blengini, G.A., 2023. Life Cycle Assessment (LCA) of Worsted and Woollen processing in wool production: ReviWool® noils and other wool co-products. J. Clean. Prod. 415, 137877. https://doi.org/10.1016/j.jclepro.2023.137877.

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

Christensen, T.H., Damgaard, A., Levis, J., Zhao, Y., Björklund, A., Arena, U., Barlaz, M. A., Starostina, V., Boldrin, A., Astrup, T.F., Bisinella, V., 2020. Application of LCA modelling in integrated waste management. Waste Manag. 118, 313–322. https://doi.org/10.1016/j.wasman.2020.08.034.

Dahlbo, H., Aalto, K., Eskelinen, H., Salmenperä, H., 2017. Increasing textile circulation—consequences and requirements. Sustain. Prod. Consumpt. 9, 44–57. https://doi.org/10.1016/j.spc.2016.06.005.

Deckers, J., Duhoux, T., Due, S., 2024. Textile waste management in Europe’s circular economy. https://www.eionet.europa.eu/etcs/etc-ce/products/etc-ce-report-2024-5-textile-waste-management-in-europes-circular-economy.

Duhoux, T., Maes, E., Hirschnitz-Garbers, M., Peeters, K., Asscherickx, L., Christis, M., Stubbe, B., Colignon, P., Hinzmann, M., Sachdeva, A., 2021. Study on the Technical, Regulatory, Economic and Environmental Effectiveness of Textile Fibres Recycling: Final Report. Commission, European Directorate-General for Internal Market Entrepreneurship and SMEs, Industry. Publications Office doi: 10.2873/828412.

Ekvall, T., Assefa, G., Björklund, A., Eriksson, O., Finnveden, G., 2007. What life-cycle assessment does and does not do in assessments of waste management. Waste Manag. 27 (8), 989–996. https://doi.org/10.1016/j.wasman.2007.02.015.

Ekvall, T., Granström, L., Jansson, R., Moberg, E., Rydberg, T., 2025. The basket-of-functions approach applied to compare the climate aspects of high-quality mechanical recycling and downcycling of plastics. Int. J. Life Cycle Assess. 30 (12), 3035–3051. https://doi.org/10.1007/s11367-025-02543-7.

Ellen MacArthur Foundation, 2017. A new textiles economy: Redesigning fashion’s future. http://www.ellenmacarthurfoundation.org/publications (accessed on 20th March 2024).

European Commission, 2022. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee Of The Regions. EU Strategy for Sustainable and Circular Textiles, Brussels, 30.3.2022.

European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2010. International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment: Detailed Guidance. Publications Office. https://data.europa.eu/doi/10.2788/38479.

European Commission: Joint Research Centre, Beton, A., Dias, D., Farrant, L., Gibon, T., Le Guern, Y., Desaxce, M., Perwueltz, A., Boufateh I., Wolf, O., Kougoulis, J., Cordella, M., Dodd, N., 2014. Environmental Improvement Potential of textiles (IMPRO Textiles). Publications Office of the European Union, Luxembourg. ISBN 978-92-79-34554-8 (pdf) ISSN 1831-9424 (online) doi: 10.2791/52624.

European Commission: Joint Research Centre, Bakowska, O., Mora, I., Walsh, S., van Duijn, H., Novak, M., Cherubini, G., Joshi, R., Morbiato, A., Visileanu, E., Veselá, A., Ryšavá, E., Holicky, M., 2025. Fate and Composition of Textile Waste from Italy, the Czech Republic and Romania, Huygens, D. editor(s), Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2760/3332076, JRC141441.

European Parliament and Council of the European Union, 2025. Directive (EU) 2025/1892 OF The European Parliament and of the Council of 10 September 2025 amending Directive 2008/98/EC on waste. Official Journal of the European Union.

European Environmental Agency, 2025a. Waste management country profile – Lithuania. https://www.eea.europa.eu/en/topics/in-depth/waste-and-recycling/municipal-and-packaging-waste-management-country-profiles-2025/lt-municipal-waste-factsheet.pdf.

European Environmental Agency, 2025b. Waste management country profile – Bulgaria. https://www.eea.europa.eu/en/topics/in-depth/waste-and-recycling/municipal-and-packaging-waste-management-country-profiles-2025/bg-municipal-waste-factsheet.pdf.

European Environmental Agency, 2025c. Waste management country profile – Slovakia. https://www.eea.europa.eu/en/topics/in-depth/waste-and-recycling/municipal-and-packaging-waste-management-country-profiles-2025/sk-municipal-waste-factsheet.pdf.

Farrant, L., Olsen, S.I., Wangel, A., 2010. Environmental benefits from reusing clothes. Int. J. Life Cycle Assess. 15 (7), 726–736. https://doi.org/10.1007/s11367-010-0197-y.

Fidan, F.Ş., Aydoğan, E.K., Uzal, N., 2021. An integrated life cycle assessment approach for denim fabric production using recycled cotton fibers and combined heat and power plant. J. Clean. Prod. 287, 125439. https://doi.org/10.1016/j.jclepro.2020.125439.

Gorreta, G., Maesani, C., Alini, S., Blangetti, M., Prandi, C., 2025. Towards fiber-to-fiber recycling of synthetic textile wastes: the problem of decolorization. Waste Manag. 205, 114979. https://doi.org/10.1016/j.wasman.2025.114979.

Hegyi, A., Vermeșan, H., Lăzărescu, A.-V., Petcu, C., Bulacu, C., 2022. Thermal insulation mattresses based on textile waste and recycled plastic waste fibres, integrating natural fibres of vegetable or animal origin. Materials 15 (4), 1348. https://doi.org/10.3390/ma15041348.

Huygens, D., Foschi, J., Caro, D., Caldeira, C., Faraca, G., Foster, G., Solis, M., Marschinski, R., Napolano, L., Fruergaard Astrup, T., Tonini, D., 2023. Techno-Scientific Assessment of the Management Options for Used and Waste Textiles in the European Union. European Union. Publications Office of the European Union, Luxembourg doi: 10.2760/6292, JRC134586.

International Energy Agency, Renewable Energy Progress Tracker, 2026. https://www.iea.org/data-and-statistics/data-tools/renewable-energy-progress-tracker (accessed 20th January 2026).

International Wool Textile Organisation, 2026. https://iwto.org/resources/statistics/(accessed on 15th January 2026).

Koligkioni, A., Parajuly, K., Sørensen, B.L., Cimpan, C., 2018. Environmental assessment of end-of-life textiles in Denmark. Proc. CIRP 69, 962–967. https://doi.org/10.1016/j.procir.2017.11.090.

Laitala, K., Klepp, I.G., 2021. Clothing Longevity: The Relationship between the Number of Users, How Long and How Many Times Garments are Used. University of Limerick doi: 10.31880/10344/10223.

Määttänen, M., Asikainen, S., Kamppuri, T., Ilen, E., Niinimäki, K., Tanttu, M., Harlin, A., 2019. Colour management in circular economy: decolourization of cotton waste. Res. J. Text. Appar. 23 (2), 134–152. https://doi.org/10.1108/RJTA-10-2018-0058.

Majumder, A., Achenza, M., Mastino, C.C., Baccoli, R., Frattolillo, A., 2023. Thermo-acoustic building insulation materials fabricated with recycled fibers – Jute, Wool and Loofah. Energy Build. 293, 113211. https://doi.org/10.1016/j.enbuild.2023.113211.

McKinsey, 2022. Scaling textile recycling in Europe – turning waste into value. https://www.mckinsey.com/industries/retail/our-insights/scaling-textile-recycling-in-europe-turning-waste-into-value.

Mizrachi, M.P., Sharon, O., 2025. Secondhand fashion consumers exhibit fast fashion behaviors despite sustainability narratives. Sci. Rep. 15 (1), 34968.

Moazzem, S., Wang, L., Daver, F., Crossin, E., 2021. Environmental impact of discarded apparel landfilling and recycling. Resour. Conserv. Recycl. 166, 105338. https://doi.org/10.1016/j.resconrec.2020.105338.

Morell-Delgado, G., Talens Peiró, L., Toboso-Chavero, S., 2024. Revealing the management of municipal textile waste and citizen practices: the case of Catalonia. Sci. Total Environ. 907, 168093. https://doi.org/10.1016/j.scitotenv.2023.168093.

Mu, B., Yang, Y., 2022. Complete separation of colorants from polymeric materials for cost-effective recycling of waste textiles. Chem. Eng. J. 427, 131570. https://doi.org/10.1016/j.cej.2021.131570.

Munasinghe Arachchilage, E.A., Stegschuster, G., Cetin, M., Rabe, M., 2025. Effective dye removal from post-consumer cotton textiles and its influence on the quality of the textiles. Textiles 5 (4), 62. https://doi.org/10.3390/textiles5040062.

Napolano, L., Foschi, J., Caldeira, C., Huygens, D., Sala, S., 2025. Understanding textile value chains: dynamic probabilistic material flow analysis of textile in the European Union. Resour. Conserv. Recycl. 212, 107888. https://doi.org/10.1016/j.resconrec.2024.107888.

Nellström, M., Grahn Lydig, S., Sandin Albertsson, G., Bolinius, D.J., 2022. Siptex Swedish Innovation Platform for Textile Sorting - A Summary Report of the Final Stage of the Project. IVL Swedish Environmental Research Institute.

Nichilo, M.J.F.A., Cavenago, G., Grosso, M., Rigamonti, L., 2025. Quantification of the environmental benefits of the reuse of goods. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-025-36788-4.

Nørup, N., Pihl, K., Damgaard, A., Scheutz, C., 2019a. Evaluation of a European textile sorting centre: material flow analysis and life cycle inventory. Resour. Conserv. Recycl. 143, 310–319. https://doi.org/10.1016/j.resconrec.2019.01.010.

Nørup, N., Pihl, K., Damgaard, A., Scheutz, C., 2019b. Replacement rates for second-hand clothing and household textiles – a survey study from Malawi, Mozambique and Angola. J. Clean. Prod. 235, 1026–1036. https://doi.org/10.1016/j.jclepro.2019.06.177.

Notarnicola, B., Puig, R., Raggi, A., Fullana, P., Tassielli, G., De Camillis, C., Rius, A., 2011. Life Cycle Assessment of Italian and Spanish Bovine Leather Production Systems. AFINIDAD.

Odonkor, 2024. An evaluation of the socio-economic impact of the second-hand clothes in Ghana. https://www.humanaitalia.org/wp-content/uploads/2024/10/240514-Ghana-Evaluation-of-the-Socio-Economic-and-Environmental-Impact-of-the-Second-Hand-Clothes-Trade.pdf (accessed 15th January 2025).

Periyasamy, A.P., Harlin, A., 2025. The need and challenges of decolorization of textile waste in textile recycling: review. ChemistrySelect 10 (29), e01130. https://doi.org/10.1002/slct.202501130.

Peters, G.M., Sandin, G., Spak, B., 2019. Environmental prospects for mixed textile recycling in Sweden. ACS Sustain. Chem. Eng. 7 (13), 11682–11690. https://doi.org/10.1021/acssuschemeng.9b01742.

Peterson, A., Wallinder, J., Bengtsson, J., Idström, A., Bialik, M., Jedvert, K., De La Motte, H., 2022. Chemical recycling of a textile blend from polyester and viscose, part I: process description, characterization, and utilization of the recycled cellulose. Sustainability 14 (12), 7272. https://doi.org/10.3390/su14127272.

Rigamonti, L., Falbo, A., Grosso, M., 2013. Improving integrated waste management at the regional level: the case of Lombardia. Waste Manag. Res.: J. Sustain. Circ. Econ. 31 (9), 946–953. https://doi.org/10.1177/0734242X13493957.

Rigamonti, L., Taelman, S.E., Huysveld, S., Sfez, S., Ragaert, K., Dewulf, J., 2020. A step forward in quantifying the substitutability of secondary materials in waste management life cycle assessment studies. Waste Manag. 114, 331–340. https://doi.org/10.1016/j.wasman.2020.07.015.

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., Luderer, G., 2022. PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew. Sustain. Energy Rev. 160, 112311. https://doi.org/10.1016/j.rser.2022.112311.

Samardzioska, T., Jovanoska, M., Grujoska, V., 2023. Sustainable thermal insulation derived from recycled textile waste. Adv. Environ. Eng. Res. 04 (01), 1–8. https://doi.org/10.21926/aeer.2301004.

Sandin, G., Roos, S., Spak, B., Zamani, B., Peters, G., 2019. Environmental assessment of Swedish clothing consumption. ISBN:978-91-89049-05-5. Mistra Future Fashion report number: 2019:05. https://mistrafuturefashion.mistraprograms.org/publikationer/G.Sandin-Environmental-assessment-of-Swedish-clothing-consumption.MistraFutureFashionReport-2019.05.pdf.

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

Schmidt, A., Watson, D., Roos, S., Askham, C., Brunn Poulsen, P., 2016. Gaining benefits from discarded textiles - LCA of different treatment pathways. TemaNord 2016:537. Nordic Council of Ministers. ISBN 978-92-893-4658-0 (PRINT). https://doi.org/10.6027/TN2016-537.

Solis, M., Huygens, D., Tonini, D., Fruergaard Astrup, T., 2024a. Management of textile waste in Europe: an environmental and a socio-economic assessment of current and future scenarios. Resour. Conserv. Recycl. 207, 107693. https://doi.org/10.1016/j.resconrec.2024.107693.

Solis, M., Tonini, D., Scheutz, C., Napolano, L., Biganzoli, F., Huygens, D., 2024b. Contribution of waste management to a sustainable textile sector. Waste Manag. 189, 389–400. https://doi.org/10.1016/j.wasman.2024.08.037.

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

Turner, D.A., Williams, I.D., Kemp, S., 2016. Combined material flow analysis and life cycle assessment as a support tool for solid waste management decision making. J. Clean. Prod. 129, 234–248. https://doi.org/10.1016/j.jclepro.2016.04.077.

United Nations Environment Programme, 2024. Global Waste Management Outlook 2024: Beyond an age of waste – Turning rubbish into a resource. Nairobi. https://wedocs.unep.org/20.500.11822/44939.

Vinted Climate Change Impact Report, 2021. https://press-center-static.vinted.com/Vaayu_x_Vinted_Full_Climate_Impact_Report_2021_045f9e5c4b.pdf.

Wiedemann, S.G., Biggs, L., Nebel, B., Bauch, K., Laitala, K., Klepp, I.G., Swan, P.G., Watson, K., 2020. Environmental impacts associated with the production, use, and end-of-life of a woollen garment. Int. J. Life Cycle Assess. 25 (8), 1486–1499. https://doi.org/10.1007/s11367-020-01766-0.

Zamani, B., Svanström, M., Peters, G., Rydberg, T., 2015. A carbon footprint of textile recycling: a case study in Sweden. J. Ind. Ecol. 19 (4), 676–687. https://doi.org/10.1111/jiec.12208.

Zhang, Y., Wen, Z., Lin, W., Hu, Y., Kosajan, V., Zhang, T., 2021. Life-cycle environmental impact assessment and plastic pollution prevention measures of wet wipes. Resour. Conserv. Recycl. 174, 105803. https://doi.org/10.1016/j.resconrec.2021.105803.