Science of the Total Environment 927 (2024) 172161

Contents lists available at ScienceDirect

Science of the Total Environment

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

Life cycle assessment of alternatives for industrial textile recycling

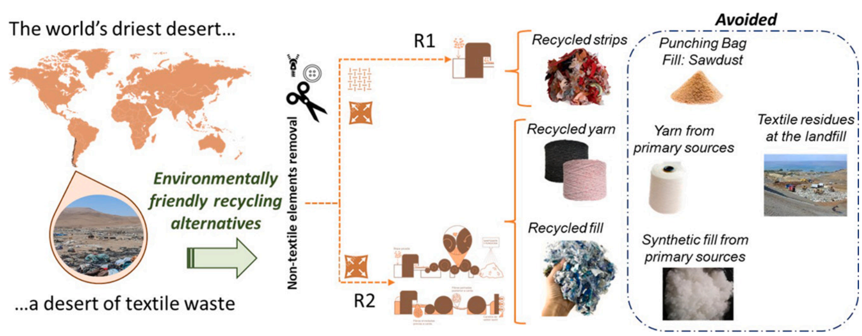
Lorena A. Espinoza-Pérez *, Andrea T. Espinoza-Pérez, Óscar C. Vásquez

University of Santiago of Chile (USACH), Faculty of Engineering, Program for the Development of Sustainable Production Systems (PDSPS), Chile
University of Santiago of Chile (USACH), Faculty of Engineering, Industrial Engineering Department, Chile

HIGHLIGHTS

- Textile residue recycling for pushing ball fill has environmental benefits.
- Environmental benefit depends on plants' location for some recycling process.
- There are several environmentally friendly textile recycling alternatives.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Deyi Hou

Keywords:
Textile residues
Life cycle assessment
Chile
Circular economy

ABSTRACT

The $882 billion textile trade in 2021 poses environmental concerns, highlighting the importance of encouraging a circular economy to attain sustainable textiles. Therefore, policies must prioritize textile recycling, particularly in developing countries, and sharing information throughout the value chain. This research aims to explore the potential environmental benefits of two industrial recycling processes for textile residues versus the traditional waste management and production process through a life cycle assessment applying the ReCiPe method at midpoint and endpoint levels focusing on generating significant data availability and broader assessment than existing literature to support decision making related to recycling systems for textile residues. Results related to the textile residues recycling process to obtain stripes (R1) and replace sawdust, to fill pushing balls, show that it would produce environmental benefits regardless of location in several midpoint categories. Furthermore, regarding the endpoint results, the DALY savings are mainly due to avoiding landfill, while the savings in ecosystem impacts are generated by avoiding landfill and sawdust production. Regarding the recycling process to obtain recycled yarn and fill (R2) net savings in global warming potential are generated if landfill avoidance is considered. Nevertheless, endpoint results show that DALYs of all the avoided processes correspond to 1.5 times the impacts of all the R2 recycling processes, mainly due to avoiding virgin yarn production. Therefore, both recycling processes are recommended. However, some strategies are required to generate greater benefits, such as applying the R2 recycling process as the first option for stretchable textile waste, and after being used, going through the R1 recycling process. In addition, the strategic placement of the R1 recycling facility should be distant from areas of sawdust production. A sensitivity analysis was carried out due to the variability of virgin products to replace in the market.

* Corresponding author at: University of Santiago of Chile (USACH), Faculty of Engineering, Program for the Development of Sustainable Production Systems (PDSPS), Chile.

E-mail addresses: lorena.espinozap@usach.cl (L.A. Espinoza-Pérez), andrea.espinozap@usach.cl (A.T. Espinoza-Pérez), oscar.vasquez@usach.cl (Ó.C. Vásquez).

https://doi.org/10.1016/j.scitotenv.2024.172161
Received 17 August 2023; Received in revised form 9 March 2024; Accepted 31 March 2024
Available online 9 April 2024
0048-9697/

1. Introduction

Textiles were the world's seventh most traded product in 2021, with a total trade of $882 billion, a 13.2 % increase from $779 billion in 2020 (Observatory of Economic Complexity (OEC), 2021). This increase is concerning, considering the fashion industry accounts for 8–10 % of global carbon emissions – more than all international flights and maritime shipping combined – (UNEP, 2018), and it consumes around 93 billion cubic meters of water per year – enough to meet the needs of five million people – contributing significantly to water scarcity in some regions (UNCTAD, 2020). Consequently, the fashion industry's environmental costs emphasize the need for more sustainable business models and practices. Several strategies can be employed to achieve this goal.

One approach involves ensuring the longevity and durability of textile products, which contribute to extending the life cycle of textiles. Additionally, optimizing resource utilization could also reduce pressures by reducing and optimizing water and energy use, air emissions, and water pollution by using safe chemicals and diversified biodegradable materials (ETC/WMGE, 2021). While the previously mentioned approaches centered around *slowing down the loop*, the realization of a circular economy, in which materials are retained in a *closed loop*, aims to extend the life of textile products through reuse and repair and keep end-of-life (EoL) materials in the economy through recycling (Schumacher and Forster, 2022; Ribul et al., 2021). Therefore, transitioning to a circular economy could support SDGs 8 - decent work and economic growth, 12 - responsible consumption and production, and 13 - climate action contributing to sustainable development (de Montellano et al., 2023). However, for this to be the case, the production processes implemented to close the loop must be significantly better compared to EoL alternatives for products like landfills.

Despite the existence of several approaches to a more sustainable textile industry globally, approximately 75 % of textile waste is disposed of in landfills, 25 % is reused or recycled, and less than 1 % of the recycled garments are converted into new materials (Juanga-Labayen et al., 2022). For instance, 38 % of the textile residues are separately collected for reuse, recycling, or other waste treatment in the EU, from which less than 1 % of textile residues are recycled into fibers for new clothing (Trzepacz et al., 2023). In the US, the Secondary Market and Recycled Textiles (SMART) trade group report estimates that only 15 % of the total used textiles are processed (45 % is sold for reuse; 30 % is used as an institutional rag; 20 % is used for stuffing, shoddy, and yarn fiber industry; and 5 % is unusable or unrecoverable due to spoilage) (Juanga-Labayen et al., 2022). China also reuses or recycles around 15 % of textile residues (Juanga-Labayen et al., 2022), while India reaches 25 %. Even worse, in developing countries such as Vietnam, considerable amounts of solid waste are being disposed of in landfills, and hardly anything is reused/recycled due to poor mechanisms to deal with rising textile waste (Nayak et al., 2019). Furthermore, these recycling achievements are related to significant issues with blended textiles related to post-consumer waste streams in the form of garments. These garments often consist of multi-material fiber compositions, making recycling very complicated because these different types of fibers need to be separated for recycling, which is difficult or even impossible (Harmsen et al., 2021). In addition, emerging countries purchase used textiles from industrialized countries in ever-increasing amounts, leading to further expansion of waste piles in these countries (Fibre2Fashion, 2021). Therefore, it is necessary to generate strategies that support the development of textile recycling, focusing on developing countries and reducing environmental impacts.

Furthermore, lack of knowledge is a common issue across the complete value chain, ranging from recyclers and manufacturers to customers and consumers. Hence, there is a need to increase knowledge, share information, and showcase possibilities by presenting examples, such as the best practices and pilot projects (van der Vegt et al., 2022). Therefore, the recent research related to recycled garments to new materials is assessed to show the current trends and environmental benefits that those recycling processes would produce.

2. Review of relevant related literature

Currently, there is limited interest in textile residue recycling globally because of a lack of recycling techniques that have proven cost-effective at full scale and the large variety of fibers and colors used in clothing (Zamani et al., 2015). Previously, Espinoza et al. (2022) presented a succinct literature review on the topic of textile recycling using the Life Cycle Assessment (LCA) tool (search date: 03 092021). Therefore, to assess the most recent related literature, the same combination of keywords, selection criteria, and review process followed by Espinoza et al. (2022) were followed. However, only articles published from 2021 (inclusive) up to 26 June 2023 were searched.

Furthermore, we augmented our search criteria by incorporating additional keywords to identify research specifically focused on assessing environmental impacts related to carbon or water footprints within the textile or yarn industry. Following, the research questions (RQ) established are presented:

- RQ1 - Research question used by Espinoza et al. (2022): "TS = ((Life cycle assessment OR ACV) AND (Textile OR Yarn) AND (recyclage OR recycled OR recycling OR recycle))"
- RQ2 - Additional research question searched: "ALL = ((Carbon Footprint OR Water footprint) AND (Textile OR Yarn) AND (recyclage OR recycled OR recycling OR recycle))"

It is worth noting that the search was conducted for both research questions across both databases, Web of Science and SCOPUS, resulting in 162 publications. The search for RQ1 yielded a total of 105 publications, and the search for RQ2 yielded a total of 57 publications. Then, a database was constructed to compile the 162 publications and select the related literature for review. The exclusion criteria in the initial screening phase involved removing duplicate entries, conference papers, books, and unavailable publications. As a result, 78 publications met the exclusion criteria, and 84 pertinent publications remained. The second selection stage corresponds to screening the remaining publications to identify those related to the main research topic. In this case, publications related to textile recycling (post-consumer) or fibers will be selected. This selection process relied on examining titles and abstracts, resulting in 48 publications. Subsequently, a final selection stage corresponded to screening the publications to identify those related to the specific research topic. In this case, this screening was conducted independently by two reviewers, involving a full-text read with a specific focus on identifying the studies employing LCA methodology in textile recycling. This rigorous scrutiny yielded a final selection of 17 publications, all different from those reviewed by Espinoza et al. (2022).

For the selected publication's assessment, we differentiate between research and review articles. For the research articles, we assess the country, functional unit, type/technology of textile recycling mentioned, the products obtained, and finally, the analyzed impact categories. A summary of the content was recorded for the literature reviews. Table 1 details the selected publication's assessment.

Regarding research articles only assessing Global Warming Potential (GWP), Levänen et al. (2021) compare the GWP impacts of five different ownership and EoL scenarios for jeans, including basic use, waste disposal, extended use, resale, recycling, and rental services. The recycling scenario involves transforming used jeans into cotton fibers. Therefore, this research only considers one of the environmental impacts generated by the textile industry including recycling, for a single type of material. Meanwhile, Payet (2021) calculates the GWP of the entire French textile industry, considering 20 companies and 17 textile products. Furthermore, they investigated multiple revaluation methods for textile residue without specifying the procedure or whether they are particular to a single type of material or blended materials, and they

Table 1
Research articles assessment. *Me: Mechanical recycling; Ch: Chemical recycling; n/a: It does not detail recycling technology; MWool: a recycled wool fiber produced by Manteco SpA; GWP: Global Warming Potential; SOD: Stratospheric ozone depletion; POF: Photochemical Ozone Formation; PM: Particulate Matter; A: Acidification; FEU: Freshwater Eutrophication; TEU: Terrestrial Eutrophication; FEC: Freshwater Eco-toxicity; LU: Land Use; WC: Water Consumption; FRS: Fossil resource scarcity; EcoTox: Ecotoxicity Freshwater; WF: Water Footprint; HH: Human Health; EQ: ecosystem quality; MEU: Marine eutrophication; TA: Terrestrial acidification; DIPM: disease incidents due to particulate matter emissions;

Reference	Country	Functional unit	Recycling technology / Product obtained	Impact category
Levänen et al. (2021)	European Union	Usage of a pair of jeans 200 times	n/a / *Re*-used products into new materials	GWP
Payet (2021)	France	Sold clothes and household linen, per 1 person per year.	Me / Yarn, insulation, or composite.	GWP
Espinoza et al. (2022)	Chile	1 t of blended textile waste	Me / Yarn and stuffing	GWP
Chen et al. (2023a)	China	1 piece of 100 % cotton T-shirt with a weight of 180 g.	n/a / T-shirt, eco T-shirt, recycled T-shirt	WC and WF
Mölsä et al. (2022)	Finland	1 hand-drying with a roller towel	Ch / Viscose or cellulose carbamate for yarn production	GWP and WC
Wiedemann et al. (2022)	Australia	1 knitted wool sweater over its lifetime	Me / Recycled Wool Blend Sweater	GWP, fossil energy demand, water stress, and WC
Bianco et al. (2022)	Italy	1 kg of MWool fibers and virgin wool fibers	Me / Mwool (secondary wool fiber)	GWP, SOD, POF, PM, A, FEU, TEU, FEC, LU, WC, Resource use.
Alam et al. (2023)	Bangladesh	1 kg of circular and heavy knitwear products	n/a / Knitwear products	GWP, FRS, LU, ECOtox, WF, HH and EQ
Horn et al. (2023)	Finland	1 use of a polyester T-shirt	Me / Polyester fiber for use, and Fluff and filling materials.	GWP, WC, FEU, MEU, TA, DIPM, and resource depletion of energy carriers.

were evaluated economically. Espinoza et al. (2022) also analyzes the GWP for textile recycling scenarios where yarn and stuffing products are obtained. It determines whether a mechanical recycling technique applied at a Chilean enterprise for household textile waste could potentially result in a net environmental benefit compared to current practices. However, this study only considers one environmental impact of textile recycling. Additionally, considering the water impacts, Chen et al. (2023a) presents a spatial water footprint assessment of a recycled cotton T-shirt in China, comparing a t-shirt with no recycled fibers, 30 % recycled fibers included, and 100 % recycling fiber. It concludes that a piece of a recycled T-shirt (100 % recycling) contributes a 96.71 % reduction in the water scarcity footprint and a 65.76 % reduction in the water eutrophication footprint compared with the conventional T-shirt. Therefore, this research only considers one of the environmental impacts generated by the textile industry including recycling, for a single type of material.

Mölsä et al. (2022) was beyond and assessed GWP and water consumption impacts. It evaluates the environmental impacts of a cotton roller towel throughout its life cycle, including EoL scenarios of incineration, dyeing, reusing, and recycling to fiber or yarns.

More extended research regarding different environmental impacts includes Wiedemann et al. (2022), which assessed the GHG emissions, water stress, fossil fuel energy use, and freshwater consumption of a recycled wool blend sweater and a virgin merino pure wool sweater in Australia, including pre-treatment, overdyeing, spinning, knitting, and finishing stages. The impacts of a recycled wool blend sweater achieved a reduction of 66 – 90% compared to the virgin pure wool sweater. Determine the impacts and hotspots of a recycled wool blend sweater, compare them to those of a virgin pure wool sweater, and quantify the effect of recycling on the impact of an average wool sweater in the market. Furthermore, Bianco et al. (2022) assessed the environmental impact of MWool®, a recycled wool fiber produced by Manteco SpA, Italy. It used the EF 3.0 method to assess climate change, ozone depletion, photochemical ozone formation, particulate matter, acidification, freshwater eutrophication, terrestrial eutrophication, freshwater ecotoxicity, land use, water use, resource use– fossils, and resource use–minerals and metals. And concludes that the impacts of recycled fibers are about 60 % less than those of virgin wool fibers. Alam et al. (2023) assessed the environmental impact of traditional knitwear production in Bangladesh considering the ReCiPe midpoint impact categories GWP, fossil resource scarcity, land use, ecotoxicity, water footprint, and impact of damage levels considering human health and ecosystem quality. The study also calculated the environmental impact of using alternative mixed fibers such as organic cotton, recycled polyester, and recycled cotton. However, it does not assess in detail the production process to obtain these recycled fibers using database information. Horn et al. (2023) assessed the environmental impacts, through the EF 2.0 method, of a polyester T-shirt's linear life cycle compared to adopting various Circular Economy (CE) strategies and their priority order in Finland, including recycling. In this case, the authors assume that the T-shirt is recycled as polyester material after its life cycle has ended after 200 uses, thus substituting virgin polyester fiber, assessing a single type of material.

The review articles all focus on the textile industry's environmental impact, but they approach the problem from various angles and propose possible solutions. Concerning post-consumer textile waste, Kamble and Behera (2021) examine the challenges of textile waste management, including environmental hazards, and emphasize the importance of recycling and upcycling textiles into higher-value products. They identify inadequate recycling systems and the complexity of treating certain textiles as key hurdles. Chopra et al. (2023) address the growing global concern of textile waste and highlight the importance of utilizing (valorizing) waste streams to reduce landfill burden. Their study explores the rapid advancements in valorization technologies for diverse textiles. And Stanescu (2021) emphasizes the environmental impact of the textile industry and advocates for a shift towards circular economy principles. This approach involves reusing post-consumer textile waste to minimize environmental footprints and promote zero-waste goals. The second theme identified is Textile Life Cycle, Munasinghe et al. (2021) addresses a critical gap in accessible Life Cycle Inventory (LCI) data for the clothing industry. Through a systematic review and meta-analysis, authors provide comprehensive data on energy use, water consumption, and greenhouse gas emissions across all stages of a textile product's life cycle. Chen et al. (2023b) examine the environmental impact of cotton clothing production across its entire lifecycle, including cultivation, ginning, spinning, weaving, dyeing, and finishing. Their study highlights the significant resource consumption and environmental consequences, such as freshwater depletion, energy use, and chemical pollution. And Moazzem et al. (2021) compare the substantial environmental impact of textile products and production processes with other goods. Their focus is on minimizing this impact within the textile supply chain. Finally, the Electronic Textiles (*E*-Textiles) theme was identified, where Dulal et al. (2022) investigates the potential of smart wearable electronic textiles (e-textiles) for personalized healthcare applications. However, they emphasize the challenges associated with material performance, sustainability, manufacturing methods, and the end-of-life processes for these technologies. Finally, Veske and Ilén (2020) reviews current literature on end-of-life (EOL) solutions for e-textiles. They highlight concerns about the sustainability and recycling of these complex technological products. In conclusion, the review of studies using the LCA methodology reveals the considerable environmental impact of the textile industry throughout the life cycle of its products. The studies also propose promising solutions, including the minimization of waste through recycling and transformation into higher-value products, the adoption of circular economy principles, and the development of sustainable technologies.

Considering the low levels of global recycling, the worsening situation of developing countries, as well as the difficulty of recycling post-consumer textile residues - garments - and the need to move towards a sustainable circular economy, this article explores the potential environmental benefits of two industrial recycling processes for blended textile residues implemented in a developing country versus the traditional waste management and production processes, expanding the alternatives for mechanical recycling of textile residues. The ultimate goal is to propose strategies that reduce the textile industry's environmental impact, also providing alternatives for developing a sustainable circular economy. This could include (i) implementing a single recycling process or (ii) integrating them, depending on the results of the environmental impact analysis, and developing guidelines on critical points to consider during implementation, such as the location of recycling plants.

The recycling processes assessed comprise the production of recycled strips from stretchable or non-stretchable textile residues for punching bag fill (R1). Additionally, a recycling process from stretchable textile residues for the production of recycled yarn for knitting and recycled fill for stuffed animals or toys is assessed (R2).

Then, considering that the textile industry's environmental impact involves carbon emissions, water consumption, water pollution, and land use, among other impacts, it is necessary to conduct a comprehensive assessment of the environmental impact of the recycling processes under consideration. Specifically, the environmental impacts are assessed with the ReCiPe method, which provides harmonized characterization factors at midpoint and endpoint levels. The midpoint approach has been widely used and has a stronger relation to the environmental flows and relatively low uncertainty; while the endpoint approach has simple and easy-to-understand damage categories, in addition to providing better information on the environmental relevance of the environmental flows, but is also more uncertain than the midpoint characterization factors (Hauschild and Huijbregts, 2015; Yi et al., 2014). This approach allows quantifying several environmental impact categories to generate a major data availability and broader assessment than existing literature to support decision-making related to recycling systems for textile residues, extending and complementing our previous work (Espinoza et al., 2022).

3. Materials and methods

According to the World Bank, over the last two decades, textile imports in Latin America and the Caribbean have more than doubled, while Chile's imports have increased by 500 % (World Integrated Trade Solution, 2021; Instituto Nacional de Estadísticas, 2019). Consequently, and because of poor waste management systems and a lack of public understanding about the impact of textile residues, the exponential development in textile and garment importation has emerged as a significant environmental challenge, represented by the world's driest desert as a desert of textile waste (Radio France Internationale and Radio Bío Bío, 2021). Currently, the Chilean government is taking the first steps to develop a circular economy strategy for textiles; therefore, this research would support decision-making by proposing alternatives to textile residue treatment focusing on its environmental impact for the transition towards sustainable circular economy (Ministerio del Medio Ambiente, Chile, 2023).

This research follows the ISO 14.040 (ISO, 2006) standards principles and structure for Life Cycle Assessment (LCA), considering the following phases: goal and scope definition, life cycle inventory analysis, impacts evaluation, and result interpretation. In this study, we assess the impacts of two textile recycling processes implemented at "Ecocitex", a Chilean enterprise born in 2020 that produces recycled strips of stretchable or non-stretchable textile residues as punching bags fill, in addition to the recycled yarn used for knitting, recycled fill used for stuffed animals or toys. SimaPro software and the Ecoinvent database were used to model the textile recycling processes under study. The Recipe impact calculation method was used, and the 18 midpoint categories and the 3 endpoint categories were analyzed.

This study provides significant insights and practical solutions to address the global concern of blended textile residue management since the recycling processes studied are easily implementable in areas where yarn-producing industries thrive and where garments characterized by multi-material fiber compositions are available as textile residue. Given that this scenario is common worldwide, the study's findings have far-reaching implications for global efforts to manage textile residues sustainably.

3.1. Goal and scope definition

The study aims to assess two recycling processes implemented by a Chilean company for household and industrial textile residues, characterized by multi-material fiber compositions, to determine if the recycling processes have a better environmental performance against the current traditional practices for managing textile residues nationally and produce virgin products. Additionally, the study seeks to identify critical points to consider during implementation, such as the location of recycling plants, to provide guidelines that support the transition towards a sustainable circular economy. It is important to note that, worldwide and in the case of Chile, the most commonly used EoL treatment for textile residues is final disposal in landfills or dumpsites.

3.2. Functional unit

This study undertakes a comparison of the environmental performance between the recycling processes and the current practices for managing textile residues nationally and producing virgin products. Viewing recycling as an EoL treatment, textile residues serve as the reference material. Consequently, the functional unit is defined as one ton (1 ton) of textile residues processed. It is worth noting that the company processes the textile residues in batches of 292 kg mainly due to technical requirements regarding color homogeneity in yarn and machine capacity. Then, the functional unit and the inventory analysis consider the primary data obtained for the batch processed.

3.3. System boundaries

The system boundaries of the study are gate-to-gate, considering that the textile residues are collected in the recycling facilities, and no distribution processes are assessed. Furthermore, depending on the textile characteristics, not stretchable or stretchable, energy consumption, raw materials, and waste generation comprise the system to produce recycled products, as Fig. 1 details in the limits demarcated by the red line. Note that stretchable textile residues could be processed in both recycling processes. In contrast, only stretchable residues could be processed to produce recycled yarns and fill.

3.3.1. Scenario of expanded boundaries

To compare the impacts of the two recycling processes with the current practices, we expanded the system boundaries, considering the emissions of the production of an equivalent product from primary resources and the impacts of final disposal treatment, as current practices.

As Fig. 1 shows outside the limits demarcated by the red line, it is considered that the impacts of the current practices would be replaced when choosing textile recycling-based products over final disposal and virgin market products.

3.4. Inventory analysis

The LCA is conducted using Simapro 9.1 software and the Ecoinvent 3.6 database in accordance with the reference standard for LCA (ISO 14040 and ISO 14044) to identify impact category indicators. The system under study consists of two textile recycling processes. As detailed earlier, the process starts at the company's entrance, where textile residues are received on behalf of the community and industries. The two recycling processes yield three products, and the production stages of each are detailed below. Table 2 shows the inventory details.

- Recycling process for not stretchable or stretchable textile residues (R1)

  Recycled Punching Bag Fill: This product is obtained by processing non-stretchable or stretchable textile residues, and the only process applied is cutting. Therefore, the flows considered are the electrical consumption of the cutting equipment and the generation of unused waste that goes to final disposal.
- Recycling process for stretchable textile residues (R2)

  Recycled Yarn: This is the company's main product, obtained from stretchable textile residues. It undergoes stages of cutting, shredding, pressing, sanitizing and mixing, carding, twisting, and spinning. The electrical consumption of each process is considered, and waste generation goes to final disposal. In the sanitizing process, in addition to the energy consumption of the machinery, raw materials such as recycled PET, along with sanitizing, anti-static, and textile lubricant chemicals mixed with water.

  Recycled Fill: This is a byproduct obtained at different stages of the recycled yarn production process in a yarn-to-fill production ratio of 3.55. Therefore, the stages for recycled yarn production are considered for recycled fill production.

Considerations:

→ The base case and the recycling cases assume that all textile residues are initially at the Ecocitex location (Las Dalias 2475, Macul, Santiago, Chile).
→ The country's energy matrix was constructed based on Ecoinvent and adapted to the Chilean electricity matrix of 2021 (Comisión Nacional de Energía, 2021).
→ The common chemical compounds used for each application were based on the data of the commercial chemist.
→ For transport inventories, the supplier's location was used only in the case of rPET. The other materials are locally purchased.
→ For the transportation of textile residues, the distance from the location of the Ecocitex production plant to the nearest final disposal plant was used (this distance was used for the base case and avoiding land-filling).
→ The EoL treatment for textile residues corresponds to "unsanitary landfill treatment of waste yarn and waste textile" of global application at Ecoinvent database due to lack of data.
→ In the expanded system, regarding the recycled yarn and fill assessment, the weight-based allocation method is used to distribute the recycling process impacts since they are byproducts.
→ In the expanded system, the recycled products were compared with the virgin products on the market to be replaced in each case.

The environmental impacts are assessed with the ReCiPe method due to ReCiPe2016 provides a state-of-the-art method to convert life cycle inventories to a limited number of life cycle impact scores on midpoint and endpoint levels. It includes 17 midpoint categories and three endpoint categories (human health, ecosystem quality, and resource scarcity) with a focus on providing characterization factors that are representative on the global scale in line with the global nature of many product life cycles (Huijbregts et al., 2017). Furthermore, the midpoint approach has been widely used and has the broadest set of midpoint impact categories compared with other methods (Powar, 2023). Additionally, the endpoint approach has advantages as it can provide easy-to-understand results by considering the damage, and it provides a more

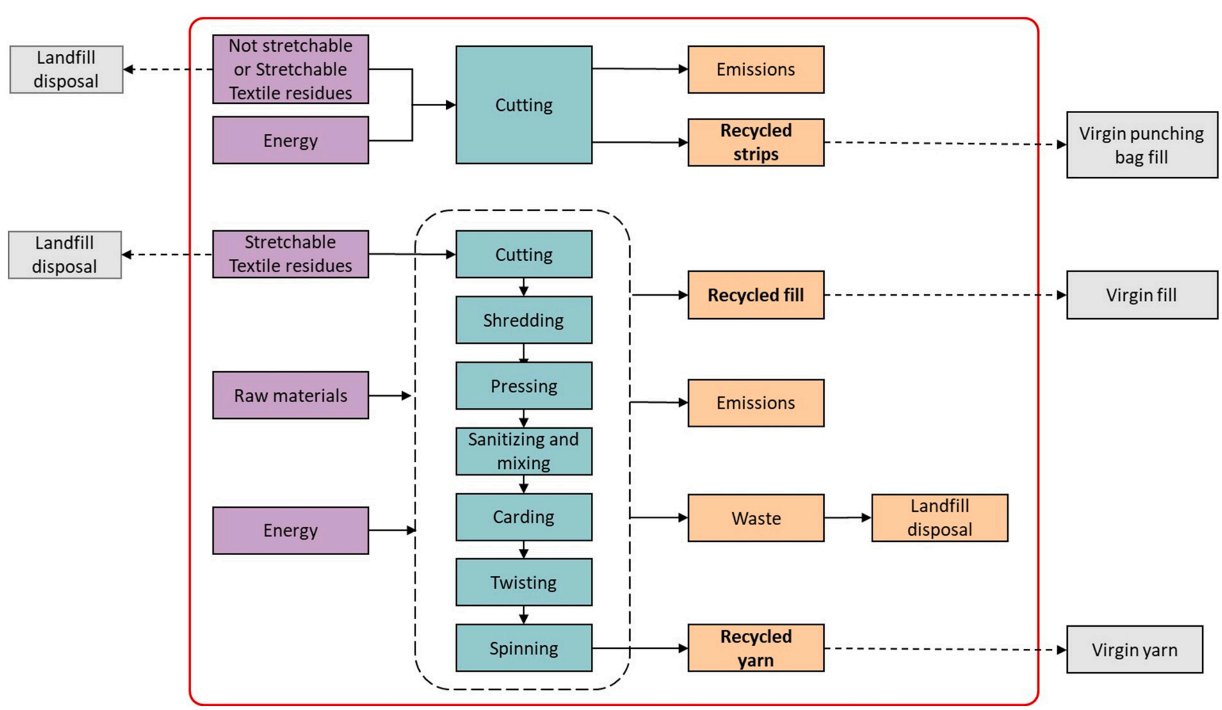


Fig. 1. System boundaries for the textile recycling process. Violet panels: Inputs; Calypso panels: Recycling processes; Orange panels: Outputs; Grey panels: avoided processes. The red line corresponds to system boundaries for the textile recycling process.

Table 2
Inventory of recycling process for not stretchable or stretchable textile residues (R1) and for stretchable textile residues (R2).

	Process	Input	Unit	Value	Output	Unit	Value
R1	Cutting	Textile residues (stretchable)	kg	1000	Waste treatment	kg	3,22
		Electrical consumption	kWh	153,42	Waste transport	tkm	0,10
	Shredding	Electrical consumption	kWh	275,21	Waste treatment	kg	11,40
					Waste transport	tkm	0,36
	Pressing	Electrical consumption	kWh	11,16	Waste treatment	kg	0,62
					Waste transport	tkm	0,02
	Sanitizing and mixing	Electrical consumption	kWh	50,96	Waste treatment	kg	1,47
		rPET production	kg	317,47	Waste transport	tkm	0,05
		rPET transport by sea	tkm	780,33			
		rPET transport by land	tkm	37,78			
		Lubricant oil	kg	4,62			
		Antiestatic	kg	4,49			
		Sanitizer	kg	0,34			
		Water	kg	45,99			
	Carding	Electrical consumption	kWh	314,18	Waste treatment	kg	36,13
					Waste transport	tkm	1,16
	Twisting	Electrical consumption	kWh	332,64	Waste treatment	kg	6,37
					Waste transport	tkm	0,20
	Spinning	Electrical consumption	kWh	71,71	Waste treatment	kg	4,79
					Waste transport	tkm	0,15
					Recycled yarn	kg	999,73
					Recycled fill	kg	281,44
R2	Cutting	Textile residues (stretchable or non stretchable)	kg	1000	Waste treatment	kg	0,94
		Electrical consumption	kWh	44,80	Waste transport	tkm	0,03
					Recycled strips	kg	291,06

concise way to interpret the LCA results (Hauschild and Huijbregts, 2015; Yi et al., 2014; Dong and Ng, 2014).

4. Life cycle impact assessment results

4.1. Midpoint results

Fig. 2a shows the Midpoint (1.04) analysis results for the 18 categories that include the methodology for both recycling processes. Values have been normalized and indicated in each impact category's units in the graph. It is evident that the recycling process R2 generates greater environmental impacts in all categories due to producing more complex products requires more production processes.

Furthermore, note that the recycling process R1 corresponds only to the cutting process, and consequently, it only consumes energy. Therefore, at first attempts, the recycling process R1 has a better environmental performance.

Considering the R2 recycling process, the process that generates the highest emissions is sanitizing, with an average contribution of 47.8 % to the 18 categories, followed by twisting yarn with 14.8 % and carding with 14.4 %. Then, Supplementary Material presents the emission sources for the sanitizing process in detail. It shows that the emissions in the sanitizing process are mainly related to the recycled PET production, while the emissions at the other processes are principally due to energy consumption.

4.2. Endpoint results

Similarly to the Midpoint results, Fig. 2b shows the results of the Endpoint analysis for both recycling processes.

Note that the R2 recycling process has a similar distribution of impacts for damage to ecosystem quality and resource scarcity, where the sanitizing and mixing processes prevail. However, regarding the damage to human health, the impact between processes is distributed more evenly. It is because the electrical consumption represents 80.8 % of DALY, while it only represents 55.7 % for species.yr and 54.8 % for USD2013. Therefore, efforts should focus firstly on changing the electricity source, although this research considers the Chilean energy matrix for 2021 incorporating renewable sources by 13 % solar photovoltaic and 8.9 % wind. Then, new production processes for rPET production are required.

4.3. Expanded boundaries: midpoint results

Fig. 3 presents the Midpoint results for the expanded boundaries by assessing the avoided impacts of replacing products in R1. Note that there are four categories in which mainly avoiding landfills allows savings, which are Global warming potential (GWP), Freshwater ecotoxicity (FEC), Marine ecotoxicity (MEC), and Human non-carcinogenic toxicity (HNC). While avoiding the sawdust production allows savings in the Land use (LU) category mainly, whereas avoiding the sawdust transport to the metropolitan region of Chile allows generating savings mainly in Stratospheric ozone depletion (SOD), Ionizing radiation (IR), Terrestrial ecotoxicity (TE), Human carcinogenic toxicity (HC), Mineral resource scarcity (MRS), and Fossil resource scarcity (FRS). In fact, considering proportional net savings for GWP, the landfill avoided treatment corresponds to 14.4 times the environmental impact generated by the recycled strips (EIRS), while all the avoided processes account for 16.5 times EIRS. Similarly, considering FEC y MEC, the landfill avoided treatment corresponds to 8.3 y 7.7 times EIRS, respectively, while all the avoided processes account for 9.4 and 9.1 times EIRS, respectively. Then, considering the sawdust production avoided, the proportional net savings for LU corresponds to 18.1 times EIRS, while all the avoided processes account for 18.9 times EIRS. Finally, considering the avoided transport for sawdust, the proportional net savings for SOD, IR, TE, HC, MRS, and FRS corresponds to 2.3, 5.5, 11.5, 0.7, 6.2, and 1.7 times EIRS, respectively, while all the avoided processes account for 3.5, 9.7, 12.7, 1, 8, and 2.6 times EIRS, respectively. Therefore, if no avoided transport is assessed, i.e., only the landfill disposal and the sawdust production are avoided, savings would still be generated in most of the categories described, except for the HC and FRS, where the impact of the processes avoided without sawdust transport would only correspond to 0.3 and 0.9 times EIRS. Note that considering proportional net savings in general for the R1 recycling process, the main benefits are obtained in categories LU, GWP, and TE. However, TE depends on avoiding sawdust transportation. Finally, this recycling process would produce environmental benefits regardless of location in categories GWP, SOD, IR, OF,H, OF,T, TE, FEC, MEC, HNC, LU, and MRS.

Despite considering avoided processes, this recycling process continues to have negative impacts on the Fine particulate matter formation

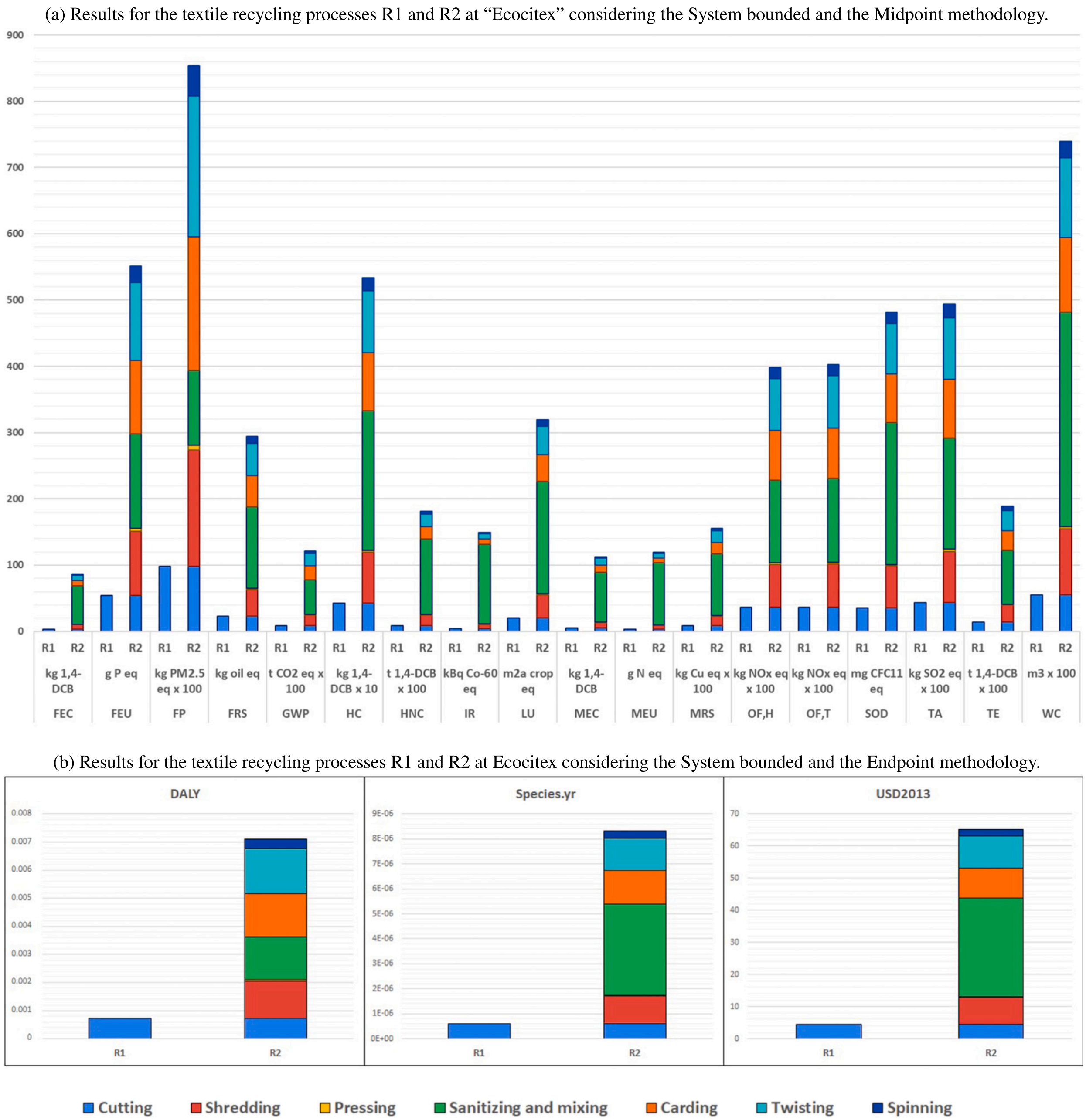


Fig. 2. GWP: Global warming Potential; SOD: Stratospheric ozone depletion; IR: Ionizing radiation; OF,H: Ozone formation, Human health; FP: Fine particulate matter formation; OF,T: Ozone formation, Terrestrial ecosystems; TA: Terrestrial acidification; FEU: Freshwater eutrophication; MEU: Marine eutrophication; TE: Terrestrial ecotoxicity; FEC: Freshwater ecotoxicity; MEC: Marine ecotoxicity; HC: Human carcinogenic toxicity; HNC: Human non-carcinogenic toxicity; LU: Land use; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity; WC: Water consumption.

(FP), Freshwater eutrophication (FEU), Marine eutrophication (MEU), and Water consumption (WC) categories. In this case, the avoided processes account only for 0.2, 0.4, 0.6, and 0.7 times EIRS, respectively. Therefore, it is relevant to assess if the endpoint results account for environmental benefits or not.

Fig. 4 presents the Midpoint results for the expanded boundaries by assessing the avoided impacts of replacing products with those obtained in R2. As Fig. 4a shows, if we consider that the disposal of textile residues in the landfill is avoided, which is the current way of treating this waste, only net savings in GWP are generated (reaching net savings of 6.13 t CO2 eq x 100, which represents a 5 % net reduction since the landfill disposition of represents 1.05 times the emissions produced by the recycling process R2), mainly because the treatment in the landfill is avoided, being almost negligible to avoid transport to the landfill. Then, regarding Fig. 4b, if we consider the impact of the R2 recycling process weighted for the recycled fill versus the virgin fill that could be replaced, savings are generated in all categories, mainly by avoiding the production of the virgin fill from fossil materials. The category with greater proportional net savings is Ionizing Radiation, where the virgin fill corresponds to 25 times the recycled fill impact; then, the Mineral Resource Scarcity lags far, where virgin fill corresponds to 15 times the recycled fill impact. Following, regarding Terrestrial Ecotoxicity, Water consumption, and Fossil resource scarcity, virgin fill corresponds to 13, 12, y 11 times the recycled fill impact, respectively. Furthermore, the Midpoint category whit less proportional net savings corresponds to Fine particulate matter formation, where virgin fill corresponds to 1.4 times the recycled fill impact. Finally, as Supplementary material S2 shows, if we compare the R2 recycling process with the replacement of

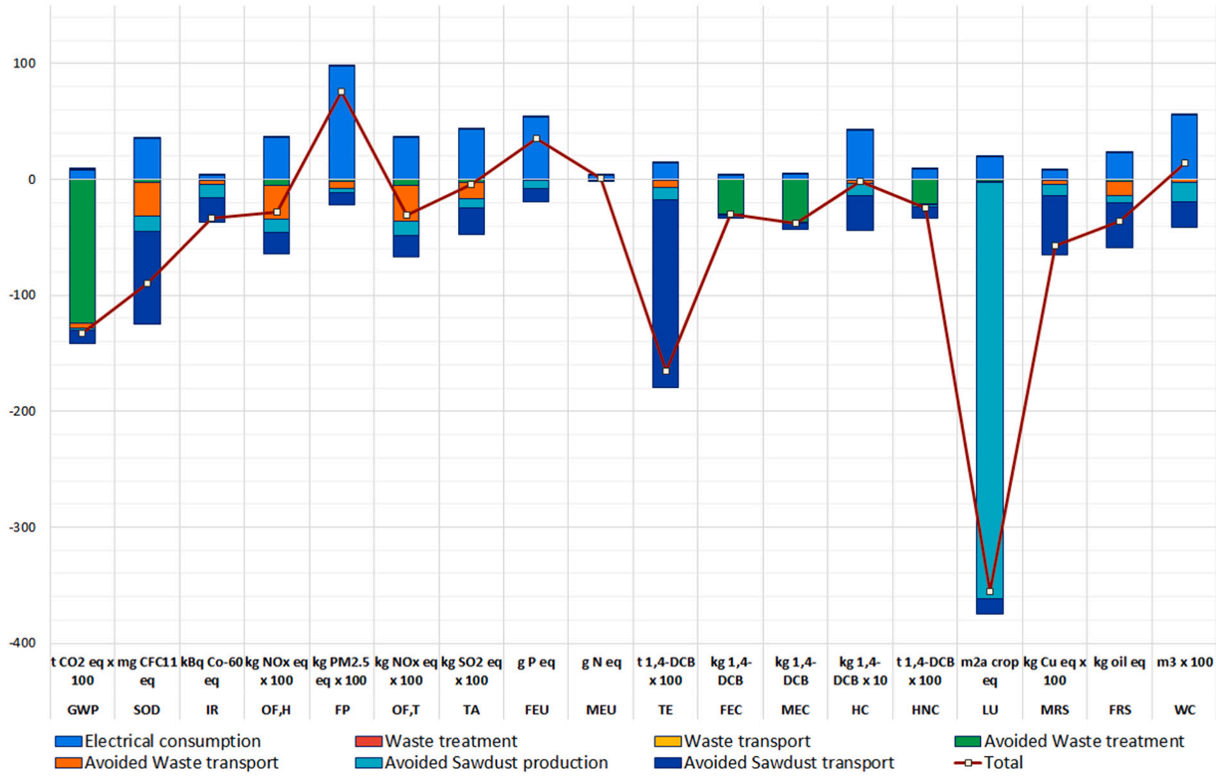


Fig. 3. Results for the textile recycling processes R1 at Ecocitex considering the System expanded boundaries and the Midpoint methodology. GWP: Global warming Potential; SOD: Stratospheric ozone depletion; IR: Ionizing radiation; OF,H: Ozone formation, Human health; FP: Fine particulate matter formation; OF,T: Ozone formation, Terrestrial ecosystems; TA: Terrestrial acidification; FEU: Freshwater eutrophication; MEU: Marine eutrophication; TE: Terrestrial ecotoxicity; FEC: Freshwater ecotoxicity; MEC: Marine ecotoxicity; HC: Human carcinogenic toxicity; HNC: Human non-carcinogenic toxicity; LU: Land use; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity; WC: Water consumption.

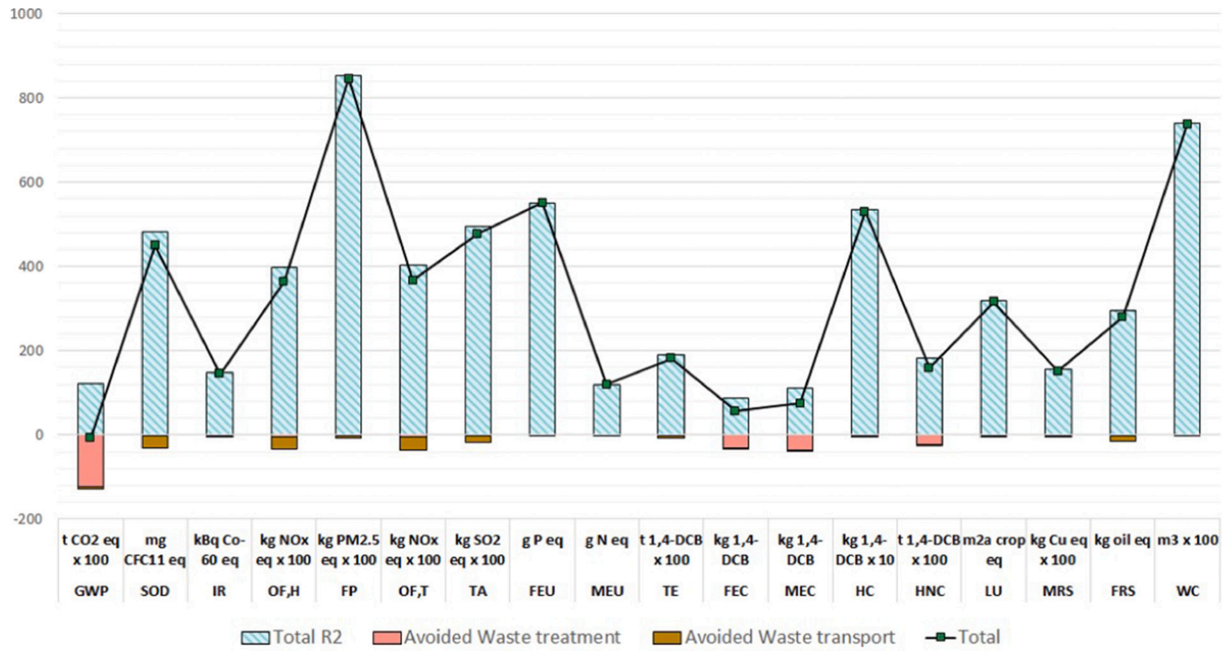
virgin cotton yarn, savings are achieved in all categories. It should be noted that the virgin product being replaced has great impacts considering land use and water consumption. Considering proportional net savings, the Land Use category highlights because the virgin yarn corresponds to 2378 times the recycled yarn impact, followed by the Water Consumption, where the virgin yarn corresponds to 980 times the recycled yarn impact. It shows that if recycled yarn replaces plant-based yarns, great environmental savings would be produced concerning land use and water consumption. Furthermore, regarding the following category impact, in Marine eutrophication, the virgin yarn corresponds to 586 times the recycled yarn impact, showing impacts of water contamination by yarn production would also be avoided by recycling textile residues to produce recycled yarns. Furthermore, similar to recycled fill, the Midpoint category with less proportional net savings corresponds to Fine particulate matter formation, but in this case, the virgin yarn corresponds to 3.4 times the recycled yarn impact.

4.4. Expanded boundaries: endpoint results

Fig. 5a presents the Endpoint results for the expanded boundaries by assessing the avoided impacts of replacing products for the recycling process R1. It shows that, despite the fact that there are some impacts in the analysis of the Midpoint assessment when evaluating the impacts under the endpoint approach for the R1 recycling process, reductions are obtained in the three aspects evaluated. Obtaining net savings for each ton of processed textile residues reaching 8.1653E-04 DALYs, 6.9446E-06 species.yr, and 20.15 USD2013. Furthermore, when analyzing which avoided process has a greater influence on those results, there are differences. For example, regarding DALY, the savings are mainly due to avoiding the disposal of textile residues in the landfill, representing 1.7 times the impacts of the R1 recycling process. In contrast, 47 % of the savings in the impact on ecosystem quality is generated by avoiding disposal in the landfill and 43 % by avoiding sawdust production. It should be noted that if we compare the impact of the R1 recycling process (600419E-07 species.yr) with the impact of the final disposal (352209E-06 species.yr), a saving of −2.92167E-06 species.yr is generated; while if it is compared with the sawdust production impact (328018E-06 species.yr) a saving of 2.67976E-06 species.yr is obtained. Regarding the impact on resource scarcity, the savings are generated mainly by avoiding transportation, firstly of sawdust, representing 5.5 times the impacts of the R1 recycling process, and secondly by avoiding transportation to the landfill, representing 3.5 times the impacts of the R1 recycling process. When evaluating the specific values, we can observe that despite the fact that the textile residues transported to landfills only correspond to 23 % of the avoided impacts on resource scarcity, this already means a saving of 1.19 USD2013 with respect to the impact of the recycling process R1. However, if only the landfill treatment and the sawdust avoided are considered, the avoided impact corresponds only to 0.6 times the impact of the recycling process R1. It means that USD2013 benefits mainly depend on the location of the recycling plant.

Fig. 5b presents the Endpoint results for the expanded boundaries by assessing the avoided impacts of replacing products for the recycling process R2. Considering the proportional net savings, the DALYs related to all the avoided process corresponds to 4.6 times the human health impacts related to all the R2 recycling processes; all the avoided process corresponds to 643.3 times the ecosystem quality impacts related to all the R2 recycling processes and to 10 times the resource scarcity impacts related to all the R2 recycling processes. This figure shows that the saved impacts on human health, ecosystem quality, and resource scarcity from avoiding the production of virgin yarn represent the largest savings. Note that the DALY related to the production of virgin yarn corresponds

(a) Results for the textile recycling processes R2 versus avoided landfill.



(b) Results for the recycled fill (R2 impacts weighted by recycled fill production) versus avoided virgin fill.

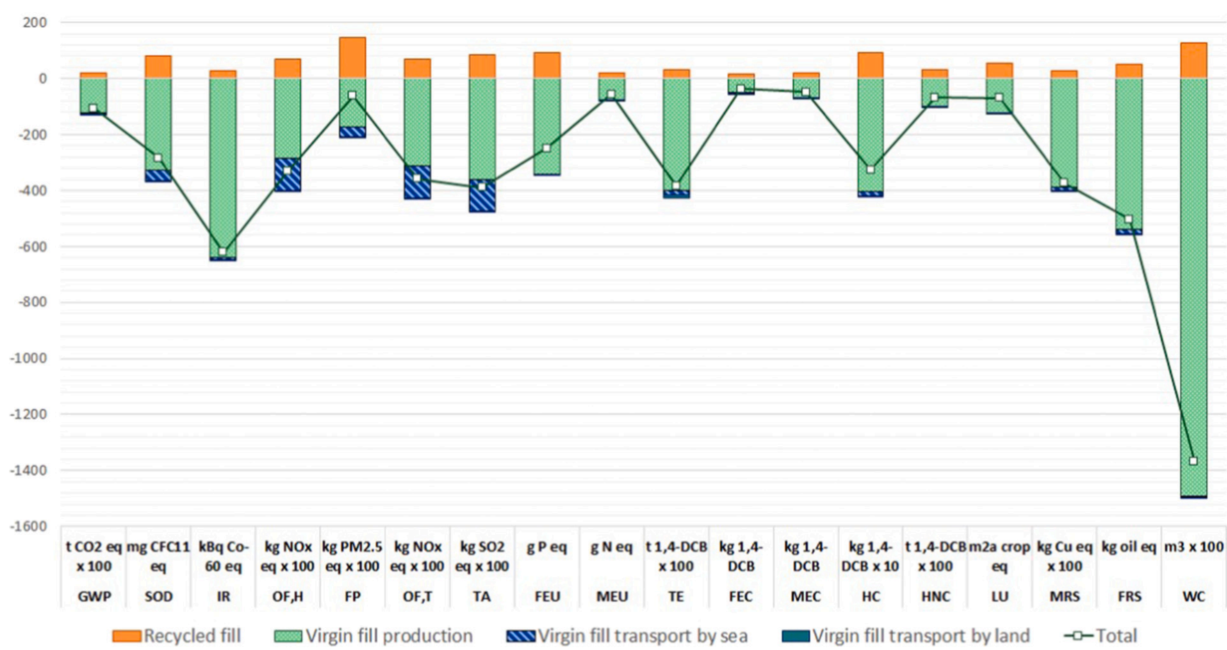
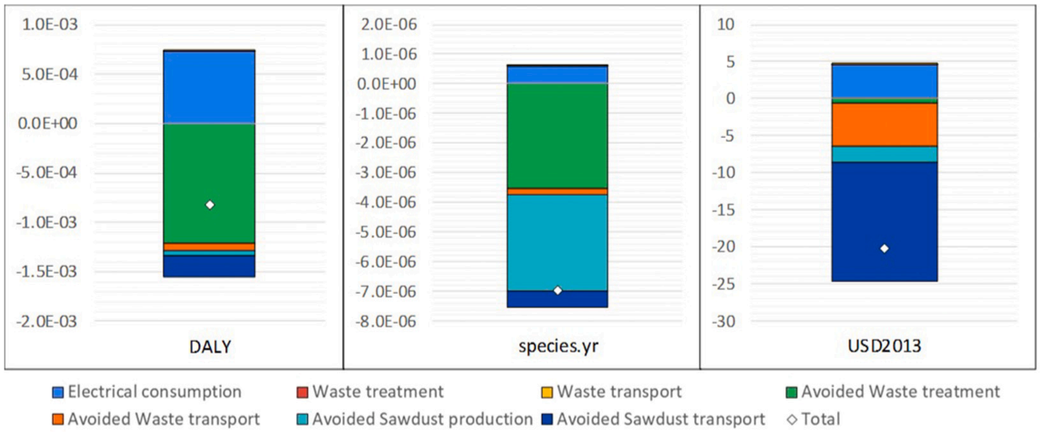


Fig. 4. Results for the textile recycling processes R2 at Ecocitex considering the System expanded boundaries and the Midpoint methodology. GWP: Global Warming Potential; SOD: Stratospheric ozone depletion; IR: Ionizing radiation; OF,H: Ozone formation, Human health; FP: Fine particulate matter formation; OF,T: Ozone formation, Terrestrial ecosystems; TA: Terrestrial acidification; FEU: Freshwater eutrophication; MEU: Marine eutrophication; TE: Terrestrial ecotoxicity; FEC: Freshwater ecotoxicity; MEC: Marine ecotoxicity; HC: Human carcinogenic toxicity; HNC: Human non-carcinogenic toxicity; LU: Land use; MRS: Mineral resource scarcity; FRS: Fossil resource scarcity; WC: Water consumption.

to 3.8 times the impacts related to all the R2 recycling processes. Furthermore, regarding the ecosystem quality, the species.yr related to the production of virgin yarn corresponds to 641.8 times the impacts related to all the R2 recycling processes. However, it only represents 6.6 times the USD2013 produced by all the R2 recycling processes. Furthermore, the final disposal of textile residues avoided only accounts for 0.2, 0.4, and 0.1 times the DALY, species.yr, and USD2013, respectively, generated by all the recycling process R2. Therefore, the savings from avoiding final disposal are not enough to equate to the impacts generated by the recycling production process R2 in any of the three categories.

Considering that Chile, a country with a population of around 20 million people, generates 572,118.9 annual tons of textile residues (Espinoza et al., 2022), mainly in the northern and central regions where no sawdust is produced, implementing both recycling processes on a large scale would result in significant positive environmental impacts, as

(a) Results for the textile recycling process R1 at Ecocitex considering the System expanded and the Endpoint methodology.



(b) Results for the textile recycling process R2 at Ecocitex considering the System expanded and the Endpoint methodology.

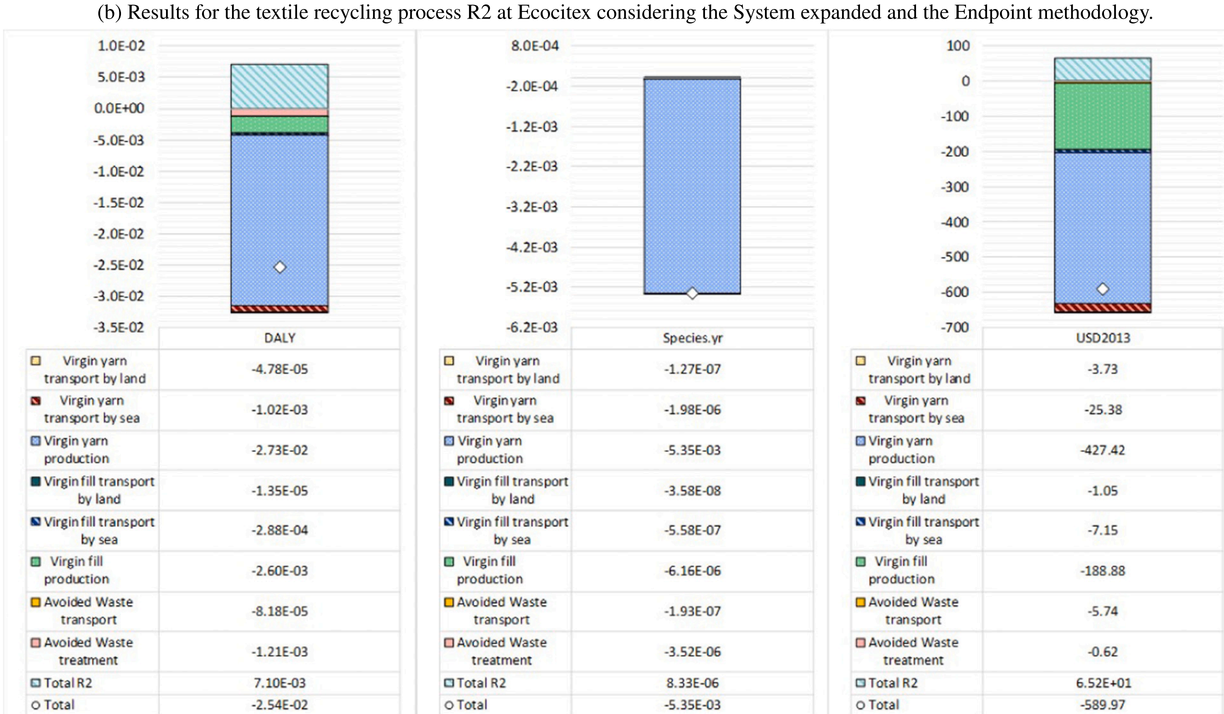


Fig. 5. Results for the textile recycling processes at Ecocitex considering the System expanded boundaries and the Endpoint methodology.

Fig. 6 depicts. For instance, if 50 % of the textile residues are processed using the R1 recycling process, and the remaining 50 % are processed using the R2 recycling process, it would lead to saving 7499 DALY, 1532 species.yr, and 174 million USD annually. Moreover, it should be noted that R1 presents lower environmental savings regarding ecosystem quality impacts, primarily because of the substantial avoided impact on ecosystem quality associated with using virgin yarns.

Finally, considering the avoided products' dependence, an

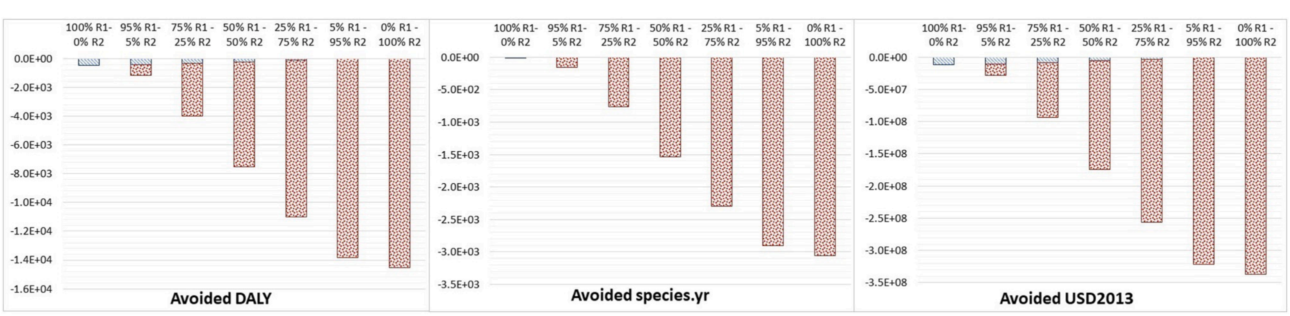


Fig. 6. Assessment for potential environmental impacts recycling the textile residues in Chile. Blue: R1 environmental impact avoided; Red: R2 environmental impact avoided.

assessment of different yarn types was carried out. For this, the cotton yarn impacts (yarn production, cotton, ring spinning, for knitting - GLO) was compared to cotton yarn for weaving (yarn production, cotton, ring spinning, for weaving - GLO); cotton yarn spun (yarn production, cotton, open and spinning - RoW); jute yarn (production - RoW); kenaf yarn (production - RoW); silk yarn short fiber (yarn production, silk, short fiber - RoW); and silk yarn long fiber (yarn production, silk, long fiber - RoW). Among those yarns available in Ecoinvent, the jute yarn has the lower impact, and the silk yarn long fiber has the higher impact in most Midpoint and Endpoint categories.

Regarding the midpoint impacts, jute yarn production-related impacts are lower than six categories (GWP; FP; FEC; MEC; HNC; and FRS) regarding the total R2 impacts, while the kenaf yarn impacts are lower in five categories (FP; FEC; MEC; HNC; and FRS). The production-related impacts of the other yarns are higher than all the R2 impacts. Furthermore, considering the avoided landfill and virgin fill replacement in the evaluation, the jute and kenaf yarns have a better performance only in FP and FRS categories, mainly because of the energy consumption in R2.

Regarding the endpoint impacts, silk yarn long fiber represents 24.2 times the all R2 recycling impact, while the jute yarn only corresponds to 0.48 times. Therefore, if jute yarn is replaced, savings would not exist related to the damage to human health. However, regarding ecosystem quality, savings are produced by all the replaced yarns. Finally, concerning resource scarcity, the silk yarn log fiber represents 41.53 times the R2 impact, while the kenaf yarn represents only 0.93 times the same impact. In this last case, savings would not exist. But, if landfill avoidance is considered, it allows to reach environmental savings in resource scarcity. Finally, considering any of the yarns assessed, in addition to landfill avoidance and virgin fill replacement (polyester fiber), environmental savings at all endpoint categories are reached. Therefore it is recommended to apply this kind of recycling process in general.

5. Conclusions and recommendations

The analysis developed in this research shows that R1 and R2 processes can generate environmental benefits, and their use is recommended. Specifically, observing the R1 recycling process endpoint impacts, considering both avoiding the production and transportation of sawdust and the disposal of in landfills, reductions of 52.73 % DALY, 92.05 % species.yr, and 81.57 % USD2013 are achieved. Concerning the R2 process endpoint impacts, without considering the savings generated by avoiding the disposal of textile residues in landfills, it is observed that the environmental impacts associated with the recycled fill (1.56E-03 DALY, 1.83E-06 species.yr, and 143 USD2013) correspond to a reduction of 46.1 % DALY, 72.7 % species.yr, and 92.7 % USD2013 concerning the emissions generated by the production of virgin fill (2.89E-03 DALY, 6.71E-06 species.yr, and 196 USD2013). At the same time, the impact of the R2 process associated with the recycled yarn (5.54E-03 DALY, 6.50E-06 species.yr, and 509 USD2013) represents a reduction of 80.4 % of DALY, 99.9 % of species.yr, and 88.8 % of USD2013 regarding the emissions generated by cotton yarn (2.83E-02 DALY, 5.35E-03 species.yr, and 453 USD2013). These values are similar to those found by Chen et al. (2023a) when evaluating recycling alternatives for cotton T-shirts in China and to those presented by Wiedemann et al. (2022) in the search for recycling a wool sweater in Australia. It demonstrates that textile recycling processes for producing yarn, fill, and final textile products, applied in different countries, both developed and developing, are environmentally recommendable globally.

However, considering this research would support decision-making by proposing alternatives to textile residue treatment focusing on its environmental impact, it is necessary to develop strategies to try to reuse the residues in such a way as to replace highly elaborated products with greater environmental impacts to generate more significant benefits. Consequently, for example, the stretchable textile residues should go through the R2 recycling process as a first option. After being used, they could go through the R1 recycling process. Nevertheless, the recycling plant to operate R1 should be strategically located far from sawdust production areas to generate greater environmental impacts by replacing the punching bag fill at the neighboring areas of the recycling plant. This production linkage prevents the production of several products from virgin raw materials in their circularity.

This research also evidences the need for more integrated investigations, including analyzing several environmental impacts of recycling alternatives, to support decision-makers worldwide in selecting textile recycling processes to implement. In this study, information from globally recognized databases was used to facilitate a comparison of the reported recycling processes. It should be noted in this context that access to databases for middle-income countries is required, as this will allow the development of this type of research and its comparison with others worldwide, relieving recycling processes that have not been evaluated and could generate a significant contribution.

Finally, as future work, textile residue recycling processes should be assessed addressing all sustainability dimensions for an effective implementation over time, considering sustainability as the strategic attainment and integration of an organization's social, environmental, economic, political, and technological aspects through the systemic coordination of the main inter-institutional business processes (Pérez and Vásquez, 2023). Particularly since economic profitability is a current challenge in this kind of industry, mainly in developing countries, and this recycling industry might create employment opportunities for social adaptation, as in the case of Ecocitex.

CRediT authorship contribution statement

Lorena A. Espinoza-Pérez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Andrea T. Espinoza-Pérez:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Óscar C. Vásquez:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The authors are grateful to Ecocitex for supporting the production process assessment. This research was partially supported by DICYT, 062317EP_Ayudante, Vicerrectoría de Investigación, Desarrollo e Innovación, Universidad de Santiago de Chile, ANID Fondecyt Iniciacion 11220493, and ANID Fondecyt Regular 1211640.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172161.

References

Alam, M.A.A., Biswas, M.K., Mahiat, T., Chowdhury, R.B., Biswas, K.F., Hossain, M.M., Sujauddin, M., Aug. 2023. Taking stock of the share of global environmental burden

of knitwear production in Bangladesh: constructing the life cycle inventory. J. Clean. Prod. 412, 137376.
Bianco, I., Gerboni, R., Picerno, G., Blengini, G.A., Apr. 2022. Life cycle assessment (LCA) of MWool recycled wool fibers. Resources 11 (5), 41.
Chen, S., Chen, F., Zhu, L., Li, Q., Wang, X., Wang, L., 2023a. A spatial water footprint assessment of recycled cotton t-shirts: case of local impacts in selected China provinces. Sustainability 15 (1), 817.
Chen, S., Zhu, L., Sun, L., Huang, Q., Zhang, Y., Li, X., Ye, X., Li, Y., Wang, L., 2023b. A systematic review of the life cycle environmental performance of cotton textile products. Sci. Total Environ. 883, 163659.
Chopra, S.S., Dong, L., Kaur, G., Len, C., Lin, C.S.K., Feb. 2023. Sustainable process design for circular fashion: advances in sustainable chemistry for textile waste valorisation. Current Opinion in Green and Sustainable Chemistry 39, 100747.
Comisión Nacional de Energía, 2021. Anuario estadístico de energía 2021.
Dong, Y.H., Ng, S.T., 2014. Comparing the midpoint and endpoint approaches based on recipe–a study of commercial buildings in Hong Kong. Int. J. Life Cycle Assess. 19, 1409–1423.
Dulal, M., Afroj, S., Ahn, J., Cho, Y., Carr, C., Kim, I.-D., Karim, N., Nov. 2022. Toward sustainable wearable electronic textiles. ACS Nano 16 (12), 19755–19788.
Espinoza, L.A., Espinoza, A.T., Vásquez, O.C., 2022. Exploring an alternative to the chilean textile waste: a carbon footprint assessment of a textile recycling process. Sci. Total Environ. 830, 154542.
ETC/WMGE, 2021. Eionet Report no 2/2021 Business Models in a Circular Economy. URL. http://europa.eu.
Fibre2Fashion, 2021. Are asian and african textile hubs sustainability ready? URL. https://www.fibre2fashion.com/industry-article/9196/are-asian-and-african-textile-hubs-sustainability-ready.
Harmsen, P., Scheffer, M., Bos, H., 2021. Textiles for circular fashion: the logic behind recycling options. Sustainability 13, 9714.
Hauschild, M.Z., Huijbregts, M.A.J., 2015. Introducing Life Cycle Impact Assessment.
Horn, S., Mölsä, K.M., Sorvari, J., Tuovila, H., Heikkilä, P., Aug. 2023. Environmental sustainability assessment of a polyester t-shirt – comparison of circularity strategies. Sci. Total Environ. 884, 163821.
Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. Recipe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147.
Instituto Nacional de Estadísticas, 2019. Estimaciones y Proyecciones a Nivel Regional de la Población de Chile 2002–2035. Tech. rep. INE, Santiago, Chile. URL. https://www.ine.cl/docs/default-source/proyecciones-de-poblacion/publicaciones-y-anuarios/base-2017/estimaciones-y-proyecciones-2002-2035_base-2017_reg_{á}rea_infograf{í}a.pdf?sfvrsn=5d8b3bcc_5.
ISO, 2006. Principles and Framework (ISO 14040). URL. https://www.iso.org/standard/37456.html.
Juanga-Labayen, J.P., Labayen, I.V., Yuan, Q., 2022. A review on textile recycling practices and challenges. Textiles 2, 174–188.
Kamble, Z., Behera, B.K., Apr. 2021. Upcycling textile wastes: challenges and innovations. Text. Prog. 53 (2), 65–122.
Levänen, J., Uusitalo, V., Härri, A., Kareinen, E., Linnanen, L., May 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), 054069.
Ministerio del Medio Ambiente, Chile, 2023. Ministerio del medio ambiente crea comité para elaborar estrategia de economía circular para textiles. URL. https://mma.gob.cl/ministerio-del-medio-ambiente-crea-comite-para-elaborar-estrategia-de-economia-circular-para-textiles-2/.
Moazzem, S., Wang, L., Daver, F., Crossin, E., Mar 2021. Environmental impact of discarded apparel landfilling and recycling. Resour. Conserv. Recycl. 166, 105338.
Mölsä, K.M., Horn, S., Dahlbo, H., Rissanen, M., Nov. 2022. Linear, reuse or recycling? An environmental comparison of different life cycle options for cotton roller towels. J. Clean. Prod. 374, 133976.
de Montellano, C.G.-S.O., Samani, P., van der Meer, Y., 2023. How can the circular economy support the advancement of the sustainable development goals (sdgs)? A comprehensive analysis. Sustainable Production and Consumption 40, 352–362.
Munasinghe, P., Druckman, A., Dissanayake, D., Oct. 2021. A systematic review of the life cycle inventory of clothing. J. Clean. Prod. 320, 128852.
Nayak, R., Akbari, M., Far, S.M., 2019. Recent sustainable trends in vietnam's fashion supply chain. J. Clean. Prod. 225, 291–303.
Observatory of Economic Complexity (OEC), 2021. Textiles Xi (Harmonized System 1992 for Section). URL. https://oec.world/en/profile/hs/textiles.
Payet, J., Feb. 2021. Assessment of carbon footprint for the textile sector in France. Sustainability 13 (5), 2422.
Pérez, A.T.E., Vásquez, O.C., 2023. How to measure sustainability in the supply chain design: an integrated proposal from an extensive and systematic literature review. Sustainability 15, 7138.
Powar, A., 2023. Lca and eco-design in the field of chemicals removal from textile waste for textile recycling. URL. https://theses.hal.science/tel-04047038.
Radio France Internationale, Radio Bío Bío, Nov 2021. Desierto de Atacama : el "cementerio tóxico" de ropa que se descarta en otras partes del mundo.
Ribul, M., Lanot, A., Pisapia, C.T., Purnell, P., McQueen-Mason, S.J., Baurley, S., 2021. Mechanical, chemical, biological: moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles. J. Clean. Prod. 326, 129325.
Schumacher, K.A., Forster, A.L., 2022. Textiles in a circular economy: an assessment of the current landscape, challenges, and opportunities in the United States. Frontiers in Sustainability 3.
Stanescu, M.D., Jan. 2021. State of the art of post-consumer textile waste upcycling to reach the zero waste milestone. Environ. Sci. Pollut. Res. 28 (12), 14253–14270.
Trzepacz, S., Lingås, N.D.B., Asscherickx, N.L., Peeters, V.K., van Duijn, V.H., Akerboom, E.M., 2023. Lca-based assessment of the management of european used textiles.
UNCTAD, 2020. Report Maps Manufacturing Pollution in Sub-Saharan Africa and South Asia. URL. https://unctad.org/news/report-maps-manufacturing-pollution-in-sub-saharan-africa-and-south-asia.
UNEP, 2018. Putting the Brakes on Fast Fashion. URL. https://www.unep.org/news-and-stories/story/putting-brakes-fast-fashion.
van der Vegt, M., Velzing, E.-J., Rietbergen, M., Hunt, R., 2022. Understanding business requirements for increasing the uptake of recycled plastic: a value chain perspective. Recycling 7, 42.
Veske, P., Ilén, E., Sep. 2020. Review of the end-of-life solutions in electronics-based smart textiles. The Journal of The Textile Institute 112 (9), 1500–1513.
Wiedemann, S.G., Biggs, L., Clarke, S.J., Russell, S.J., Jan. 2022. Reducing the environmental impacts of garments through industrially scalable closed-loop recycling: life cycle assessment of a recycled wool blend sweater. Sustainability 14 (3), 1081.
World Integrated Trade Solution, 2021. Textiles and clothing imports by country. URL. https://wits.worldbank.org/CountryProfile/es/Country/BRA/StartYear/1989/EndYear/2019/TradeFlow/Import/Indicator/MPRT-TRD-VL/Partner/BY-COUNTRY/Product/50-63_TextCloth#.
Yi, S., Kurisu, K.H., Hanaki, K., 2014. Application of lca by using midpoint and endpoint interpretations for urban solid waste management. J. Environ. Prot. 05, 1091–1103.
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.