Waste Management 182 (2024) 74–90

Contents lists available at ScienceDirect

Waste Management

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

Research Paper

# Life cycle assessment applications to reuse, recycling and circular practices for textiles: A review

Samuele Abagnato *, Lucia Rigamonti, Mario Grosso

*Politecnico di Milano, Department of Civil and Environmental Engineering, Environmental section, Piazza Leonardo da Vinci 32, 20133 Milano, Italy*

A B S T R A C T

To understand which are the best strategies for textile waste management and to analyse the effects on the environment of applying circular economy practices to textile products, a review of 45 publications where life cycle assessment (LCA) is applied to these topics has been carried out. The separate collection of textiles, followed by reuse and recycling brings relevant environmental benefits, with impacts related to reuse resulting lower than those of recycling. At the opposite, when mixed municipal solid waste is addressed to energy recovery, the textile fraction is the second most impacting on climate change, right after plastics, while for landfill disposal impacts textiles directly follow the more biodegradable fractions. Textiles manufacturing using recycled fibres generally gives lower impacts than using virgin ones, with a few exceptions in some impact categories for cotton and polyester. The circular practices with the lowest impacts are those that ensure the extension of the textiles service life. Another aim of this review is to identify the main variables affecting the life cycle impact assessment (LCIA). These resulted to be the yield and material demand of recycling processes, the use phase variables, the assumptions on virgin production replaced by reuse or recycling, the substitution factor in reuse, and transportation data in business models based on sharing. Thus, in LCA modelling, great attention should be paid to these variables. Future research should address these aspects, to acquire more relevant data, based on industrial-scale processes and on people habits towards the circular economy strategies applied to textiles.

## 1. Introduction

Global textile fibres demand is growing: in the last 20 years, the worldwide production has almost doubled from 58 million tonnes in 2000 to 113 million tonnes in 2021 and is expected to grow to 149 million tonnes in 2030 if business as usual continues (Textile Exchange, 2022). This means that, together with the textile production, also the amount of textile waste will increase. The other factor that brings to higher waste production is the fact that worldwide the average number of times a garment is worn before it ceases to be used has decreased by 36 % compared to 15 years ago (Ellen MacArthur Foundation, 2017). In addition, the environmental impacts of the textile industry are relevant: in 2015, greenhouse gas (GHG) emissions from textiles production totalled 1.2 billion tonnes of $CO_2$ equivalent and it was estimated that 20 % of industrial water pollution globally is attributable to the dyeing and treatment of textiles (Ellen MacArthur Foundation, 2017). It is clear that the implementation of circular economy principles and the elimination of phenomena such as the textiles overproduction or the destruction of unsold items is crucial to limit the environmental burdens of textiles. Since about 5.8 million tonnes of textiles are discarded every year in the European Union (EU) (European Commission, 2022), in 2019 the European Commission identified textiles as a priority product category to be addressed within the circular economy framework (European Commission, 2019). In order to lead the textile sector towards lower environmental impacts, it is necessary to improve the production processes and to fully develop the circular economy principles with a correct waste management: in particular, following the waste hierarchy, reuse and recycling could give and important contribution to make textile industry more sustainable. Measuring the sustainability of the circular strategies is an important step which is required before (to help decision making) and after their implementation. Life cycle assessment (LCA) is the mainstream methodology to measure the environmental impacts of products, processes and services. In the present work, after a brief overview of the current practices in textile waste management (especially in Europe), LCA publications about textile waste management and circular strategies for textiles are reviewed in order to answer the five research questions defined in Section 2.

### 1.1. Current practices about textile waste management

Two main typologies of textile waste can be identified: pre-consumer and post-consumer. The first is made of rags and scraps discarded by textile industries, while the second consists of textile products discarded by consumers after the use phase. Pre-consumer textile waste is easier to

* Corresponding author.
*E-mail address:* samuele.abagnato@polimi.it (S. Abagnato).

https://doi.org/10.1016/j.wasman.2024.04.016
Received 15 December 2023; Received in revised form 20 March 2024; Accepted 9 April 2024
Available online 20 April 2024
0956-053X/

manage because of its well-known composition which allows its recycling within the same processes or within other factories, in an industrial symbiosis framework. The management of post-consumer textile waste is more difficult because of the enormous variety of products and because of technological and economic barriers. Its correct management includes collection, sorting, reuse, recycling and final disposal, and each of this step involves different players.

The EU policies (European Parliament, 2008) oblige Member States to establish separate collection of textile waste by 2025, ensuring that this will not be addressed to incineration or landfilling. Policies also encourage setting up systems for repair and reuse of textiles to prevent waste generation in the first place. Investments are needed to ensure sufficient capacity to manage the separately collected waste, supporting the installation of textile hubs and the development of technologies that can ensure higher recycling rates.

Post-consumer textile waste is usually collected by charities and professional collectors. After the collection, sorting has the aim to remove foreign materials and to produce textiles streams of defined qualities for subsequent reuse or recycling (EuRIC, 2021). The suitability for reuse or recycling shall be checked manually by trained professionals. According to Köhler et al. (2021), personnel in charge of manual sorting can sort between 100 to 150 kg of textiles per hour. Manual sorting is likely to remain the first step for sorting any post-consumer textile that can be reused, while to feed the recycling markets it must be followed by automated sorting of the non-reusable fraction by fibre type and colour (van Duijn et al., 2022), because the recycling processes need well defined types of fibres as an input. Advanced facilities for automated sorting are suited to sort between 900–1500 kg per staff member each hour (Köhler et al., 2021). Among the most promising technologies are near-infrared spectroscopy (NIR), hyper-spectral imaging and radio frequency identification (RFID).

After the sorting step two streams can be identified: the first one is composed of reusable products, while the second is constituted by the textiles that could be recycled. Reuse is the best option from the economic point of view for the organisations that manage discarded textiles, and it is often seen as the most favourable route for the environment. Non-reusable textiles currently present an economic burden for collectors due to the low price which can often barely pay for the transport to recycling facilities (European Commission, 2020). Data on the fate of used textile products on the global markets are usually provided by the wholesale sorting companies, and today there are no reporting obligations on these companies. The fraction that cannot be reused is addressed to recycling. With mechanical recycling, machines pull the fibres apart and these fibres are transformed into yarn by spinning. The mechanically recycled fibres are usable for different applications: fibre-to-fibre recycling for the best quality fractions or downcycling such as fibres for insulation, filling or non-woven textiles. During the recycling process fibres are shortened, and this fact is usually compensated by blending the recycled fibres together with virgin ones (van Duijn et al., 2022). Mechanical recycling technologies are currently the most widespread (Köhler et al., 2021). In chemical recycling, fibres are broken down to their base components, to the polymer or monomer level, which can then be re-spun into new fibres, yarns and textiles. Chemical recycling uses more energy than mechanical recycling, but the quality of this yarn is often higher. The recycling technologies include pulping processes to recycle cotton and viscose, solvent-based processes to recycle polyester and polycotton, processes such as glycolysis, hydrolysis and enzymatic processes (biochemical recycling) that bring polyester and polyamide back to monomers (van Duijn et al., 2022). Large-scale recycling facilities are still under development, and chemical recycling for non-plastic fibres such as wool or cotton is not currently at the same technological readiness level as polyester recycling (Köhler et al., 2021), but even for polyester the chemical recycling has not spread at industrial scale, since 99 % of recycled polyester is mechanically recycled (Textile Exchange, 2022). The mechanical and chemical recycling do not exclude each other: in fact, a chemical process could be often preceded by a mechanical step. Pure synthetic textiles could also be suitable in the future as feedstock for emerging thermomechanical processes, which use heat and pressure to melt synthetic textiles. However, at the moment, the purity requirements are extremely high for the technology to work, and this presents a challenge for post-consumer textiles. An aspect that must be considered for all the recycling technologies is the suitability of textiles as feedstock for recycling. This is determined by the composition of the fabric, by the presence of disruptors (fastener, button, zipper, fabric patch), by the colour and by the structure of the textiles. For instance, there are mono-layer products that are made of one layer or type of textile, while multi-layer products are made of more than one distinct layer, each of which may be composed of different materials (van Duijn et al., 2022).

When recycling is not a viable option from the technological and economic point of view, the collected textile waste is incinerated, with or without energy recovery depending on the available facilities in each specific country, or disposed in landfill (Köhler et al., 2021).

### 1.2. *Life cycle approach for sustainable textiles*

A correct evaluation of the environmental impacts related to circular strategies and waste management processes is fundamental to avoid drawbacks. LCA is the most applied methodology to estimate the potential environmental impacts of products and processes, from the raw material extraction to the end-of-life, and when applied to waste management systems it is useful to identify the options that bring to the lowest impacts. The aim of this paper is to review publications about LCA applied to textile waste management and circular strategies for textile products, in order to find research gaps and discuss the main issues about LCA application on these topics. Due to the high concern for the environmental impacts of the textile sector, LCA has been widely applied to this topic. Shen et al. (2010) assess the environmental impacts of the production of cellulose-based fibres, and several papers analysed the lifecycle of textile products with the aim to find out the most impactful processes in the lifecycle and to identify the solutions to decrease those impacts (Moazzem et al., 2021a; L'Abbate et al., 2018; Baydar et al., 2015; Yasin & Sun, 2019; Bianco et al., 2023). Lenzo et al. (2018) present, in addition to LCA, also the application of Social-LCA to a textile product. From the policies point of view, the interest into this topic is proved by the development of the Product Environmental Footprint Category Rules (PEFCRs) for the category of Apparel and Footwear, that is a specific guideline for the impact calculation for textiles (Pesnel & Payet, 2019).

This paper aims to follow the work of other reviews addressed to LCA applied to textiles. Munasinghe et al. (2021) provides life cycle inventory data on energy use, water use and GHG emissions for a range of materials across all stages of the life cycle of garments. Amicarelli et al. (2022) focus their review on the environmental concerns of textiles production and consumption through LCA. Sandin & Peters (2018) is focused on reuse and recycling of textiles. The present work aims to follow the perspective of the review by Sandin & Peters (2018) with the addition of some specific analysis about the main variables that have more influence on the results of LCA studies applied to the textile waste management sector.

## 2. Materials and methods

Publications for the literature analysis have been selected through the Web of Science and Scopus scientific libraries. Articles and conference proceedings have been considered. The following research strings have been adopted: "textile" AND "recycling" OR "reuse" OR "waste management" OR "waste" AND "LCA" OR "impact assessment" OR "impact evaluation" OR "impact analysis" OR "environmental assessment" OR "environmental evaluation". The aim of the review is to identify the state of the art of LCA application to textile waste management and circular practices for textile products and to find out the main trends about this topic. In details, this review aims to answer to five research questions (RQs) related to the environmental impacts of textile waste management:

RQ1: What are the best strategies for a country or a region to manage textile waste?

RQ2: What is the contribution of textile waste management in terms of environmental impacts when compared to the other municipal solid waste (MSW) fractions?

RQ3: What are the environmental impacts related to recycling processes?

RQ4: What is the contribution that different circular economy initiatives (reducing, refurbishing, sharing, reusing, recycling) can have on the lifecycle impacts of a textile product?

RQ5: What are the main variables that influence environmental impacts in LCA studies about textile waste management and about circular economy strategies for textile products?

The authors have selected papers published after 2010 to have the state of the art of the research developed in this field in the last few years. Other review articles were excluded from the literature analysis. Publications about different types of products made with textile fibres (garments, healthcare equipment, carpet, mattresses, insulation panels) have been included. Papers where LCA methodology was not clearly applied have been excluded, together with publications where textile fibres were not the focus of the study (for instance, if the object of the study was a leather product the paper was not considered in the review). In the end, papers where LCA was applied to textile products without reuse, recycling or other circular economy strategies were excluded from this review.

The reviewed publications have been selected according to the PRISMA model (Page et al., 2021), as showed in Fig. 1. In the identification stage, 1816 publications have emerged, and 791 of them have been removed because they were duplicated records. In the screening stage, 962 publications have been excluded because they were other review studies or because not in line with the aims and scope of the research. 63 publications have been assessed for eligibility and 18 of them have been excluded because they were published before 2010 (n = 1), because the LCA methodology was not clearly applied (n = 4), because textiles were not the focus of the publication (n = 3) or because they did not apply reuse, recycling or other circular practices to textiles (n = 10). At the end of this process, 45 studies have been included in this review.

The selected studies have been analysed and classified according to: (i) location and year of publication; (ii) goal and scope; (iii) functional unit and system boundaries; (iv) textile fibres composition; (v) waste management operations and circular practices applied to textiles; (vi) impact categories and impact assessment methods.

The main life cycle impact assessment results (LCIA) together with the scenarios and the sensitivity analyses applied in the reviewed studies have been carefully analysed to answer to the five RQs.

From the analysis of the selected publications and with the answers to the five RQs, this review aims to make the state of the art of LCA application to textile waste management and to identify the main issues that should be developed in the future research.

## 3. Results of the literature analysis

45 publications have been considered eligible for the literature analysis about LCA applied to textile waste management.

The full list of all the reviewed publications, classified according to location, functional unit, textile fibres composition, waste management operations, impact categories and impact assessment method, scenarios and sensitivity analyses, is available in the Supplementary Materials.

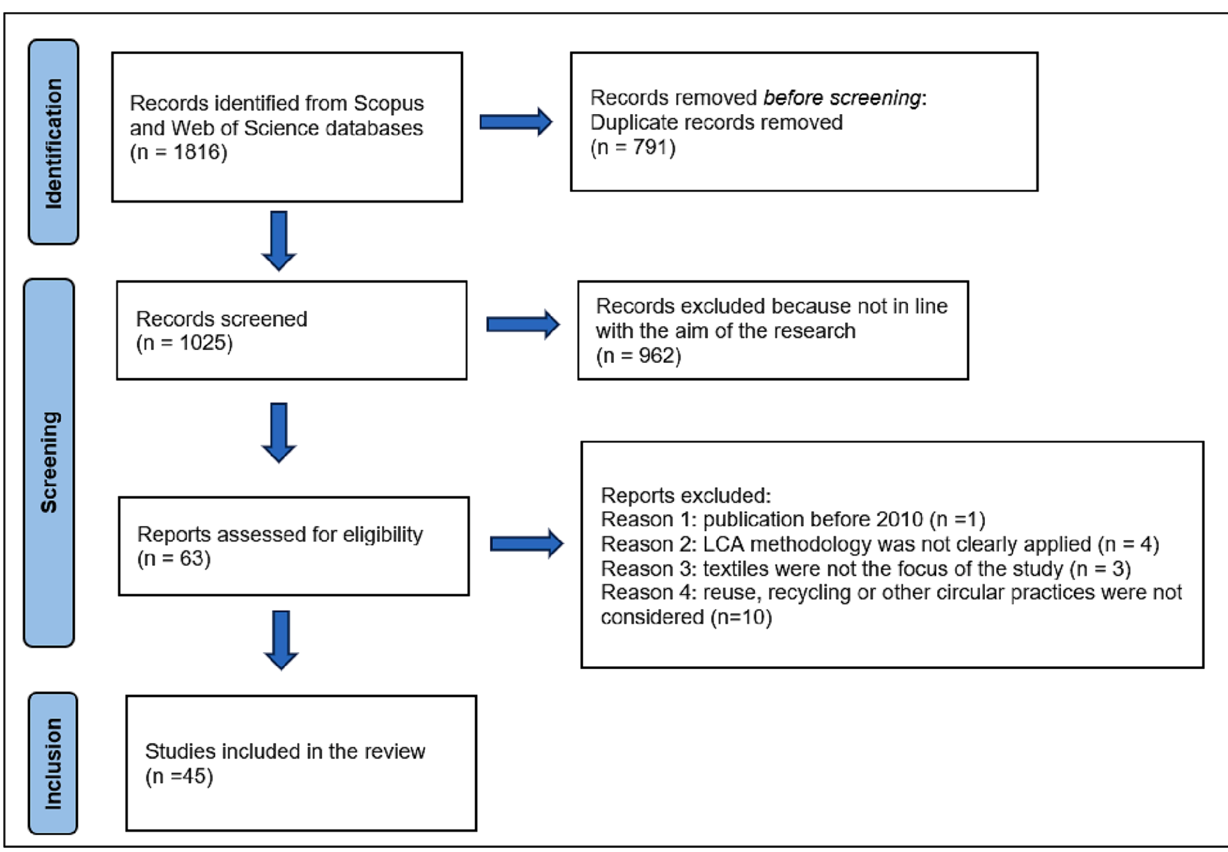


**Fig. 1.** PRISMA model flow figure. .
Source: Personal elaboration by the authors on Page et al. (2021)

### 3.1. Location of the studies and year of publication

When LCA studies are performed, it is important to specify the location where the study is carried out, because country-specific aspects can influence the results. Most of the selected studies are related to Europe (25 papers), followed by Asia (9), Australia (3), North America (3) and South America (3). The location is not specified in 2 studies. More than 50 % of the reviewed studies have been published after 2020, revealing the growing interest about this topic in the last few years.

### 3.2. Goals, functional unit and system boundaries of the publications

Among the reviewed publications, a good variety of goal formulation can be found. Most of the studies aims to assess the environmental impacts of the waste management system of a specific country or region. Among this first group of studies, 8 papers (Amicarelli & Bux, 2022; Zamani et al., 2015; Dahlbo et al., 2017; Espinoza Pérez et al., 2022; Farrant et al., 2010; Koligkioni et al., 2018; Semba et al., 2020; Moazzem et al., 2021b) are only focused on the textile waste fraction, while 4 publications (Faraca et al., 2019; Salemdeeb et al., 2022; Vergara et al., 2016; Corsten et al., 2013) considered also the other MSW fractions.

The goal of 20 % of the selected publications was to estimate the impacts of the production of recycled fibres (Muthu et al., 2012) or of a finished textile product with a certain recycled content. Six of them (Fidan et al., 2021; Bianco et al., 2022; Esteve Turrillas & de la Guardia, 2017; Liu et al., 2020; Qian et al., 2021; Yurtaslan et al., 2022) provide a comparison with virgin fibres. The impact assessment of a specific waste treatment process was the goal of 18 % of the papers. In seven publications (Luedemann et al., 2022; Peters et al., 2019; Phan et al., 2023; Rosson & Byrne, 2020; Yousef et al., 2019; Popescu et al., 2022; Oelerich et al., 2015) the focus was on a particular recycling process, while in Arafat et al. (2015) the goal was to assess the impacts of various treatments for MSW fractions, not only textiles. The aim of 11 % of the papers was to assess the environmental impacts during the lifecycle of a textile product with a certain recycled fibres content (Pegoretti et al., 2014; Braun et al., 2021; Chen et al., 2023; Wiedemann et al., 2022) or that is addressed to recycling at the end of its service life (Sim and Prabhu, 2018). 9 % of the papers defined their goal as the comparison of different circular economy practices during the lifecycle of a textile product. In particular, Glew et al. (2012) compared various end-of-life scenarios for a mattress, Horn et al. (2023) and Levanen et al. (2021) analysed circular economy strategies for apparels, and Mölsä et al. (2022) compared reuse and recycling processes for a hand-drying roller towel. Vozzola et al. (2018), Giungato et al. (2021) and Snighda et al. (2023) performed a LCA to compare durable textile products with disposable options for the healthcare sector. The impact assessment of sharing models, with the reuse of garments between different users, was the goal of 3 publications (Zamani et al., 2017; Castellani et al., 2015; Fortuna & Diyamandoglu, 2017). In the end, one publication (Payet, 2021) aimed to estimate the environmental impacts of the textile sector of a country, with different production pathways and end-of-life scenarios.

In 44 % of the studies the functional unit is defined as the treatment or the management of a certain amount of MSW, of textile waste or of textile products addressed to reuse centres before they become waste. In these studies, waste is usually considered free of environmental burdens from its previous life. Only in Salemdeeb et al. (2022) and in Luedemann et al. (2022) also the impacts related to the production and the transport of a product before it becomes waste are included in the analysis. Collection is often included in the system boundaries, but without further information in the impact assessment, usually because their impacts are negligible, as stated in Zamani et al. (2015). The sorting process is mentioned only in Dahlbo et al. (2017), where NIR technology is applied for separating the different types of materials. System expansion is applied to evaluate the avoided impacts from virgin production by the majority of the publications focused on LCA of waste treatment processes.

The production of a certain amount of recycled fibres or of a finished product with a recycled content is the functional unit of 22 % of the publications. These studies are usually cradle-to-gate, with the use and the end-of-life phases excluded from the system boundaries. Among the cradle-to-gate studies, Bianco et al. (2022) is the only publication which considered in the system boundaries the wastewater treatment and the production and end-of-life of plastic bags used as packaging for the textile garment. Subramanian et al. (2020) included in the system boundaries also the production of glucose-syrup as a by-product from textile recycling to recover polyester fibres.

The lifecycle of a textile product is the functional unit of 33 % of the analysed publications. Some of them scaled the results on a certain number of uses of the product (Horn et al., 2023; Levanen et al., 2021; Mölsä et al., 2022; Vozzola et al., 2018), while others simply evaluated the impacts of a single product with a recycled fibres content (Pegoretti et al., 2014; Wiedemann et al., 2022; Braun et al., 2021; Chen et al., 2023). In Castellani et al. (2015) and in Zamani et al. (2017) the functional unit was defined respectively as the acquisition of a garment from a reuse centre and as one average use of a garment shared between different users in a clothing library business model. Most of these studies are cradle-to-grave, but there are some exceptions. Chen et al. (2023) excluded the end-of-life from the system boundaries and Castellani et al. (2015) only considered the virgin production impacts avoided by the acquisition of a second-hand garment. System expansion is applied by Glew et al. (2012), Horn et al, (2023), Levanen et al. (2021) and Mölsä et al. (2022) to estimate the avoided impacts for energy production from energy recovery processes and landfilling, and the avoided impacts of virgin production in case of reuse or recycling.

### 3.3. Impact categories and IA methods

Most of the papers considered only one impact category and only 22 % assessed the impacts in more than 10 categories. All studies adopted mid-point indicators. Subramanian et al. (2020) and Arafat et al. (2015) also included end-point indicators in their assessment. The most studied category is climate change, followed by water depletion, due to the high consumption of water in the textile sector. The optional normalisation stage was included only in four publications (Dahlbo et al., 2017; Horn et al., 2023; Rosson & Byrne, 2020; Arafat et al., 2015), while the weighting step is developed only by Arafat et al. (2015). The impact assessment method used is explicitly indicated by 60 % of the reviewed studies. CML and ReCiPe, with different versions, are the most used IA methods, followed by the EF method. The IA method adopted by each study is available in the Supplementary Materials.

### 3.4. Waste treatment processes in publications

In the reviewed publications, all the steps of the waste hierarchy have been found. In 62 % of the analysed publications, more than one waste management option is assessed through LCA. In Fig. 2, the occurrence of each option is represented, with information about the fibres composition of the waste or of the textile product.

In Fig. 2, all the practices that extend the service life of a textile product before it becomes a waste have been included in the category “waste prevention”, for instance best practices during the use phase (Wiedemann et al., 2022; Horn et al., 2023), reuse between different users through sharing platforms or reuse centres (Zamani et al., 2017; Levanen et al., 2021, Castellani et al., 2015; Fortuna & Diyamandoglu, 2017), or reusable textile products instead of disposable ones (Snighda et al., 2023; Giungato et al., 2021; Vozzola et al., 2018). Reuse can be seen as a waste prevention process, if it happens between different users before the product is discarded, but it is also a process that concerns the textile waste treatment chain, after the collection, the sorting and the preparation for reuse steps (Salemdeeb et al., 2022; Vergara et al., 2016; Dahlbo et al., 2017; Corsten et al., 2013; Semba et al., 2020). Among the recycling treatment options, the open-loop mechanical recycling is the

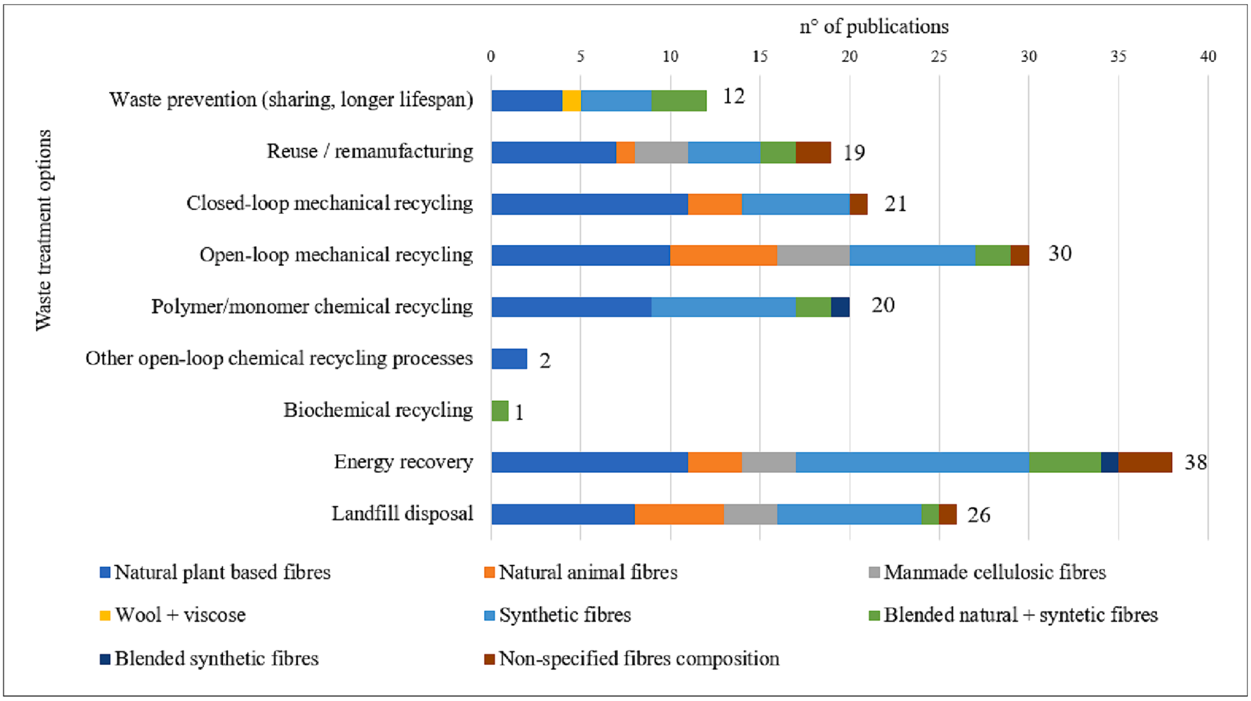


**Fig. 2.** Type of waste treatment processes and of textile fibres in the reviewed papers. The number of the reviewed papers that apply the different waste treatment options is reported in this graph. Each bar also reports the composition of the textiles considered by the reviewed publications.

most common in the reviewed publications. It can be applied both to natural and synthetic fibres to make cleaning wipers (Farrant et al., 2010; Faraca et al., 2019; Semba et al., 2020), filler materials (Espinoza Pérez et al., 2022), insulation panels (Moazzem et al., 2021b; Wiedemann et al., 2022; Pegoretti et al., 2014) or felt fabrics (Semba et al., 2020). Mechanical fibre-to-fibre recycling allows to produce new yarns which can be re-spun, usually with the addition of virgin yarns (Chen et al., 2023; Fidan et al., 2021; Yurtaslan et al., 2022). Also closed-loop mechanical recycling is applied both to natural and synthetic textiles in the reviewed publications. The number of analysed publications which considered chemical recycling is lower, but it is not negligible. Among these papers, some considered the production of cellulose-pulp from cotton textile waste (Oelerich et al., 2017; Paunonen et al., 2019), while Rosson & Byrne (2020) studied a particular pre-treatment process for the chemical recycling of cotton. The recovery of cellulose-pulp from cotton can be classified as a polymer recycling because the cellulose polymer is recovered from waste cotton. Among synthetic fibres, the most studied for chemical recycling is polyester (Zamani et al., 2015; Peters et al., 2019; Moazzem et al., 2021b; Semba et al., 2020). For synthetics, the recovery of the polymer or of the monomer can happen. For instance, Zamani et al. (2015) and Moazzem et al., (2021b) considered the production of dimethyl-terephthalate (DMT) from polyester textile waste, while Sim & Prabhu (2017) assumed the recovery of caprolactam from a nylon carpet. In addition, chemical processes are adopted to separate cellulose from synthetic fibres when blended textiles are treated (Zamani et al., 2015; Yousef et al., 2019) or to separate elastane from other synthetic fibres (Phan et al., 2023). Polymer recycling is applied also in Subramanian et al. (2020) after a separation process of a blended cotton-polyester fabric with the use of enzymes, that also allowed the recovery of glucose-syrup as a by-product: this was the only publication focused on bio-chemical recycling treatments. In the category "other open-loop chemical recycling processes" in Fig. 2, is considered the production of ethanol from cellulose based textile waste (Popescu et al., 2022; Glew et al., 2012).

When approaching to the last steps of the waste hierarchy, energy recovery has been found in a higher number of publications than landfill disposal. In several papers, these two waste treatment operations are considered as baseline scenarios, in order to estimate the benefits of textile reuse or recycling. In the reviewed publications, three types of energy recovery have been found: gasification (Arafat et al., 2015), production of secondary solid fuel (Semba et al., 2020) and incineration with energy recovery, the latter being the most studied. The avoided impacts from electricity production are often considered when incineration with energy recovery is applied (Dahlbo et al., 2017; Salemdeeb et al., 2022; Luedemann et al., 2022; Koligkioni et al., 2018), while only Moazzem et al., (2021b) explicitly included in the analysis the credits due to gas capture from landfill.

## 4. Discussion

In this section, answers to the RQs are provided through the analysis of the life cycle impact assessment (LCIA) results and of the sensitivity analyses of the reviewed publications. A short answer to each RQs is summarised in Fig. 3. In addition, methodological aspects about LCA applied to textile reuse and recycling, and future research development are discussed.

### *4.1. LCA application to identify the best strategies to manage textile waste in a national or regional context (RQ1)*

According to the results of the examined studies, reuse operations usually allow to avoid more impacts than recycling. The benefits on climate change impacts of different waste treatment options are summarized in Table 1, considering eight studies focused on the textile waste management of a country and comparing, for each study, the baseline scenario with scenarios where reuse or recycling are implemented. It is not the intention of the authors to compare the results of different LCA studies, but to compare the scenarios within each paper to identify some trends in the results. For instance, among the studies in Table 1, four of them evaluated both a reuse and a recycling scenario, with the first always resulting in lower impacts than the second (Dahlbo et al., 2017; Farrant et al., 2010; Semba et al., 2020; Zamani et al., 2015).

Impacts of textile waste collection and sorting seem to be negligible

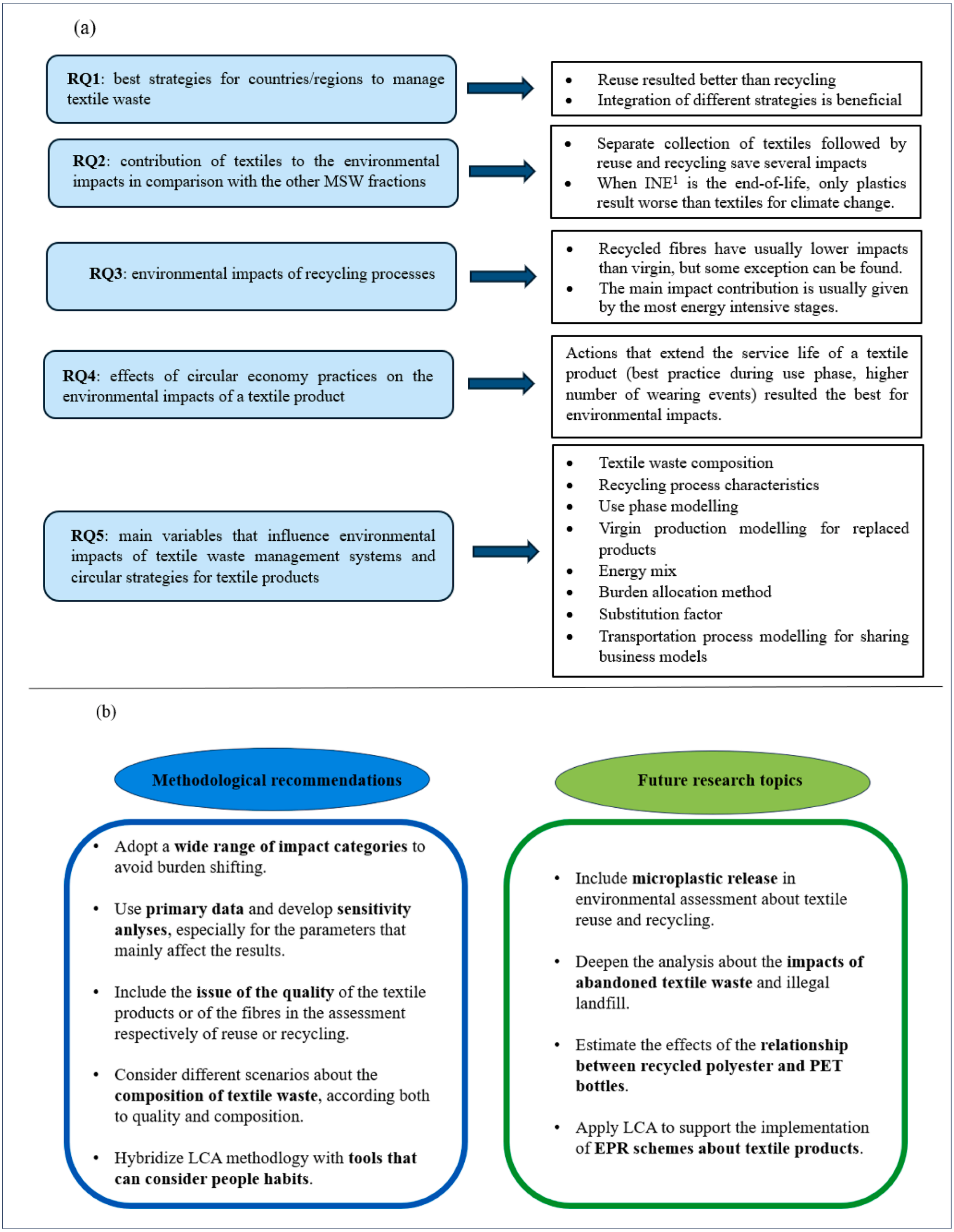


**Fig. 3.** Short answers to the research questions (a), methodological recommendations and future research topics (b).

(Dahlbo et al., 2017, Farrant et al., 2010), because the impacts are dominated by the contribution of avoided production from virgin materials. In Zamani et al. (2015) the textile remanufacturing to produce bags is the best option both for climate change (−8 t $CO_2$ eq./t waste) and for primary energy usage (−165 GJ/t waste), while the polyester chemical recycling brings avoided impacts but less than the other techniques (−1 t $CO_2$ eq./t waste, −25 GJ/t waste). In Dahlbo et al. (2017) the increased reuse scenario (40 % reuse, 2 % recycling, 58 % incineration with energy recovery) reveals better performance than the increased recycling scenario (20 % reuse, 22 % recycling, 58 %

**Table 1**
Research question 1: LCA application to the textile waste management of a country.

| Publications | Functional unit | LCIA method | Baseline scenario definition | Alternative scenarios with climate change impacts variation[1] |
|---|---|---|---|---|
| Amicarelli & Bux (2022) | Treatment of textile waste generated in 2018 in 6 European countries | n.a.[2] | Current separate collection and recycling rates | • High separate collection and recycling rate: −16 %<br>• Low separate collection and recycling rate: −4% |
| Dahlbo et al. (2017) | Treatment of textile waste discarded in Finland in 2012 | ReCiPe 1.12 | Current separate collection and recycling rates | • Increased reuse scenario: −113 %<br>• Increased recycling scenario: −94 % |
| Espinoza Peréz et al. (2022) | Treatment of 1 t of textile waste in Chile | ReCiPe 2016 | LF + virgin production[3] | Recycling scenario: −83 % |
| Farrant et al. (2010) | The use of 100 s-hand garments collected in Sweden, Denmark and Estonia | n.a. | Direct disposal | Cotton t-shirt case study:<br>• Reuse in Estonia: −13 %<br>• Reuse in Sweden: −12 %<br>• Recycling in wipes: −3% |
| Koligkioni et al. (2018) | Treatment of 1 t of discarded textiles in Denmark | ILCD 2011 | INE[4] | • Reuse in Denmark: −1381 %<br>• Reuse outside Europe: −1129 %<br>• Reuse in Europe: −1100 %<br>• Integrated scenario: −731 % |
| Moazzem et al., (2021b) | Treatment of 1 t of discarded textiles in Australia | CML-2015 and ReCiPe 1.11 | LF with electricity production from methane | • Open-loop mechanical recycling of all type of fibres (wipes): −3290 %<br>• Fibre cotton mechanical recycling: −1083 %<br>• Open-loop mechanical recycling of cotton (insulation material): −200 %<br>• Polyester chemical recycling: −111 % |
| Semba et al. (2020) | Treatment of textile waste discarded in Japan in 1 year | n.a. | INE + virgin production | • Reuse abroad: −100 %<br>• Open-loop mechanical recycling (wipes, felt): −96 %<br>• Polyester chemical recycling: −60 % |
| Zamani et al. (2015) | Treatment of 1 t of discarded textiles in Sweden | n.a | INE[4] | • Remanufacturing: −3578 %<br>• Cellulose-polyester separation process: −2491 %<br>• Polyester chemical recycling: −491 %<br>• Integrated scenario: −4448 % |

[1]The variations of the climate change impacts in comparison to the baseline scenario are highlighted. Impact variation = (alternative scenario impacts – baseline scenario impacts) / baseline scenario impacts. For each study the alternative scenario with the highest benefit compared with the baseline scenario has been highlighted in green.
[2]Not available.
[3]Landfilling.
[4]Incineration with energy recovery.

incineration with energy recovery) in all impact categories, even if both scenarios are definitely better than the baseline one (16 % reuse, 2 % recycling, 82 % incineration with energy recovery). If reuse takes place in the country where textile waste is collected rather than abroad, the impacts are typically lower (Payet, 2021; Koligkioni et al., 2018). In Moazzem et al., (2021b), where reuse is not considered as waste treatment strategy, the highest impacts avoidance for climate change and land use is given by the recycling into cleaning wipes, because this technique is applied to all type of fibres, while for acidification and water depletion the best option is mechanical recycling of cotton fibres. In Zamani et al. (2015) and in Dahlbo et al. (2017), after incineration with energy recovery, chemical recycling appears to be the operation with the highest impacts among the waste management options. Where also thermal recycling to produce secondary solid fuel is considered (Semba et al., 2020), this is the strategy which brings the worst environmental performances. In Amicarelli & Bux (2022), the $CO_2$ equivalent emissions decrease with increasing separate collection and recycling rate, while the energy consumption increases because of the lower amount of textile waste sent to incineration with energy recovery, which gives lower credits. In the papers where the system expansion is applied, the avoided impacts from virgin production represent the most important contribution to the benefits of reuse or recycling. Even if reuse showed better environmental performances than recycling, they do not exclude each other, since they are addressed to different fractions of the waste. In fact, the integration of all the waste management technologies brings a great impact reduction. For instance, according to Zamani et al. (2015), climate change impacts fall to −10 t $CO_2$ eq./t waste from 0.2 t $CO_2$ eq./t waste of the incineration scenario, while for primary energy demand the impacts decrease from –22 GJ/t waste to −170 GJ/t waste. In Koligkioni et al. (2018) the integration of different reuse pathways brings to avoid climate change impacts eight times more than the incineration with energy recovery scenario.

### 4.2. *Contribution of textile waste fraction to environmental impacts in MSW management (RQ2)*

When textile waste management impacts are compared to those of other MSW fractions, reuse and recycling, in alternative to incineration with energy recovery or to landfill disposal, are confirmed as two strategies which can highly contribute to the impacts reduction (Faraca et al., 2019; Vergara et al., 2016; Corsten et al., 2013). If textiles are addressed to incineration with energy recovery, climate change impacts are considerable, especially if the synthetic textile fraction is relevant: in fact, only plastics result worse than textiles when incineration is considered as end-of-life (Arafat et al., 2015; Salemdeeb et al., 2022; Faraca et al., 2019; Corsten et al., 2013). The main results about the textile fraction contribution to climate change impacts in publications about LCA applied to MSW treatment are summarised in Table 2. The results of these studies should not be compared within each other, but they show that when textiles are diverted from incineration with energy recovery or from landfilling by reuse or recycling, their contribution to the impact saving is not negligible. According to Faraca et al. (2019), almost 1.7 t $CO_2$ eq. can be saved for each tonne of textile waste if recycling is replacing incineration with energy recovery, and the main benefit of textile recycling is the substitution of primary materials, which represents 53 % of total savings in climate change. Salemdeeb et al. (2022), considering also the impacts embedded in all the different waste fractions, stated that when considering the whole lifecycle, textiles cover 30 % of the impacts on climate change, 29 % of impacts on air quality and 23 % of impacts on water use, even if they represent only 3 % of the total household waste. When MSW are landfilled, according to Salemdeeb et al. (2022), the fractions with highest climate change impacts are paper, wood and food waste, followed by textiles. Vergara et al.

**Table 2**
Research question 2: textile fraction contribution to the impacts of municipal solid waste (MSW) treatment.

| Publications | Functional unit | LCIA method | Mass % of textiles in MSW | Ranking of MSW fractions: CC impacts of the end-of-life[1] | Most important results on climate change[2] |
|---|---|---|---|---|---|
| Corsten et al. (2013) | Management of MSW generated in the Netherlands in 1 year | n.a.[3] | 3.9 % | n.a. | Additional savings covered by textiles in recycling scenario: 17 % |
| Faraca et al. (2019) | Management of the yearly amount of recyclable waste mis-collected as small combustible waste at Danish recycling centres | ILCD | 13 % | INE:[4]<br>1. Plastics<br>2. Textiles<br>3. WEEE[5] | • INE scenario: 623 kg $CO_2$ eq./t textile waste<br>• Recycling scenario: −102 kg $CO_2$ eq./t textile waste<br>• Additional savings covered by textiles in recycling scenario: 38 % |
| Salemdeeb et al. (2022) | Management of municipal solid waste generated in Scotland in 2018 | ILCD 2011 | 3 % | LF of 1 t of waste[6]:<br>1. Paper<br>2. Organic waste<br>3. Textiles<br>INE of 1 t of waste:<br>1. Plastics<br>2. Textiles<br>3. Glass | • Textiles represent the 30 % of the impacts on CC (when also the previous life is considered)<br>• Considering only the end-of-life phase, textiles cover the 6 % of CC impacts for INE and the 7 % for LF.<br>• Reuse and recycling textiles contribute to the 9 % of the savings in CC. |
| Vergara et al. (2016) | Treatment of municipal solid waste generated in Bogotà in 2010 | n.a. | 6 % | n.a. | • Contribution of textiles in LF scenario is around 10 %<br>• Considering informal reuse of textiles brings to a decrease of −967 % in CC impacts if compared to the scenario where textile reuse is not applied. |
| Arafat et al. (2015) | Treatment of 1 kg of waste | CML 2001 (mid-point), Eco-indicator 99 (endpoint) | 1 t of each MSW fraction is considered | INE:<br>1. Plastics<br>2. Textiles<br>3. Food waste | • INE scenario: 2.1 t $CO_2$ eq. / t textile waste<br>• Gasification scenario: 1.1 t $CO_2$ eq. / t textile waste |

[1]To show the impact contribution of textiles incineration with energy recovery (INE) or of textiles landfilling (LF) in comparison to other MSW fractions, the ranking column reports the three most impactful MSW fractions.
[2]Results about the textile contribution to the total savings on climate change (CC), about the textile contribution to the total impacts on CC and about the results of the impact on CC are reported, according to the availability of these data for each study. As "additional savings" should be intended the impact benefits due to a reuse and recycling scenario in comparison to the baseline scenario of the study.
[3]not available.
[4]incineration with energy recovery.
[5]waste from electrical and electronic equipment.
[6]landfilling.

(2016) assessed the MSW management impacts in Bogotà with and without textile reuse. In the baseline scenario, the total impacts increased from −6.5 to 0.75 Mt $CO_2$ eq. when textile reuse is not considered. Arafat et al. (2015) compared different energy recovery options for MSW fractions: for textiles, incineration is better than gasification from the energy production point of view viewpoint (5 MJ/kg vs 4 MJ/kg). Only plastics incineration results in higher electricity production than textiles, but high climate change impacts are related to this high energy density: incineration leads to the emission of more than 2 kg $CO_2$ eq./kg textile waste, the highest value among all waste fractions except from plastics.

**Table 3**
Research question 3: difference between the production of recycled and virgin fibres.

| Publications | Functional unit | System boundaries[1] | LCIA method | CC[2] impacts variation[3] | WD[4] impacts variation | AC[5] impacts variation | Freshwater EU[6] impacts variation |
|---|---|---|---|---|---|---|---|
| Bianco et al. (2020) | Production of 1 kg of wool fibres | Raw materials, fibres production, packaging, wastewater treatment | EF 3.0 | −99.2 % | −99.3 % | −99.5 % | −99.7 % |
| Esteve-Turrillas & de la Guardia (2017) | Production of a cotton t-shirt | Raw materials, fibres production, t-shirt manufacturing | n.a.[5] | −98.7 % | −100 % | −99.5 % | −99.5 % |
| Fidan et al. (2021) | Production of 1.5 $m^2$ of denim cotton fabric | Raw materials, fabric production, packaging | CML-2002 | −50.0 % | −98.0 % | −60.0 % | −65.0 % |
| Liu et al. (2020) | Production of 1 t of cotton yarns | Raw materials, fibres production | ReCiPe 2013 | −60.2 % | −83.4 % | −3.77 % | +607 % |
| Qian et al. (2021) | Production of 100 kg of polyester fibres | Raw materials, fibres production | n.a. | +865 % | −68.2 % | n.a. | +26.3 % |
| Yurtaslan et al. (2021) | Production of 1 kg of cotton yarns | Yarn manufacturing | CML baseline | +4.19 % | n.a. | +4.72 % | +4.69 % |

[1]In "System boundaries" as raw materials should be considered the processes for the acquisition of virgin raw materials (in case of virgin production) and the processes related to the waste collection in case of recycled fibres production. In the same way the production is intended as virgin production or as the recycling process.
[2]climate change.
[3]Impact variation = (recycled fibres impact – virgin fibres impact) / virgin fibres impacts. Negative results mean that the impact of recycled fibres is lower than virgin fibres production impact.
[4]water depletion.
[3]acidification.
[4]eutrophication.
[5]not available.

### 4.3. Environmental impacts of recycling processes (RQ3)

As reported in Table 3, in the majority of the reviewed publications, recycled textile fibres have lower environmental impacts than virgin fibres. The results of the papers in Table 3 should not be compared across papers because of the variability of functional units, system boundaries and LCIA methods, but some trends can be identified. Among the reviewed publications, recycled wool always shows better environmental performances than virgin wool (Bianco et al., 2022; Wiedemann et al., 2022), while exceptions are found for polyester (Quian et al. 2021) and cotton (Liu et al., 2020; Yurtaslan et al., 2021) in some impact categories. According to Liu et al. (2020), the impacts of cotton recycling are lower than those of virgin production in 9 out of 16 impact categories. The categories where the recycled fibres impacts are higher are human toxicity (+0.6 %), freshwater eutrophication (+607 %), ozone depletion (+76 %), freshwater ecotoxicity (+55 %), ionizing radiation (+200 %), marine ecotoxicity (+94 %) and terrestrial ecotoxicity (+6296 %). In Yurtaslan et al. (2021), the virgin production impacts avoided are not accounted for, and the higher recycled yarns production impacts are given by the higher energy consumptions than the spinning from virgin cotton.

The main impact contribution, in the analysis of recycling processes, is usually given by the most energy intensive stages. In Subramanian et al. (2020) the pre-treatment of cotton-polyester fabrics is the most energy intensive step and it has the highest impacts in all the three end-point indicators, in Liu et al. (2020) and in Paunonen et al. (2019) the cotton spinning stage is the dominant contributor towards most of impact categories, and in Yurtaslan et al. (2022) electricity consumption covers more than 90 % of environmental burdens in all impact categories. According to Espinoza Peréz et al. (2022), the recycling stages which mainly contribute to GHG emissions are sanitizing and mixing, especially due to the production of recycled polyester. The presence of elastane in textiles is considered an important barrier to recycling (Boschmeier et al., 2023) but in the reviewed papers only in Phan et al. (2023) LCA is addressed to estimate the impacts of the separation process of elastane from other synthetic fibres. According to this study, the virgin production of elastane gives the main contribution to the carbon footprint (41 %), meaning that future research should be addressed to methods to recover also elastane and not only textile fibres. When a recycling process is compared to a baseline scenario characterized by incineration with energy recovery or landfilling, the impacts are typically lower, as reported in Table S1 in Supplementary Materials. Also in this case, the results should not be compared across different studies since there are significant differences, especially in the textile waste composition. The aim of Table S1 is to show the effects on the environmental impacts of different recycling processes when compared to a "linear" scenario. Only in Peters et al. (2019) the recycling process showed impacts higher than the baseline scenario in some impacts categories, such as acidification or climate change: these higher impacts are given by some specific chemical recycling steps, like hydrolysis, glycol separation and acidification. In several other studies the impacts of the recycling options are always lower than the baseline scenario (Table S1). The main recycling benefits on LCIA results are given by virgin textiles replacement. For instance, according to Zamani et al. (2015), the replacement of virgin yarns contributes to more than 50 % of the savings in the cellulose-polyester separation process. The contribution of virgin production is underlined also by Luedemann et al. (2022), where in the baseline scenario the polyester fibres production covers more than 60 % of the impacts in all categories. When different recycling methods are compared, the most impactful is the one characterised by the highest energy and chemicals consumption. Rosson & Byrne (2020) compared two recycling methods, in particular alkali and acid pre-treatment for chemical recycling of cotton. The first one required more electricity and 20 times more chemicals: these aspects result in potential impacts 13.6 times higher for climate change and 33.1 times higher for ozone layer depletion. After the normalisation step, in both the pre-treatment methods the most important impact categories are marine aquatic ecotoxicity, human toxicity, freshwater aquatic ecotoxicity and climate change. In Zamani et al. (2015) the difference in climate change impact between the cellulose-polyester separation process and the polyester chemical recycling process is equal to 4.6 t $CO_2$/eq./t textile waste in favour of the first option. In chemical recycling the main contribution is given by the incineration of residues and by dimethyl terephthalate (DMT) production step. According to Moazzem et al., (2021b) the difference in climate change impact between the best (open-loop mechanical recycling in wipes) and the worst option (polyester chemical recycling) is of 4.0 t $CO_2$/eq./t textile waste.

### 4.4. Effects of circular strategies on environmental impacts of textile products (RQ4)

In this review, the considered circular practices are: (i) sharing model consumptions; (ii) the adoption of reusable textile products instead of disposable ones in the healthcare sector; (iii) the reuse of a product or of a component; (iv) the recycling at the end of the service life of a textile product; (v) the use of recycled fibres in the manufacturing phase; (vi) the adoption of best practices during the use phase of a garment. The circular practices applied by different papers are listed in Table 4, together with their effects on the impacts assessed by LCA in comparison with the baseline scenario of each study. When a sharing model for textiles is analysed, a particular attention should be given to the impact of transport between users, since transport covers a relevant part of the impacts in a "share scenario" (20 % in climate change according to Levanen et al., 2021). Zamani et al. (2017) is the most complete study about different reuse and sharing scenarios, because they combined different lifespan of a garment (x2 or x4 compared to the baseline), different number of customers (11, 22, 44), two types of exchange methods (online with pick-up point or offline with physical shop) and three types of transport between users (100 % car, 50 % car – 50 % bus, 100 % bike/walking/bus). According to this study, impacts are lower when the garment lifespan is longer, when the garment is bought online and collected from a pick-up point and when the distance from home to the pick-up point is covered by bike or walking. The combination of these variables in the different scenarios can greatly influence the results. Usually, from the analysis of the reviewed papers, most of the environmental benefits are given by the actions that extend its service life. According to Vozzola et al. (2018), Giungato et al. (2021) and Snighda et al. (2023), reusable textiles for healthcare applications are better than disposable ones for almost all impacts categories. Since reusable textile product need to be washed, in this type of studies the assumptions about the modelling of the laundry phase are very relevant for the impact assessment of the water consumptions. According to Vozzola et al. (2018) the laundry operations account for 68 % of energy consumption, 67 % of greenhouse gas emissions, and 20 % of blue water consumption in the lifecycle of reusable gowns, but the environmental savings realized from manufacturing fewer gowns more than offset the additional burden of the laundry process. For Snighda et al. (2023), instead, the water depletion impact is doubled when reusable option is assessed. This difference is due to the different primary data referred to water consumption in the life cycle inventories of the two studies. The reuse of a textile product brings, in the reviewed publications, to higher benefits if compared to the recycling at the end of the service life, because, as stated by Horn et al. (2023), recycling processes consume energy, and the recycling of fabrics requires virgin materials to be added, which diminishes the achieved benefit. Combining the reuse of a non-textile component with the textile fibre recycling can bring to higher benefits. In Glew et al. (2012), climate change impacts strongly decreased (−90 %) in comparison with mattress landfilling when the metallic components of the mattress are reused and textile fibres are recycled, while in Braun et al. (2021) the manufacturing of a workwear jacket with polyester recycled from a previous jacket together with reusing the zip, resulted better than jacket manufacturing from PET

**Table 4**
Research question 4: effects on environmental impacts of circular strategies applied to textile products during their lifecycle.

| Publications | Functional unit | LCIA method | Baseline scenario | Effects of circular options on environmental impacts[1] |
|---|---|---|---|---|
| Braun et al. (2021) | Lifecycle of 1 polyester workwear jacket (4 years) | EF 3.0 | "Linear jacket" addressed to INE[2] | **"Circular jacket 1" (polyester from PET bottles)**<br>CC[3]: −18 %; freshwater EU[4]: −25 %; freshwater ET[5]: −23 %; WD[6]: −38 %<br>**"Circular jacket 2" (polyester recycled and zip reused)**<br>CC: −35 %; freshwater EU: −39 %; freshwater ET: −53 %; WD: −88 % |
| Glew et al. (2012) | Lifecycle of a natural fibres mattress (1 $m^2$, 10 years) | n.a.[7] | Mattress sent to LF[8] | **Reuse springs and frame**<br>CC: −6%<br>**Ethanol conversion**<br>CC: −23 %<br>**Recycling fibres**<br>CC: −52 % |
| Horn et al. (2023) | Lifecycle of a polyester t-shirt (1 use) | EF 2.0 | "Linear t-shirt" addressed to INE | **Best use phase practices**<br>CC: −33 %; freshwater EU: −41 %; WD: −28 %<br>**Reuse by another user**<br>CC: −23 %; freshwater EU: −14 %; WD: −18 %<br>**Remanufacture**<br>CC: −22 %; freshwater EU: −14 %; WD: −17 %<br>**Use of recycled polyester**<br>CC: −9%; freshwater EU: −5%; WD: −6%<br>**Recycling**<br>CC: −8%; freshwater EU: −5%; WD: −5% |
| Levanen et al. (2021) | Lifecycle of a pair of cotton jeans (200 uses) | CML-2016 | "Linear jeans" addressed to INE | **Extended use**<br>CC: −63 %<br>**Reuse by another user**<br>CC: −32 %<br>**Sharing**<br>CC: +21 %<br>**Recycling**<br>CC: −1% |
| Mölsä et al. (2022) | Lifecycle of a roller-towel (1 hand-drying) | ReCiPe | "Linear towel" to INE | **Reuse**<br>CC: −24 %; WD: −47 %<br>**Recycling**<br>CC: +3%; WD: 0 % |
| Pegoretti et al. (2014) | Lifecycle of a car acoustic insulation panel (10 years) | CML-2002 | "Linear polyurethane panel" to INE | **Manufacturing with recycled cotton**<br>CC: −42 %; freshwater EU: −23 %; freshwater ET: +97 % |
| Wiedemann et al. (2022) | Lifecycle of a polyester + wool sweater (1 use) | EF (year 2019) | Sweater made from virgin wool addressed to LF or INE (55 %-45 % share) | **Best use phase practices**<br>CC: −75 %; WD: −73 %<br>**Use of recycled wool**<br>CC: −69 %; WD: −48 % |
| Zamani et al. (2017) | Lifecycle of a garment in a sharing platform model (1 use) | Different characterisation model for each impact category[9] | "Linear jeans" 98 % cotton – 2 % elastane (life x1, car transport) | **Sharing (life x2, car)**<br>CC: −27 %; freshwater EU: −29 %; freshwater ET: −18 %; WD: −50 %<br>**Sharing (life x2, bike/walk)**<br>CC: −47 %; freshwater EU: −43 %; freshwater ET: −45 %; WD: −50 %<br>**Sharing (life x4, car)**<br>CC: −46 %; freshwater EU: −48 %; freshwater ET: −54 %; WD: −75 % |

[1]The effects of the circular options are calculated as (circular option impact – baseline scenario impact) / baseline scenario impact.
[2]incineration with energy recovery.
[3]climate change.
[4]eutrophication.
[5]ecotoxicity.
[6]water depletion.
[7]not available.
[8]landfilling.
[9]GWP100 (IPCC, 2013), consumptive freshwater use (Swiss Ecoscarcity model), ecotoxicity potential (USEtox model) and freshwater eutrophication potential (EUTREND model).

bottles. The combination of reuse and recycling brings to the highest benefits also according to Mölsä et al. (2022): reusing a cotton towel and recycling it at the end of the life in viscose fibres can bring to a decrease of −25 % in climate change and of −80 % in water depletion if compared to the baseline scenario. The use of recycled fibres, however, is better than the baseline linear scenarios in several studies (Braun et al., 2021; Horn et al., 2023; Wiedemann et al., 2022). According to Pegoretti et al. (2014), a recycled-cotton insulation panel shows higher impacts than a virgin polyurethane panel for the ecotoxicity categories (freshwater and terrestrial): this is due to the allocation of the cotton production impacts.

Best practices adopted during the use phase ensure the life service extension of a garment, lowering the lifecycle impacts (Horn et al., 2023; Wiedemann et al., 2022; Levanen et al., 2021), as reported in Table 4. As best practices during the use phase, a higher number of wearing events, the elimination of tumble-drying methods and a lower water and detergent consumption during washing are considered in the reviewed publications. These practices resulted the best option in several papers in Table 4, with lower impacts if compared with recycling options, as in Wiedemann et al. (2022)..

### 4.5. Main variables affecting LCIA results (RQ5)

To give an answer to RQ5, all the scenarios and the sensitivity analyses investigated in the reviewed publications have been classified in several categories (Figure S1 in Supplementary Materials). The aim is to identify the most investigated variables and then focus the analysis on the sensitivities and modelling choices which commonly impacted LCIA outcomes. The effects on LCIA results of different scenario and sensitivity analyses in several papers are summarised in Table 5. The impact variations shown in Table 5 must not be compared between different studies, since they are referred to different processes and different functional units. Table 5 aims to show how the different variables used to model the analysed processes influence the LCIA results.

The most investigated aspect in the selected studies is the variability of the waste treatment options and of the circular practices applied to textiles, followed by textile fibres composition. The type of waste management operation is strictly related to the textile composition (Fig. 2), especially because the most suitable recycling process depends on the waste composition. Moazzem et al., (2021b) and Zamani et al. (2015) showed that when the share of synthetic textile waste increases, the benefits brought by chemical recycling increase accordingly. Subramanian et al. (2020) considered recycling of polyester, studying the influence of the addition of PET bottle to polyester recycled fibres, finding that the environmental impacts on all three end-point indicators increased as the percentage of waste PET bottle chips decreased. When incineration with energy recovery is adopted as end-of-life strategy, the impacts in climate change are higher for synthetic textile waste (Glew et al., 2012; Popescu et al., 2022), while the presence of only 10 % of polyester, together with cotton waste, brings the chemical recycling impacts to + 79 % in climate change according to Oelerich et al. (2017). The choice of the textile material obtained by a recycling process can also influence results: for instance, in Mölsä et al. (2022) cotton recycling as cellulose carbamate brings to lower climate change impacts and higher water depletion in comparison with recycling into viscose.

Another aspect widely investigated is the variability in the modelling of recycling processes, including variation of the plant scheme (Paunonen et al., 2019), different recycling treatment scenarios (Rosson & Byrne, 2020), the yield of the process (Zamani et al., 2015; Phan et al., 2023) or the demand for chemicals, water or other materials (Oelerich et al., 2017; Subramanian et al., 2020; Liu et al., 2020). The influence of the aforementioned variables on the LCIA results can change among the studies. For instance, according to Zamani et al. (2015), a variation in the recycling process yield has lower influence on the results if compared with the rate of reuse of textiles. In Liu et al. (2020), a lower water consumption during the washing step in cotton recycling does not significantly affect water depletion impacts, while in Bianco et al. (2022) the dry recycling technique allow to save several impacts compared to the recycling techniques with higher water demand.

When included in the system boundaries, the modelling of the use phase of a textile product can largely influence the impact assessment. For instance, Wiedemann et al. (2022) considered as best use phase strategies a higher number of wearing events (200 instead of 109), lower washing frequency (14 wears per wash instead of 5.2), higher washing load (2.1 kg instead of 1.6 kg), higher washing machine efficiency (0.1 kWh/kg and 43 l per load instead of 0.19 kWh/kg and 46 l) and less energy demanding drying methods (50 % outdoor and 50 % in unheated rooms instead of 41 % in heated rooms, 44 % in unheated rooms and 15 % outdoor). The combination of all these practices in a recycled wool garment lifecycle brought to −60 % in climate change impacts, −56 % in fossil energy demand, −64 % in water stress and −66 % in freshwater consumption. In Horn et al. (2023), since the use phase is the most impactful stage, the adoption of best practices (washing in 50 % of use times, instead of 75 %, and avoidance of tumble drying) are the best strategy to reduce environmental impacts. According to Mölsä et al. (2022), a doubled service life of a cotton towel (use for 100 washes instead of 50) brings to a 25 % reduction in climate change impacts and 47 % in water consumption.

Since the environmental benefits of reuse and recycling are given by the replacement of textiles from virgin materials, the modelling of the virgin production processes can strongly influence the results of reuse or recycling processes. In Zamani et al. (2015) the variation of the material losses during the production stages from primary resources (loss was set to 35 %, 20 % and 5 %) highly influences the results. Peters et al. (2019) state that the environmental benefits of the analysed recycling system, in relation to a conventional system, for most indicators is determined by the environmental performance of the fibres production process, in both recycling and virgin scenarios. This means that the LCIA results are highly site and process dependent.

Since the highest impact contribution is often given by the most energy intensive processes, energy mix and energy demand can influence the results. Recycling operations are more dependent than reuse on the variables related to energy. Faraca et al. (2019) show the effects of choosing two different energy mixes for the management of the textile fraction in MSW: when assuming a fossil-based energy mix, the total savings in climate change are almost equal to 0, while in the base case, when a mix with gas, wind and biomass energy was considered, they were equal to −1.7 t $CO_2$ for each tonne of textile waste. In Vozzola et al. (2018) a 10 % decrease in laundry energy consumption resulted approximately in −7% for energy consumption and global warming. In Oelerich et al. (2017), electricity and heat consumptions depend on textile waste composition. In fact, when 100 % white cotton waste is processed to obtain cellulose pulp, the energy demand is lower than for blended cotton-polyester textile waste (58.4 kWh/100 kg of pulp vs 63.8 kWh/100 kg of pulp, and 169 MJ/100 kg of pulp vs 427 MJ/100 kg of pulp). As a consequence, environmental impacts are lower when treating 100 % white cotton waste (−44 % for climate change and for water consumption). Fidan et al. (2021) assessed the impacts of the production of a fabric with different recycled content values (0 %, 20 %, 50 %, 100 %) and two types of energy mix (energy from Turkish grid and energy from a combined heat and power plant), concluding that the recycled content had more influence on LCIA results.

When different burden allocation methods are compared in the same study, LCIA results can vary significantly. From this point of view, the most important considerations are made in Bianco et al. (2022) about the use of the Circular Footprint Formula (CFF), which results in much higher impacts than when it is not implemented (impacts assessed with the CFF are at least 5 times higher than those assessed without CFF, according to the impact category). Similar analyses and considerations about the use of the CFF can be found also in other LCA publications about different topics: Dolci et al. (2020) applied different allocation methods to railway sleepers, Farrapo et al. (2023) to briquette production, and Malabi Eberhardt et al. (2020) to the building sector. A sensitivity analysis about the allocation of environmental burdens from the previous life of a product is developed also by Pegoretti et al. (2014) and by Levanen et al. (2021): when a 50/50 allocation is considered, the impacts in climate change increased respectively by 5 % and 70 %. Such a big range is probably due to the difference between the two analysed products (an insulation panel and a pair of jeans).

An important variable in LCA systems about reuse processes is the substitution factor (SF). The SF, or replacement rate, is defined as the degree to which the purchase of second-hand clothing and other used textiles replaces the purchase of similar new items (Trzepacz et al.,

**Table 5**
Research question 5: influence of the modelling variables on the LCIA results.

| Publications | Functional unit | LCIA method | Type of scenario or sensitivity analysis | Options | Effects on environmental impacts[1] |
|---|---|---|---|---|---|
| Glew et al. (2012) | Lifecycle 1 $m^2$ of pocket spring mattress over 10 years | n.a.[2] | Textile waste composition | 1) INE[3] of a natural fibres mattress<br>2) INE of a synthetic fibres mattress | CC[4]: +13 % |
| Moazzem et al., (2021b) | Treatment of 1 t of discarded textiles in Australia | CML-2015 and ReCiPe 1.11 | Textile waste composition | 1) Waste composition: natural fibres 65 % – synthetic fibres 35 %<br>2) Waste composition: natural fibres 35 % – synthetic fibres 65 % | CC: +48 % for cotton fibre recycling; −78 % for polyester recycling<br>AC[5]: +47 % for cotton fibre recycling; −825 % for polyester recycling<br>WD[6]: 0 % for cotton fibre recycling; 0 % for polyester recycling |
| Mölsä et al. (2022) | 1 hand-drying by a roller towel | ReCiPe | Composition of the textiles obtained after recycling | 1) Towel recycling into viscose<br>2) Towel recycling into cellulose carbamate | CC: −5 %; WD: +36 % |
| Oelerich et al. (2017) | Production of 100 kg of cellulose-pulp from textile waste | ReCiPe | Textile waste composition | 1) Chemical recycling 100 % white cotton waste<br>2) Chemical recycling 90 % cotton – 10 % polyester waste | CC: +79 % |
| Popescu et al. (2022) | Treatment of 1 kg of textile waste | n.a. | Textile waste composition | 1) INE of 37 % cotton – 63 % synthetic waste<br>2) INE of 100 % cotton waste | CC: −37 % |
| Subramanian et al. (2020) | Production of 1 kg of polyester fibres | ReCiPe | Source of polyester waste | 1) Ratio recycled polyester / PET bottles chips = 20 % – 80 %<br>2) Ratio recycled polyester / PET bottles chips = 80 %-20 % | CC: +282 %; AC: +292 %; EU[7]: +251 %; WD: +281 % |
| Zamani et al. (2015) | Treatment of 1 t of discarded textiles in Sweden | CML-2007 | Textile waste composition | 1) Pure polyester in waste = 25 %<br>2) Pure polyester in waste = 50 % | CC: −133 % for polyester chemical recycling |
| Bianco et al. (2022) | Production of 1 kg of wool fibres (virgin or recycled) | EF 3.0 | Water demand in recycling process | 1) Wet recycling process<br>2) Dry recycling process | CC: −63 %; AC: –40 %; Freshwter EU: –78 %; WD: –86 % |
| Liu et al. (2020) | Production of 1 t of cotton yarns (virgin vs recycled) | ReCiPe 2013 | Water demand in recycling process | 1) Cotton recycling (baseline)<br>2) Cotton recycling with lower (−5%) water demand in washing step | CC: −0.23 %; WD: –1.7% |
| Oelerich et al. (2017) | Production of 100 kg of cellulose-pulp from textile waste | ReCiPe | Use of catalyst in recycling process | 1) Production of recycled cellulose pulp<br>2) Production of recycled cellulose pulp with the use of a biocatalyst | CC: –23 % |
| Peters et al. (2019) | Treatment of 850 t of textile waste | EF | Variation of resource demand and of emission factors in recycling process | 1) Chemical recycling of cotton and polyester<br>2) Chemical recycling of cotton and polyester: −50 % in emissions and resource demand in cellulosic fibres production | CC: –22 %; AC: –33 %; Freshwater EU: –57 %; WD: –11 % |
| Phan et al. (2023) | Treatment of 1 kg of textile waste | n.a. | Recycling process efficiency | 1) Dissolution process of polyester/ elastane waste<br>2) Dissolution process of polyester/ elastane waste with increased efficiency (+900 % in solid/liquid ratio) | CC: −53 % |
| Rosson & Byrne (2020) | Pre-treatment of 10 g of cotton waste | CML baseline | Type of recycling process | 1) Acid pre-treatment for chemical recycling of cotton<br>2) Basic pre-treatment for chemical recycling of cotton | CC: −93 %; AC: –94 %; EU: –94 % |
| Subramanian et al. (2020) | Production of 1 kg of polyester fibres | ReCiPe 2016 | Chemical demand in recycling process | 1) Biochemical recycling of cotton + polyester waste (baseline)<br>2) Biochemical recycling of cotton + polyester waste with lower (−10 %) urea consumption during pre-treatment | CC: −1.6 % |
| Zamani et al. (2015) | Treatment of 1 t of discarded textiles (cotton and polyester) in Sweden | CML-2007 | Efficiency of remanufacturing process | 1) Remanufacturing process (base)<br>2) Remanufacturing with higher (+70 %) yield | CC: −63 % |
| Zamani et al. (2015) | Treatment of 1 t of discarded textiles (cotton and polyester) in Sweden | CML-2007 | Efficiency of recycling process | 1) Chemical recycling of polyester (base)<br>2) Chemical recycling of polyester with higher yield (+11%) | CC: −22 % |
| Chen et al. (2023) | The lifecycle of a t-shirt until the use phase | Regionalised water footprint metrics | Content of recycled fibres | 1) RC[8] = 30 %<br>2) RC = 100 % | WD: −96 %; EU: –58 % |
| Fidan et al. (2021) | The production of 1.5 $m^2$ of finished denim fabric with weight 638.2 g | CML-2002 | Content of recycled fibres | 1) RC = 20 %<br>2) RC = 50 % | CC: −17 %; WD: –37 %; AC: –21 %; EU: –25 % |

(continued on next page)

**Table 5** (*continued*)

| Publications | Functional unit | LCIA method | Type of scenario or sensitivity analysis | Options | Effects on environmental impacts[1] |
|---|---|---|---|---|---|
| Fortuna & Diyamandoglu (2017) | Management of 1000 kg of used cotton garments | n.a. | Substitution factor | 1) SF[9] = 0 %<br>2) SF = 50 % | CC: −173 % |
| Koligkioni et al. (2018) | Management of 1 t of discarded textiles in Denmark | ILCD 2011 | Substitution factor | 1) SF = 30 % in Denmark, 60 % in Europe, 80 % in ROW<br>2) SF = 100 % everywhere | CC: −89 % |
| Vergara et al. (2016) | Treatment of municipal solid waste generated in Bogotà in 2010 | n.a. | Substitution factor | 1) SF = 0 %<br>2) SF = 80 % | CC: −913 % |
| Wiedemann et al. (2022) | The lifecycle of a sweater (virgin vs recycled fibres) | EF | Content of recycled fibres | 1) RC = 10 %<br>2) RC = 50 % | CC: –19 %; WD: –11 % |

[1]The effects are calculated as follows: (option 2 impacts – option 1 impacts)/option 1 impacts.
[2]not available.
[3]incineration with energy recovery.
[4]climate change.
[5]acidification.
[6]water depletion.
[7]eutrophication.
[8]recycled content.
[9]substitution factor.

2023). This variable is needed to estimate the avoided impacts from virgin production when the reuse of a product occurs. The SF depends on socioeconomic factors and on personal consumers' behaviour, and it can usually be estimated trough surveys (Farrant et al., 2010; Castellani et al., 2015). Its variation can change the ranking of the scenarios in the results, as in Koligkioni et al. (2018). In the first step of their analysis, the SF was set to 100 % in all scenarios, and the reuse in Denmark, where the textile waste was produced, resulted the best scenario. In a second step, a SF of 30 %, 60 % and 80 % was assigned respectively to Denmark, Eastern Europe and to the rest of the world, leading to the best results for the reuse abroad rather than in Denmark. This mean that impact savings given by high SF values can compensate for the emissions due to longer transport distances. Fortuna & Diyamandoglu (2017) showed that climate change impacts decreased linearly with the increasing of the SF, stating that the emission savings from reuse are higher than the other processes impact for SF $\geq$ 40 %. Dahlbo et al. (2017) found that when the SF was reduced from 100 % to 50 %, the environmental benefits of all scenarios decreased significantly, even if the avoided impacts were still greater than those generated by the waste management operations. Vergara et al. (2016) confirmed the importance of the SF for reuse processes within their sensitivity analysis. In the baseline scenario it was assumed at 80 %, and then values of 50 %, 20 % and 0 % were tested, with the result of increasing the GHG emissions by 3, 5 and 7 Mt $CO_2$ eq. respectively. When the impacts of a textile product manufacturing are assessed, the content of recycled fibres contributes to the variation of the results. Chen et al. (2023), Wiedemann et al. (2022) and Fidan et al. (2021) apply a scenario or sensitivity analysis to the recycled content in a textile product, always showing a reduction in environmental impacts with the increase of the recycled fibres used to produce a garment. Wiedemann et al. (2022) assessed the effect of the increase of recycled content in a market perspective, showing the reduction in the impacts due to the production of a recycled wool sweater in a market comprised only of virgin pure wool sweater.

The variation of separate collection, recycling and reuse rate is applied by publications focused on integrated textile waste management systems: Amicarelli & Bux (2022) find that increasing separate collection and recycling is beneficial for climate change but not for energy consumption, while Dahlbo et al. (2017) and Zamani et al. (2015) find out that reuse rate is more influent on results than recycling rate (Table 1).

The last important aspect that must be underlined is the influence of transportation processes. Their contribution is often negligible (Dahlbo et al., 2017; Farrant et al., 2010) but in some cases this variable is important. According to Bianco et al. (2022) the recycling of wool from pre-consumer waste has lower impacts than that from post-consumer waste due to the lower distance covered to transport it. Transport can influence the results also at the small scale, especially when the object of the study is a sharing model where customers rent textile products. Some examples about impacts reduction thanks to walking or bike transport instead of car transport can be found in Levanen et al. (2021) (−16 % in climate change impacts) and in Zamani et al. (2017) (–32 % in climate change and −58 % in freshwater ecotoxicity). Fortuna & Diyamandoglu (2017) estimated that in a sharing model, when the substitution factor is higher than 55 %, the impacts of long distances travels for exchanges become negligible.

### 4.6. *Methodological considerations and future research*

The power of LCA methodology is the estimate of the potential environmental impacts towards different environmental compartments, with the use of several impact categories. The best way to avoid burden shifting is the adoption of a wide range of these categories. For example, in Levanen et al. (2021), where only climate change is considered, is stated that recycling provides only moderate global warming reduction. Studies where different impact categories are considered can evaluate if the reduction on a certain category correspond to an increase in the impacts of another category. For instance, in Liu et al. (2020), recycled cotton is better than virgin for climate change but not for freshwater eutrophication.

In the publications about the waste management system of a country, it would be preferable if reuse, recycling, energy recovery and landfill are all applied at the same time to different textile waste fractions in an integrated scenario, in order to assess the impacts of the whole system, varying the share of textile waste addressed to each option, according to different scenarios of textile quality and composition, as it was applied by Dahlbo et al. (2017), Zamani et al. (2015), Amicarelli & Bux (2022).

In fact, in the publications focused on the textile waste management system of a country, the composition of textile waste is usually heterogeneous. Amicarelli & Bux (2022), Dahlbo et al. (2017), Koligkioni et al. (2018) and Moazzem et al., (2021b) establish the fibre composition from that of the textiles put on the market in the geographic area of interest, while Espinoza Pérez et al. (2022) and Semba et al. (2020) assessed the fibre composition from direct data from companies that manage the waste. When a publication is focused on the assessment of an integrated waste management system, all the waste hierarchy steps are considered at the same time (from reuse to energy recovery or final disposal). In these cases, it is necessary to develop a waste flow analysis to quantify the textile waste streams addressed to each waste treatment option. Material flow analysis (MFA) is a methodology used to estimate these fluxes, as can be found in Amicarelli & Bux (2022), Dahlbo et al. (2017) and Farrant et al. (2010). Data quality is one of the main issues for all LCA studies, and publications about textile waste management are not an exception. A particular attention should be given to the data used in the modelling of the variables that mainly affect results, such as the virgin production when reuse or recycling is applied, with a system expansion approach. Often, in the reuse scenario a doubling of service life of a product is assumed as hypothesis, but it would be better if this assumption is supported by data about the customers' habits. The substitution factor should be based on the socio-economic aspects of the country where the reuse happens, as in Koligkioni et al. (2018) and Farrant et al. (2010). The quality issue is true also for recycled fibres, because, at the moment, their content in a textile product is affected by technical limits. As stated in Bianco et al. (2022) and in Chen et al. (2023), the direct comparison between recycled and virgin fibres could be questionable because of their different quality, mainly related to their length, to their spinnability and to the mechanical properties of the yarns. Methods to include these aspects in LCA studies should be developed. Another variable that can influence the LCIA results is the transportation process modelling when the sharing of textile products is evaluated (Zamani et al., 2017; Levanen et al., 2021). In these type of studies, different type of allocation of the transport burden could be investigated, because in sharing platform models often the user can transport a product in a trip which is not only addressed to that purpose but also to others, and this can change the impacts evaluation.

To model waste management operations, such as recycling processes, the use of primary data from companies involved in this sector would be preferable (Espinosa Pérez et al., 2022; Semba et al., 2020), while to model processes connected to circular economy practices where people are involved, it is necessary to use tool and methodologies suitable to investigate individual habits and behaviours (Farrant et al., 2010). The LCA methodology can be hybridized with other methodologies such as the Practice Theory (Niero, 2023) to investigate social acceptance of new form of collaborative consumption, people motivations to discard textiles or habits toward the separate collection of textiles, to estimate how many textiles are still discarded in mixed MSW. The development of models based on practice theory and consumer habits towards textiles can be useful to link the amount of products on the market with the amount of potential textile waste. Filling these data gaps could enable LCA practitioners to have more realistic information in the modelling of the studied system.

Some environmental aspects related to textile waste management should be further evaluated in future research. An important issue is the phenomenon of abandoned textile waste and illegal landfilling dumping: the amount of abandoned waste is often very difficult to estimate, but to have a complete overview on the environmental impacts of textile waste, also this fate should be analysed, and its impacts evaluated. The other issue of concern about textiles lifecycle is the microplastics release. In their review, Henry et al. (2019) state that the simple metric of mass or number of microfibres released combined with data on their persistence in the environment, could provide a useful interim mid-point indicator in sustainability assessment tools about this topic. The evaluation of the environmental impacts from microplastics release must be taken into account if the presence or absence of recycled fibres is a factor which influence the microfibre loss. According to The Microfibre Consortium (2023), after testing 251 polyester fabrics, there was no general difference in microfibre loss between fabrics from virgin polyester and those made from recycled polyester.

Future research about textile waste management should support policies where all the waste hierarchy steps are involved. The environmental benefits of waste reduction and prevention should be evaluated, especially because one of the main problems of the textile sector is the over-production of goods put on the market (Klepp et al., 2023). LCA application could be also useful for the analysis of the Extended Producer Responsibility (EPR) schemes about textiles that are being established in several European countries. The formulation of EPR schemes should consider that, according to the waste hierarchy and to the LCA studies, reuse delivers to higher environmental benefits than recycling. The latter should than be addressed to non-reusable textile waste fractions, but needs further investments to overcome the technical limits.

Further research about the possible future composition of textile waste should be done, because the quality of the discarded textiles strongly influences the strategies for the integrated waste management system. The increasing role of online sharing platforms in used clothes exchange, together with the compulsory separate collection for EU Member States, is expected to cause a fall down in the quality of textiles addressed to waste management facilities in Europe. This must be taken into account, especially from the economic point of view, in the establishment of the EPR schemes, because at the moment the reusable fraction of the textile waste guarantees the most important revenues that can cover the cost of the other services.

The last topic that, according to the authors, is worth to examine in future research is the relationship between polyester recycling and PET bottles. According to the Preferred Fiber & Materials Market Report (Textile Exchange, 2022), recycled polyester is mainly made from PET bottles with an estimated share of 99 % of all recycled polyester. The analysis of this phenomenon, both from the environmental point of view and from the point of view of the consequences on the market of secondary raw materials, should be evaluated.

Methodological recommendations and future research topics are summarised in Fig. 3.

### 4.7. Limitations and recommendations of this study

This review was carried out on 45 studies, which have been identified according to the research string reported in Section 2. As highlighted by Estrela (2015), using LCA as primary search term for the tool limits the coverage of literature reviews on LCA methodologies and case studies. This means that papers about similar topics but without the use of "LCA" (or the other terms in the research string described in Section 2) in the title, abstract or keywords may have been excluded from the selection of the publications. In future works the number of reviewed studies could be increased, using a wider range of research terms that are often used as synonyms of "life cycle assessment".

A recommendation from the authors of this review is to consider this work as an investigation of trends in the results of LCA studies about textile waste management and circular practices. This mean that the LCIA results of different studies can not be directly compared, since a direct comparison between products or systems cannot be done across existing studies (European Commission – JRC, 2010). In Table 1-5 papers analysing similar topics have been grouped not to compare the results of different studies but to identify the main trends and to show the variability of the results among the scenarios and the sensitivity analyses.

## 5. Conclusions

The present article performed a literature review considering 45 scientific publications about LCA applied to textile waste management systems and circular strategies applied to textile products. The goal was to answer to the five research questions. From the analyses carried out, it is difficult to define unique results, because of the high variability of the analysed publications in terms of functional units, system boundaries, LCIA methods and assumptions. In order to show this high variability, quantitative results have been highlighted through the tables in the discussion section, but, as a conclusion, it is only possible to answer to the RQs in a qualitative way.

The analysis of the LCIA results of the reviewed studies reveals that, with the current technologies, reuse allows to save more impacts than recycling, but the two strategies do not exclude each other and should be integrated, because they are addressed to different quality of textile waste (RQ1). The separate collection of textile waste and its correct management (reuse and recycling) can save several impacts. In fact, when incineration is considered as end-of-life for MSW, among all the waste fractions, only plastics show higher impacts than textiles in climate change (RQ2). When the focus is on recycling processes, recycled fibres usually show lower environmental impacts than virgin ones, but some exceptions can be found in literature, especially about polyester or cotton recycling, where recycled fibres can have higher impacts than virgin ones in some impact categories. The main impact contribution, in the analysis of recycling processes, is usually given by the most energy intensive stages (RQ3). Anyway, several variables can influence the LCIA results. When different circular economy practices are compared, most of the environmental benefits are given by the actions that extend the service life of a textile product, as best practice during the use phase or the reuse (RQ4).

The main variables influencing the LCIA results (RQ5) are the textile waste composition, the recycling process characteristics (yield, chemical and water demand), the modelling of the use phase, the modelling of the virgin production for replaced products, the energy mix, the burden allocation method, the substitution factor and the modelling of the transportation processes (especially for sharing business models). Future research in this field should focus on the analysis of these variables, in order to acquire more relevant data, based on industrial-scale processes and on people habits towards the circular economy strategies applied to textiles, also with the use, in addition to LCA, of different methodologies, such as the Practice Theory.

## CRediT authorship contribution statement

**Samuele Abagnato:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Lucia Rigamonti:** Writing – review & editing, Supervision, Conceptualization. **Mario Grosso:** Writing – review & editing, Supervision, 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.].

## Data availability

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

## Acknowledgements

This research is included in a PhD programme funded by Regione Lombardia in the project “Progetto Innnovazione Polimi – Regione Lombardia: strategies for the further improvement of waste management in advanced contexts”.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.04.016.

## References

Amicarelli, V., Bux, C., 2022. Quantifying textile streams and recycling prospects in Europe by material flow analysis. Environ. Impact Assess. Rev. 97 https://doi.org/10.1016/j.eiar.2022.106878.

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

Arafat, H.A., Jijakli, K., Ahsan, A., 2015. Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. J. Clean. Prod. 105, 233–240. https://doi.org/10.1016/j.jclepro.2013.11.071.

Baydar, G., Ciliz, N., Mammadov, A., 2015. Life cycle assessment of cotton textile products in Turkey. Resour. Conserv. Recycl. 104, 213–223. https://doi.org/10.1016/j.resconrec.2015.08.007.

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

Bianco, I., De Bona, A., Zanetti, M., Panepinto, D., 2023. Environmental impacts in the textile sector: a life cycle assessment case study of a woolen undershirt. Sustainability (switzerland) 15 (15). https://doi.org/10.3390/su151511666.

Boschmeier, E., Archodoulaki, V.M., Schwaighofer, A., Lendl, B., Ipsmiller, W., Andreas Bartl, A., 2023. New separation process for elastane from polyester/elastane and polyamide/elastane textile waste. Resour. Conserv. Recycl. 198 https://doi.org/10.1016/j.resconrec.2023.107215.

Braun, G., Som, C., Schmutz, M., Hischier, R., 2021. Environmental consequences of closing the textile loop-life cycle assessment of a circular polyester jacket. Applied Sciences (switzerland) 11 (7). https://doi.org/10.3390/app11072964.

Castellani, V., Sala, S., Mirabella, N., 2015. Beyond the throwaway society: a life cycle-based assessment of the environmental benefit of reuse. Integr. Environ. Assess. Manag. 11 (3), 373–382. https://doi.org/10.1002/ieam.1614.

Chen, S., Chen, F., Zhu, L., Li, Q., Wang, X., Wang, L., 2023. A spatial water footprint assessment of recycled cotton T-shirts: case of local impacts in selected China provinces. Sustainability (switzerland) 15 (1). https://doi.org/10.3390/su15010817.

European Commission (2019). Commission Staff working document - Sustainable Products in a Circular Economy - Towards an EU Product Policy Framework contributing to the Circular Economy. Brussels, 4.3.2019 SWD(2019) 91 final.

European Commission, 2020. Guidance for separate collection of municipal waste - Final deliverable of the study to support the Commission in establishing guidelines for separate collection of waste. http://publications.europa.eu/resource/cellar/bb444830-94bf-11ea-aac4-01aa75ed71a1.0001.01/DOC_1 (accessed 3 April 2023).

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 COM(2022) 141 final.

Corsten, M., Worrell, E., Rouw, M., van Duin, A., 2013. The potential contribution of sustainable waste management to energy use and greenhouse gas emission reduction in the Netherlands. Resour. Conserv. Recycl. 77, 13–21. https://doi.org/10.1016/j.resconrec.2013.04.002.

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

Dolci, G., Rigamonti, L., Grosso, M., 2020. Potential for improving the environmental performance of railway sleepers with an outer shell made of recycled materials. Transport. Res. Interdiscipl. Perspect. 6 https://doi.org/10.1016/j.trip.2020.100160.

Ellen MacArthur Foundation, 2017. A new textiles economy: Redesigning fashion's future. http://www.ellenmacarthurfoundation.org/publications (accessed 8 May 2023).

Espinoza Pérez, L.A., Espinoza Pérez, A.T., Vásquez, Ó.C., 2022. Exploring an alternative to the chilean textile waste: a carbon footprint assessment of a textile recycling process. Sci. Total Environ. 830 https://doi.org/10.1016/j.scitotenv.2022.154542.

Esteve-Turrillas, F.A., de la Guardia, M., 2017. Environmental impact of recover cotton in textile industry. Resour. Conserv. Recycl. 116, 107–115. https://doi.org/10.1016/j.resconrec.2016.09.034.

Estrela, S. (2015). I publish, therefore I am. Or am I? A reply to A bibliometric investigation of life cycle assessment research in the web of science databases by Chen et al. (2014) and Mapping the scientific research on life cycle assessment: a bibliometric analysis by Hou et al. (2015). Int. J. Life Cycle Assessm. *20:1601–1603.* doi: 10.1007/s11367-015-0951-2.

EuRIC, 2021. Handling & Sorting Specifications For re-use and recycling of used textiles. https://euric.org/images/Position-papers/EuRIC_Handling_Sorting_Specs_July2021.pdf (accessed 27 March 2023).

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. doi: 10.2788/38479.

European Parliament (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance).

Textile Exchange (2022). Preferred Fiber & Materials Market Report https://textileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf (accessed 4 September 2023).

Faraca, G., Edjabou, V.M., Boldrin, A., Astrup, T., 2019. Combustible waste collected at danish recycling centres: Characterisation, recycling potentials and contribution to

environmental savings. Waste Manag. 89, 354–365. https://doi.org/10.1016/j.wasman.2019.04.007.
Farrant, L., Olsen, S. I., & Wangel, A. (2010). Environmental benefits from reusing clothes. In *International Journal of Life Cycle Assessment* (Vol. 15, Issue 7, pp. 726–736). doi: 10.1007/s11367-010-0197-y.
Farrapo, A.C., Matheus, T.T., Lagunes, R.M., Filleti, R., Yamaji, F., Lopes Silva, D.A., 2023. The application of Circular footprint formula in bioenergy/bioeconomy: challenges, case study, and Comparison with life cycle assessment allocation methods. Sustainability (switzerland) 15 (3). https://doi.org/10.3390/su15032339.
Fidan, F.S., Aydogan, 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.
Fortuna, L.M., Diyamandoglu, V., 2017. Optimization of greenhouse gas emissions in second-hand consumer product recovery through reuse platforms. Waste Manag. 66, 178–189. https://doi.org/10.1016/j.wasman.2017.04.032.
Giungato, P., Rana, R.L., Nitti, N., Cavallari, C., Tricase, C., 2021. Carbon footprint of surgical masks made in Taranto to prevent Sars-Cov-2 diffusion: a preliminary assessment. Sustainability (switzerland) 13 (11). https://doi.org/10.3390/su13116296.
Glew, D., Stringer, L.C., Acquaye, A.A., McQueen-Mason, S., 2012. How do end of life scenarios influence the environmental impact of product supply chains? Comparing biomaterial and petrochemical products. J. Clean. Prod. 29–30, 122–131. https://doi.org/10.1016/j.jclepro.2012.02.005.
Henry, B., Laitala, K., Klepp, I.G., 2019. Microfibres from apparel and home textiles: prospects for including microplastics in environmental sustainability assessment. Sci. Total Environ. 652, 483–494. https://doi.org/10.1016/j.scitotenv.2018.10.166.
Horn, S., Mölsä, K.M., Sorvari, J., Tuovila, H., Heikkilä, P., 2023. Environmental sustainability assessment of a polyester T-shirt – Comparison of circularity strategies. Sci. Total Environ. 884 https://doi.org/10.1016/j.scitotenv.2023.163821.
Klepp, I. G., Berg, L. L., Sigaard, A. S., Tobiasson, S., & Gleisberg, L., 2023. The Plastic Elephant: overproduction and synthetic fibres in sustainable textile strategies. . (accessed 9 September 2023).
Köhler, A., Watson, D., Trzepacz, S., Löw, C., Liu, R., Danneck, J., 2021. Circular Economy Perspectives in the EU Textile Sector - Final Report. https://doi.org/10.2760/858144.
Koligkioni, A., Parajuly, K., Sørensen, B.L., Cimpan, C., 2018. Environmental assessment of end-of-life textiles in Denmark. Procedia CIRP 69, 962–967. https://doi.org/10.1016/j.procir.2017.11.090.
L'Abbate, P., Dassisti, M., Cappelletti, G.M., Nicoletti, G.M., Russo, C., Ioppolo, G., 2018. Environmental analysis of polyester fabric for ticking. J. Clean. Prod. 172, 735–742. https://doi.org/10.1016/j.jclepro.2017.10.045.
Lenzo, P., Traverso, M., Mondello, G., Salomone, R., Ioppolo, G., 2018. Sustainability performance of an italian textile product. Economies 6 (1). https://doi.org/10.3390/economies6010017.
Levanen, J., Uusitalo, V., Harri, A., Kareinen, E., Linnanen, L., 2021. Innovative recycling or extended use? Comparing the global warming potential of different ownership and end-of-life scenarios for textiles. Environ. Res. Lett. 16 (5) https://doi.org/10.1088/1748-9326/abfac3.
Liu, Y., Huang, H., Zhu, L., Zhang, C., Ren, F., Liu, Z., 2020. *Could the recycled yarns substitute for the virgin cotton yarns: a comparative LCA*. https://doi.org/10.1007/s11367-020-01815-8.
Luedemann, L., Felber, A., Golder, M., 2022. Development of a recycling process for textiles made from PET, and proof of its environmental preference with life cycle assessment. Int. J. Technol. Managem. 88.
Malabi Eberhardt, L.C., Stijn, A.V., Rasmussen, F.N., Birkved, M., Birgisdottir, H., 2020. Towards circular life cycle assessment for the built environment: a comparison of allocation approaches. IOP Conference Series: Earth and Environmental Science 588 (3). https://doi.org/10.1088/1755-1315/588/3/032026.
Moazzem, S., Crossin, E., Daver, F., Wang, L., 2021a. Assessing environmental impact reduction opportunities through life cycle assessment of apparel products. Sustainable Production and Consumption 28, 663–674. https://doi.org/10.1016/j.spc.2021.06.015.
Moazzem, S., Wang, L., Daver, F., Crossin, E., 2021b. Environmental impact of discarded apparel landfilling and recycling. Resour. Conserv. Recycl. 166 https://doi.org/10.1016/j.resconrec.2020.105338.
Mölsä, K.M., Horn, S., Dahlbo, H., Rissanen, M., 2022. Linear, reuse or recycling? an environmental comparison of different life cycle options for cotton roller towels. J. Clean. Prod. 374 https://doi.org/10.1016/j.jclepro.2022.133976.
Munasinghe, P., Druckman, A., & Dissanayake, D. G. K. (2021). A systematic review of the life cycle inventory of clothing. In *Journal of Cleaner Production* (Vol. 320). Elsevier Ltd. doi: 10.1016/j.jclepro.2021.128852.
Muthu, S.S.K., Li, Y., Hu, J.Y., Ze, L., 2012. Carbon footprint reduction in the textile process chain: recycling of textile materials. Fibers Polym. 13 (8), 1065–1070. https://doi.org/10.1007/s12221-012-1065-0.
Niero, M., 2023. Implementation of the European Unions packaging and packaging waste regulation: a decision support framework combining quantitative environmental sustainability assessment methods and socio-technical approaches. Cleaner Waste Systems 6. https://doi.org/10.1016/j.clwas.2023.100112.
Oelerich, J., Bijleveld, M., Bouwhuis, G.H., Brinks, G.J., 2017. The life cycle assessment of cellulose pulp from waste cotton via the SaXcell™ process. IOP Conference Series: Materials Science and Engineering 254 (19). https://doi.org/10.1088/1757-899X/254/19/192012.
Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., et al., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Br. Med. J. 372 (71) https://doi.org/10.1136/bmj.n71.
Paunonen, S., Kamppuri, T., Katajainen, L., Hohenthal, C., Heikkilä, P., Harlin, A., 2019. Environmental impact of cellulose carbamate fibers from chemically recycled cotton. J. Clean. Prod. 222, 871–881. https://doi.org/10.1016/j.jclepro.2019.03.063.
Payet, J., 2021. Assessment of Carbon footprint for the textile sector in France. Sustainability 13, 2422. https://doi.org/10.3390/su13052422.
Pegoretti, T.D.S., Mathieux, F., Evrard, D., Brissaud, D., Arruda, J.R.D.F., 2014. Use of recycled natural fibres in industrial products: a comparative LCA case study on acoustic components in the brazilian automotive sector. Resour. Conserv. Recycl. 84, 1–14. https://doi.org/10.1016/j.resconrec.2013.12.010.
Pesnel, S., & Payet, J. (2019). *Product Environmental Footprint Category Rules (PEFCR) T-shirts*.
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.
Phan, K., Ügdüler, S., Harinck, L., Denolf, R., Roosen, M., O'Rourke, G., De Vos, D., Van Speybroeck, V., De Clerck, K., De Meester, S., 2023. Analysing the potential of the selective dissolution of elastane from mixed fiber textile waste. Resour. Conserv. Recycl. 191 https://doi.org/10.1016/j.resconrec.2023.106903.
Popescu, A.P., Cheah, Y.K., Varbanov, P.S., Klemeš, J.J., Kabli, M.R., Shahzad, K., 2022. Exergy footprint assessment of cotton textile recycling to polyethylene. Energies 15 (1). https://doi.org/10.3390/en15010205.
Qian, W., Ji, X., Xu, P., Wang, L., 2021. Carbon footprint and water footprint assessment of virgin and recycled polyester textiles. Text. Res. J. 91 (21–22), 2468–2475. https://doi.org/10.1177/00405175211006213.
Rosson, L., Byrne, N., 2020. Comparative gate-to-gate life cycle assessment for the alkali and acid pre-treatment step in the chemical recycling of waste cotton. Sustainability (switzerland) 12 (20), 1–15. https://doi.org/10.3390/su12208613.
Salemdeeb, R., Saint, R., Pomponi, F., Pratt, K., Lenaghan, M., 2022. Beyond recycling: an LCA-based decision-support tool to accelerate Scotland's transition to a circular economy. Res. Conserv. Recycling Adv. 13 https://doi.org/10.1016/j.rcradv.2022.200069.
Sandin, G., & Peters, G. M. (2018). Environmental impact of textile reuse and recycling – A review. In *Journal of Cleaner Production* (Vol. 184, pp. 353–365). Elsevier Ltd. doi: 10.1016/j.jclepro.2018.02.266.
Semba, T., Sakai, Y., Ishikawa, M., Inaba, A., 2020. Greenhouse gas emission reductions by reusing and recycling used clothing in Japan. Sustainability (switzerland) 12 (19). https://doi.org/10.3390/su12198214.
Shen, L., Worrell, E., Patel, M.K., 2010. Environmental impact assessment of man-made cellulose fibres. Resour. Conserv. Recycl. 55 (2), 260–274. https://doi.org/10.1016/j.resconrec.2010.10.001.
Sim, J., Prabhu, V., 2018. The life cycle assessment of energy and carbon emissions on wool and nylon carpets in the United States. J. Clean. Prod. 170, 1231–1243. https://doi.org/10.1016/j.jclepro.2017.09.203.
Snigdha, H., Bandyopadhyay, S., 2023. Environmental footprints of disposable and reusable personal protective equipment - a product life cycle approach for body coveralls. J. Clean. Prod. 394 https://doi.org/10.1016/j.jclepro.2023.136166.
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 https://doi.org/10.1016/j.resconrec.2020.104989.
The Microfibre Consortium, 2023. Leading the textile industry in reducing microfibre release to protect our environment. https://www.microfibreconsortium.com/resources-1 (accessed 10 July 2023).
Trzepacz, S., Dina Bekkevold Lingås, N., Lise Asscherickx, N., Karolien Peeters, V., Hilde van Duijn, V., & Marieke Akerboom, E. (2023). LCA-based assessment of the management of European used textiles https://euric.org/images/Position-papers/lca-based-assessment-of-the-management-of-european-used-textiles_corrected.pdf (accessed 21 June 2023).
van Duijn, H., Papú Carrone, N., Bakowska, O., Huang, Q., Akerboom, M., Rademan, K., Vellanki, D., 2022. Sorting for circularity Europe - An evaluation and commercial assessment of textile waste across Europe (https://reports.fashionforgood.com/report/sorting-for-circularity-europe/ accessed 14th April 2023).
Vergara, S.E., Damgaard, A., Gomez, D., 2016. The efficiency of informality: quantifying greenhouse gas reductions from informal recycling in Bogotá Colombia. J. Ind. Ecol. 20 (1), 107–119. https://doi.org/10.1111/jiec.12257.
Vozzola, E., Overcash, M., Griffing, E., 2018. Environmental considerations in the selection of isolation gowns: a life cycle assessment of reusable and disposable alternatives. Am. J. Infect. Control 46 (8), 881–886. https://doi.org/10.1016/j.ajic.2018.02.002.
Wiedemann, S.G., Biggs, L., Clarke, S.J., Russell, S.J., 2022. Reducing the environmental impacts of Garments through industrially scalable closed-loop recycling: life cycle assessment of a recycled wool blend sweater. Sustainability (switzerland) 14 (3). https://doi.org/10.3390/su14031081.
Yasin, S., Sun, D., 2019. Propelling textile waste to ascend the ladder of sustainability: EOL study on probing environmental parity in technical textiles. J. Clean. Prod. 233, 1451–1464. https://doi.org/10.1016/j.jclepro.2019.06.009.
Yousef, S., Tatariants, M., Tichonovas, M., Sarwar, Z., Jonuškienė, I., Kliucininkas, L., 2019. A new strategy for using textile waste as a sustainable source of recovered cotton. Resour. Conserv. Recycl. 145, 359–369. https://doi.org/10.1016/j.resconrec.2019.02.031.

Yurtaslan, Ö., Altun Kurtoğlu, Ş., Yılmaz, D., 2022. Closed-loop mechanical recycling opportunities in industrial cotton wastes. J. Nat. Fibers 19 (15), 11802–11817. https://doi.org/10.1080/15440478.2022.2044961.

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.

Zamani, B., Sandin, G., Peters, G.M., 2017. Life cycle assessment of clothing libraries: can collaborative consumption reduce the environmental impact of fast fashion? J. Clean. Prod. 162, 1368–1375. https://doi.org/10.1016/j.jclepro.2017.06.128.