Does Textile Recycling Reduce Environmental Impact? A Probabilistic and Parametric Analysis for a Case of Open-Loop Recycling

Audrey Tanguy and Valérie Laforest

Abstract In recent years, textile recycling has emerged as an important strategy for reducing the environmental impact of supply chains for various products. But the environmental benefits of recycling might not be systematic, and it is useful to know under which conditions using recycled textile fibers is preferable than virgin materials. The objective of this study is to investigate the potential of textile recycling to reduce environmental impact using a probabilistic life cycle assessment (LCA) approach, applied to a case of open-loop recycling to replace virgin thermoplastics by polyester textiles. The variations of some sensitive parameters are used to test their influence on the probability of the recycling scenario outperforming the reference one using virgin materials. The parameters evaluated are the waste collection distance, the product distribution distance, the amount of additives added to the recycled fibers, the replacement rate, and the origin of the substituted reference product. Out of the 18 impact categories assessed, the recycling scenario outperforms the reference one for eight of them and for every instance of calculations. On the contrary, for other categories, the product made from recycled fibers presents greater environmental impacts, even when large background uncertainties are considered. Therefore, multicriteria assessment is highly recommended when assessing the environmental impact of textile recycling. Well-studied parameters such as the replacement rate or the substituted product's origin affect confident decision-making for seldomly studied, local impact categories such as terrestrial ecotoxicity. While demonstrated here for a specific case of open-loop recycling, these results can be generalized to other cases where used textile substitutes virgin plastic materials.

Keywords Textile recycling · LCA · Uncertainty · Influential parameters · Environmental impact · Open-loop · Polyester recycling

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1   Introduction

From 2000 to 2014, global clothing production has increased by 100%. Nowadays, an average consumer buys 60% more clothes and uses them half the time than 15 years ago. These changes in consumption behavior generate a great amount of textile waste (Islam & Bhat, 2019). In 2019, in Europe, only 26% of these waste flows were recycled (Islam & Bhat, 2019). There rest was landfilled, which contributes to environmental pollution including groundwater contamination and greenhouse gases release during decomposition (Dissanayake et al., 2018).

Circularity is currently a central strategy of the textile sector to implement its transition towards sustainable production (Harmsen et al., 2021). The European Union released recently its strategy for sustainable and circular textiles that encompasses "actions to ensure that by 2030 textile products placed on the EU market are long-lived and recyclable, made as much as possible of recycled fibers, free of hazardous substances and produced in respect of social rights and the environment"(European Commission, 2022). A quick search on Scopus using the term "circular fashion" led to 31 results, with the highest number of papers published in 2021. Circularity in the textile industry is thus gaining momentum and, with it, the well-known R strategies of the waste hierarchy (Reduce, Reuse, Recycling).

Recycling is especially put at the forefront of circular endeavours (Pensupa, 2020). In recycling value chains, the textile fibers can keep their initial function via closed loops (Braun et al., 2021) or they can be used for another function or product in open loops (Rahman, 2022). In both cases, the focus is to reduce the amounts of discarded textile waste by creating and substituting new resources, i.e., to retain the material intrinsic value of textile fabrics and garments (Haupt & Hellweg, 2019). However, increased circularity and reduced environmental impact are not synonyms and many of the circularity assessment frameworks lack quantitative metrics to include the environmental impacts of circular strategies such as recycling (Haupt & Hellweg, 2019).

Sandin and Peters (2018) published a review paper on the potential environmental benefits of textile recycling and reuse. Analyzing the findings of 41 publications, the authors noted that, generally, recycling was preferable than incineration and landfilling and that the use of recycled fibers was less impactful than the manufacturing of new products. However, their study revealed also some cases for which recycling was not preferable. For example, the use of fossil energy in the recycling process can be a cause for greater environmental impact (Sandin & Peters, 2018). The study of Liu et al. (2020) presented seven impact categories for which recycled cotton had a greater environmental impact than virgin cotton, but without investigating further. Therefore, the environmental benefits of textile recycling might not be systematic, which is reinforced by the fact that a limited number of impact categories are assessed in most studies conducting life cycle assessments (LCA) (Peters et al., 2019; Sandin & Peters, 2018). To the authors' knowledge, no study has yet analyzed the environmental prevalence of textile recycling, considering the

influence of different parameters, an uncertain background context and different impact categories.

The objective of this chapter is to investigate the potential of textile recycling to reduce environmental impact using a probabilistic and parametric analysis to obtain robust conclusions for an open-loop recycling case (polyester recycling to manufacture a new product). More particularly, we investigate the influence of some well-studied parameters, such as the replacement rate, on the probability that textile recycling outperforms a reference scenario, without recycling, for 18 impact categories. Conducting this analysis allows highlighting the conditions that might constraint the possibility of recycling to present environmental benefits for a specific case study, e.g., an impact category or a too uncertain influential parameter.

This chapter is structured as follows. First, a brief literature review on the environmental impact of polyester recycling is presented. Then, the second part describes the methods, including the recycling LCA model and the probabilistic approach. The comparative results are detailed for the deterministic and probabilistic analyses. Finally, the environmental benefits of textile recycling are discussed along with the advantages and limitations of the uncertainty analysis performed in this study.

2   Literature Review

The textile sector includes three main types of fibers: (1) natural fibers produced from natural resources such as cotton and wool (2) regenerated fibers derived from natural polymers, but requiring treatment and processing (3) synthetic fibers mainly derived from petrochemical (and therefore non-renewable) resources such as polyester, polypropylene and nylon (Shirvanimoghaddam et al., 2020).

Textile recycling refers to the treatment of pre- or post-consumer textile waste for use in new textile or non-textile products (Sandin & Peters, 2018). Recycling involves different types of routes such as mechanical, chemical or thermal. Combinations of these three routes are usually used for three types of recycling: fabric recycling (product to product), fiber recycling (the fabric is disassembled, but the original fibers are preserved), polymer/oligomer recycling (the fibers are disassembled, but the polymers or oligomers are preserved) and monomer recycling (the monomers are preserved) (Sandin & Peters, 2018).

Life cycle assessment has been widely used to assess the environmental impact of various textile recycling techniques and scenarios (Muthu, 2015). In their literature review, Sandin and Peters (2018) noted that the most frequently assessed cases were cotton and polyester recycling with fiber recycling being the most studied recycling route. In the case of polyester recycling, closed-loop scenarios are often assessed (Muthu et al., 2012; Spathas, 2017; Zamani et al., 2015) along with some examples of open-loop systems (Intini & Kühtz, 2011). One common methodological choice is the expansion method to account for the avoided impact of virgin materials and incineration and/or landfilling. Since polyester derives from fossil fuels, many studies report environmental benefits from polyester recycling for

primary energy consumption, global warming and terrestrial acidification (Zamani et al., 2015; Spathas, 2017; Schmidt et al., 2016).

Nevertheless, most of the reviewed studies are deterministic analyses, i.e., they do not account for uncertainties that may hamper the robustness of the conclusions. Uncertainty in LCA has become a hot topic in recent years (Igos et al., 2019), especially when conducting comparative LCAs (Gregory et al., 2013; Mendoza Beltran et al., 2018). Including uncertainties in such analyses can (1) improve the level of confidence of decisions regarding the preferred scenario, (2) determine whether the difference observed is actually significant and (3) enable the exploration of a broad range of possible combinations of all sorts of input data (Mendoza Beltran et al., 2018).

3 Materials and Methods

3.1 The Recycling LCA Model

This study conducts a comparative analysis of two alternatives for sport plot production that will be commercialized and used in Europe. The first alternative is a production based on polyester recycling of discarded sport jerseys, located in France. The recycling process modelled in this comparative LCA is based on the process developed by industrial partners who gave all relevant technical data. The second alternative, called the reference scenario, is the conventional production of sport plot using primary polyvinyl chloride (PVC) that is manufactured in China. The goal and scope of this LCA and data sources are further described in the next sections.

3.1.1 Functional Unit

Two functions are considered to compare the scenarios: the treatment of used sport jerseys and the supply of sport plots.

The functional unit is therefore to treat 16,000 used sport jerseys (about 1920 kg of used polyester) and to manufacture 160,000 sport plots with their support bars.

3.1.2 System Boundaries

This study is a cradle-to-gate analysis, i.e., it includes only the upstream stages of the plot production when the plots are ready to use. Indeed, it is assumed that the plot production strategy (using recycled fibers or not) does not influence a plot's average lifetime. The product made from recycling sport jerseys is designed according to the robustness criteria relevant for this product category. This assumption will
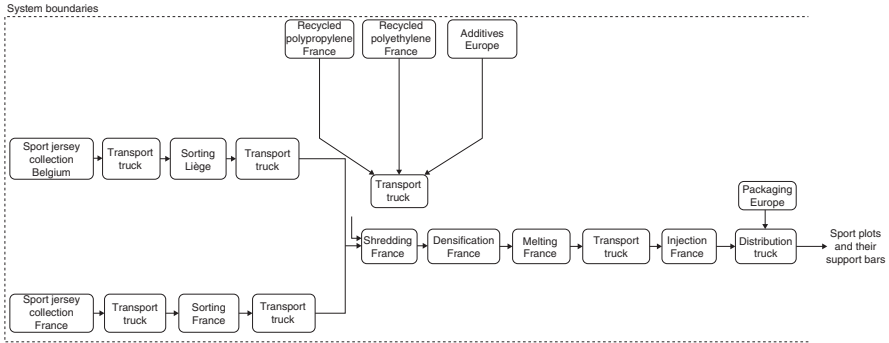
Fig. 1 System boundaries for the recycling scenario

be however tested in the sensitivity analyses. Moreover, the distribution stage is also included because the transportation distances and modes vary between the two scenarios.

Figure 1 shows the system boundaries for the scenario using recycled textile fibers, which will be called "recycling scenario" in the rest of the chapter.

The scenario includes the jersey collection at various collection points such as sport clubs, sport events and stores in France and Belgium. The jerseys are then sorted in French or Belgium facilities, with a sorting efficiency of 93%. All the waste jersey flows are transported to a French facility where they undergo a thermo-mechanical treatment involving the shredding of the polyester fibers, their densification and melting to form plastic granules. For the melting process, other materials and chemicals are added to the compound to ensure the technical performance of the final product. In this case study, recycled propylene (PP) and recycled polyethylene (PE) are used as well as other organic chemicals, not disclosed here for confidentiality reasons. The recycled plastics come with no upstream environmental burden, as per the cut-off approach. Only the impact of the waste collection and recycling into PP or PE granules is accounted. The efficiency of the whole treatment process is 91%. The granules are then transported to an injection plant where the plots get their final form. They leave the plant to be distributed and commercialized in Europe.

Figure 2 represents the system boundaries for the reference scenario, in which conventional sport plots are manufactured. To assess functionally equivalent systems, the reference scenario includes the end-of-life treatment of the sport jerseys in the case they are not used for sport plots production. They can be landfilled or incinerated without energy recovery or recovered to get new materials or energy. If so, these environmental benefits are not accounted in the system boundaries according to the cut-off approach.

The conventional route to manufacture sport plots which are the most frequently found on the French market is PVC production and injection in Chinese plants. PE is used for the bar production process. The sport plots and their support bars are then transported in sea containers to a French harbour and by truck to the final
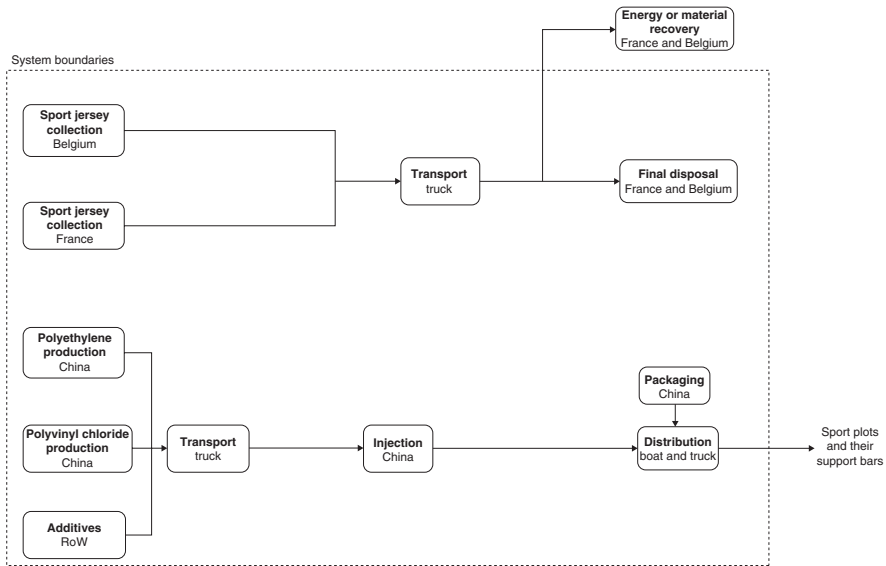
Fig. 2 System boundaries of the reference scenario

destination, which is the same than the recycling scenario. According to the industrial partners of this study, conventional sport plots manufactured in Portugal can also be found in the market. This assumption will be tested in the sensitivity analyses.

3.1.3 Data Collection and Sources

The main data sources are presented in Table 1. Primary data which are specific to the case study are related to (1) the sport jersey collection and (2) the polyester recycling process developed by the industrial partners. Secondary data come mainly from the ecoinvent v.3.8 database using the cut-off system model. They refer to the unit environmental impact of transport, sorting, the recycling of PE and PP in the recycling scenario, the additives production process, the injection process and landfilling. The dataset of the plastic injection stage has been modified to reflect the French and Chinese electricity mixes (or Portugese for the sensitivity analyses). For the reference scenario, data on the end-of-life treatment of used textiles were retrieved from material flow analysis studies conducted in Belgium and France which reported the current final disposal rates at the national level. Tables 2 and 3 present the foreground data for both scenarios.

Table 1 Data sources

Life cycle stages	Primary data sources	Secondary data sources
Resource extraction and transformation		For both scenarios: ecoinvent v.3.8 (cut-off)
Resource transport		
Material production (PE, PVC, additives)		
Jersey collection	Collected quantities and distances given by the industrial partners	Transport unit impact: ecoinvent v.3.8 (cut-off)
Jersey sorting		ecoinvent v.3.8 (cut-off)
Recycled PE	Quantities and origin given by the industrial partners	Recycling unit impact: ecoinvent v.3.8 (adaptation du mix électrique)
Recycled PP	Quantities and origin given by the industrial partners	Recycling unit impact: ecoinvent v.3.8 (adaptation du mix électrique)
Polyester recycling (shredding, densification, melting)	Quantities, energy consumption and process efficiencies given by the industrial partners	Additive unit impact: ecoinvent v.3.8
Injection		For the recycling scenario: ecoinvent v.3.8 (cut-off) dataset adapted with the French electricity mix + removed additive inputs (already present in the recycling process) For the reference scenario: ecoinvent v.3.8 (cut-off) dataset adapted with the Chinese electricity mix
Distribution	Distances with Google Maps	Transport unit impact: ecoinvent v.3.8 (cut-off)
Jersey end-of-life treatment (Reference scenario)		Payet (2021) for France and Dupont (2018) for Belgium + ecoinvent v.3.8 (cut-off) for landfilling unit impact

Table 2 Foreground data for the recycling scenario

Life cycle stages	Parameter	Unit	Value
Jersey collection	Distances	km	1803
	Transported amount	kg	2280
	Transport mode	N.A.	Camions (EURO4)
Jersey sorting	Process efficiency	%	7
Recycled PE and PP	Mass	kg	3613
	Supply distance	km	773 (PE), 112 (PP)
Polyester recycling	Additives	kg	1051
	Electricity consumption	kWh	4132
	Water consumption	m³%	93
	Process efficiency		9
Distribution	Distances	km	800
	Transported quantities	kg	6480
	Transport mode	N.A.	Trucks (EURO4)

Table 3 Foreground data for the reference scenario

Life cycle stages	Parameter	Unit	Value
PVC production	Amount	kg	6438
PE production	Amount	kg	201
Distribution	Distances (truck EURO4)	km	300
	Distances (cargo ship)	km	20,000
	Transported amount	kg	6600
Jersey end-of-life treatment	Final disposal rate (France)	%	34
	Final disposal rate (Belgium)	%	0
	Transport distance to landfill	km	50

3.2 The Probabilistic Approach

3.2.1 Uncertainty Characterization

The LCA literature distinguishes between three main sources of uncertainty: parameters (data quantities), scenarios (normative choices) and the model (mathematical relationships between the parameters) (Lloyd & Ries, 2007). Within each source, the nature of uncertainties is also diverse (Igos et al., 2019): they can be stochastic, i.e., they come from an inherent variability, or epistemic, arising from a lack of knowledge or representativeness (spatial, temporal, or technological).

In this work, the uncertainty characterization is based on the uncertainty data provided by the ecoinvent database V3.8. These data are provided thanks to Pedigree values that are available for each input of each dataset. These semi-quantitative assessment of epistemic uncertainty is then converted to lognormal distributions, which are used for the uncertainty calculations with the software (Muller et al., 2016). Therefore, this study considers only background epistemic parameter uncertainty. The Pedigree values of the modified datasets (indicated in Table 1) were modified accordingly.

3.2.2 Uncertainty Propagation and Calculations

The uncertainty propagation is performed with the SimaPro software v9.3, using the uncertainty analysis function. SimaPro uses the Monte Carlo simulation method to create a sampling of inventory data inputs. When two systems are assessed simultaneously during an uncertainty analysis, the sampling is dependent, i.e., at each Monte Carlo run, the same values of the technology and environmental matrices are fed to calculate both inventories. The impact results of each system are then stored and compared. In this study, 5000 Monte Carlo runs were performed for each uncertainty analysis.

SimaPro uses a discernibility analysis to quantify the statistical significance of the comparative results (Mendoza Beltran et al., 2018). It means it calculates the probability (P_R) that one system is superior to the other based on the number of runs said system had a lower environmental impact than the other. Equation 1 shows the

calculations of P_R for the impact category i (Mendoza Beltran et al., 2018). One disadvantage of this method is that it disregards the distance between the mean scores (Mendoza Beltran et al., 2018).

$$P_R = \frac{\#_{r=1}^{5000}\left(\text{Impact}_{i,\text{Rec},r} - \text{Impact}_{i,\text{Ref},r} > 0\right)}{5000}$$

(1)

Where # is the symbol of the counting function, r is the index of the Monte Carlo simulations ($r = 1,…,5000$), Impact$_{i,\text{Rec},r}$ the impact result of the recycling scenario for the category i and Impact$_{i,\text{Ref},r}$ the impact result of the reference scenario for the category i.

3.2.3   The Sensitivity Analysis of the Probabilistic Results

The conditions that frame the environmental performance of textile recycling are represented in this study by the min-max variations of different parameters. These parameters and their min-max intervals are presented in Table 4. Some parameters are numerical, e.g., the average waste collection distance, while others are categorical, e.g., the substituted product's origin. The selection of these parameters is based on both a literature review of textile recycling LCAs that identified these parameters as influential and the specific context of the study for which some inventory parameters were quite uncertain.

The sensitivity analysis is performed in two steps. First, a best- and a worst-case analyses are conducted to assess the min-max variation of P_R. The best-case analysis is the most favorable to the recycling scenario (all parameters have their min values) while the worst-case analyses is the least favorable (all parameters have their max values). This first step allows for discriminating categories for which P_R does not vary, i.e., categories for which the performance of textile recycling is not sensitive to the selected parameters.

Second, sensitivity analyses are conducted on the remaining impact categories by varying the parameters individually while keeping the other parameters at their mean value. This step allows to observe the sensitivity of P_R to each parameter.

Table 4 Selected parameters for the sensitivity analysis

Parameters	Min-Max intervals	Mean value	Unit	Sources for the parameter's choice
Waste collection distance	[300–1200]	600	km	Case study
Sport plot distribution distance	[100–1500]	800	km	
Additive quantity in the polyester recycling process	[901–1201]	1051	kg	
Replacement rate	[1:2–2:1]	1:1	–	Sandin and Peters (2018)
Substituted product's origin	Portugal, China	China	–	Peters et al. (2019) and Zamani et al. (2015)

4 Results and Discussion

4.1 Comparative Results Using a Determinist Approach

Figure 3 shows the normalized impacts of the recycling and conventional scenarios. The results in absolute values are presented in the Appendix (Table 5).

For almost all the impact categories (17/18), the relative impact difference between the two scenarios is more than 20%, except for freshwater ecotoxicity. These gaps can be considered significant in a deterministic analysis. Therefore, we may conclude on the superiority of one scenario for these 17 categories.

The recycling scenario performs better for 14 impact categories. The gap is especially large (over 60%) for categories relating to atmospheric emissions (global warming, stratospheric ozone depletion, ground-level ozone formation, fine particle formation), terrestrial acidification and human non-carcinogenic toxicity. These results are consistent with the findings of Zamani et al. (2015) who compared the global warming impact of recycled polyester fibers and virgin polyester manufactured in China. The substitution of virgin petrochemical compounds such as PVC allows for significant fossil fuels and chloride emissions savings, which explain the large differences between the two scenarios. Furthermore, these results suggest that avoiding PVC production may lead to a significant decrease in water consumption, such as in the study of Spathas (2017).

The impact of the recycling scenario for the ecotoxicity categories (terrestrial and marine) is a little bit more surprising. The source of this impact is road transportation by trucks, which causes heavy metal dissipation on the roadway due to the tire abrasion. The recycling scenario includes more road transportation, to collect waste and distribute the final products, than the reference scenario, which relies instead on maritime transportation by cargo ships (from China to Europe). Some
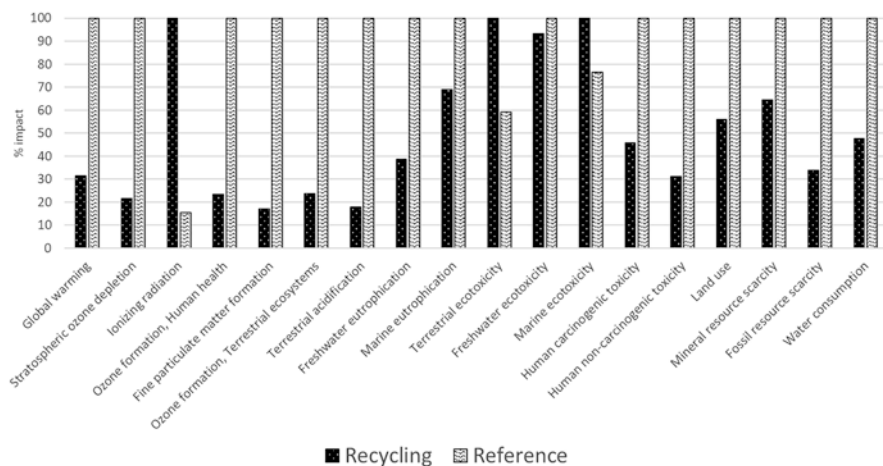

Fig. 3 Normalized impacts of the recycling and reference scenarios

studies found transportation activities to have insignificant impact in closed-loop (Liu et al., 2020) and open-loop scenarios (Shen et al., 2011) of recycling systems. But these studies either did not consider or did not investigate further the ecotoxicity categories. The influence of transportation distances will be tested in subsequent sensitivity analyses.

4.2 Comparative Results Using a Probabilistic Approach

4.2.1 Best- and Worst-Case Scenario Analysis

Figure 4 shows the pair-wise uncertainty analyses of the midpoint impact categories. The black bars express the probability that the scenario using recycled textile performs better than the reference scenario using virgin materials (P_R). The results are illustrated on two extreme cases (best and worst case), which represent the parameters' variation ranges.

Parameter uncertainty influences the recycling scenario's performance but does not always imply a change in the preferred scenario. A previous study considered that a probability (P_R) higher or equal to 80% is enough to select a scenario with a high level of confidence (AzariJafari et al., 2018).

For nine impact categories, the conclusions on the preferred scenario remain unchanged in comparison to the determinist analysis presented in Sect. 4.1, i.e., for global warming, stratospheric ozone depletion, ionizing radiation, ozone formation—human health and terrestrial ecosystems, fine particulate matter formation, terrestrial acidification, freshwater eutrophication and fossil resource scarcity. Indeed, the difference between the recycling and reference scenarios is 100%, suggesting that the recycling scenario performs better in nearly every instance of calculations. These impact categories are mainly driven by the PVC production process in the reference product's supply chain, except for ionizing radiation, which depends on the French electricity mix used in the recycling scenario. Therefore, results for these categories are not directly affected by the parameters' variations.

Water consumption offers an example of a probabilistic analysis that contradicts determinist calculations. Indeed, despite being largely favorable to the recycling scenario in Sect. 4.1, Fig. 4 suggests that there is no preferred scenario for water consumption because both scenarios present 50% of cases in which they perform better. This may be due to uncertainties related to the PVC production and wastewater treatment processes in the reference scenario, which have opposite effects on the results—PVC production contributes positively to the water consumption impact while wastewater treatment contributes negatively—but both contributions are similar in range. This result suggests that specific efforts on data collection for these background processes are required to elicit a robust conclusion for this impact category.

Figures 2a, b show a change in the preferred scenario for marine eutrophication, terrestrial ecotoxicity, human non-carcinogenic toxicity, land use and mineral resource scarcity. These categories are more influenced by the variations of the
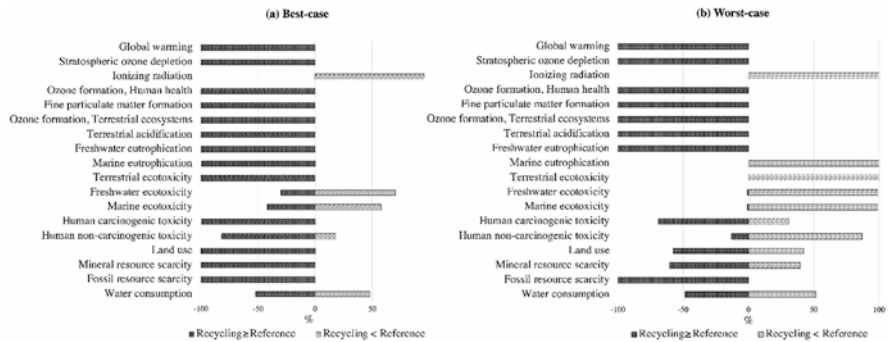
Fig. 4 Pair-wise uncertainty analyses for the best- and worst-case scenarios

parameters than by background uncertainty provided by the ecoinvent database, which was not the case for the previously mentioned impact categories. The recycling scenario performs worse for marine and freshwater ecotoxicity in both best case and worst-case scenarios, thus resolving the issue noted for freshwater ecotoxicity in Sect. 4.1.

4.2.2   Sensitivity to the Selected Parameters

Figure 5 shows the sensitivity of the comparative analysis to five parameters: the average collection and distribution distances, the additive quantity added during the recycling process, the product replacement rate and the origin of the substituted product (sport plots with virgin materials). More specifically, the variations of the probability that the recycling scenario performs better than the reference one (P_R) are presented. These variations are represented on the figure by colored boxes, whose lengths match the P_R's ranges for each impact category. Only the impact categories which showed a sensitivity on Fig. 2 were considered for this analysis.

The upper and lower probability values, i.e., the cases where the recycling scenario is superior (or inferior) to the reference scenario with a high confidence level, are indicated on Fig. 5. Within these ranges, the choice for the preferred scenario is unambiguous: either the recycling scenario performs better statistically ($P_R > 80\%$) or it performs worse statistically than the reference scenario ($P_R < 20\%$).

Figure 5 shows that P_R is highly affected by three parameters, i.e., the product's replacement rate, the origin of the substituted product and, to a lesser extent, the distribution distance in the recycling scenario. The collection distance and the additive quantity do not influence the final conclusion since the largest P_R's variation observed for these parameters does not exceed 8 points.

However, this influence is observed for a limited number of impact categories: terrestrial ecotoxicity, marine eutrophication, land use and human toxicity (carcinogenic and non-carcinogenic). Terrestrial ecotoxicity (the orange box) is the most sensitive category. There is no confident decision-making on the preferred scenario within the space of plausible values of some parameters, especially the replacement rate and the
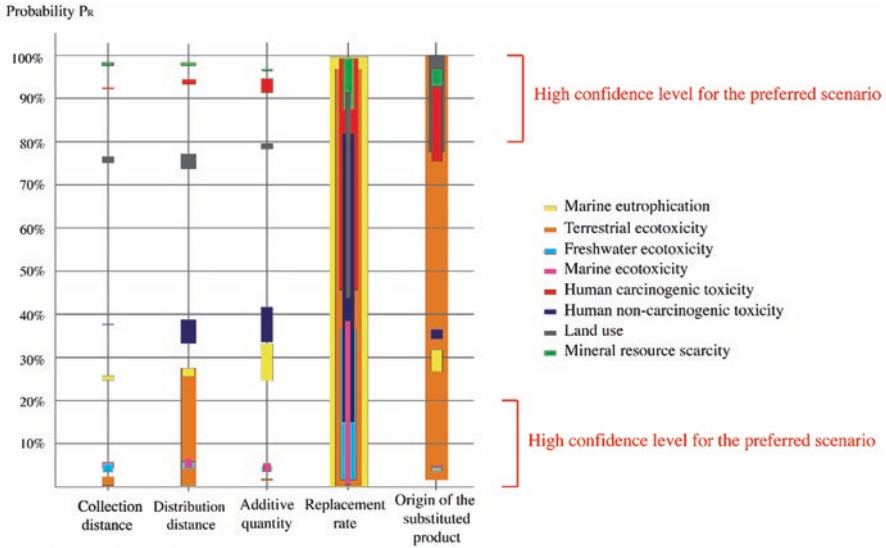
Fig. 5 Sensitivity analysis on the probability that the recycling scenario outperforms the reference one (P_R)

substituted product's origin. For example, if the replacement rate is 1:2, i.e., if one sport plot from recycled fibers is functionally equivalent to two conventional sport plots (considering that all other parameters keep their median values), the recycling scenario is preferred in 97% of cases. It drops to 0% for a replacement rate of 2:1.

For other impact categories, a high P_R variability is not detrimental to decision-making. For example, the origin of the substituted product highly influences the recycled scenario's performance on human carcinogenic toxicity, i.e., the P_R's range is close to 20 points. However, the P_R values are still close to 80%: they vary between 77% and 92%. The same observation can be made for mineral resource scarcity. This is an important reminder that a high sensitivity to a parameter's variability does not necessarily mean an impossibility to draw conclusions.

4.3 Discussion

4.3.1 Potential of Textile Recycling to Reduce Environmental Impact

Based on these study's results, the environmental benefits of textile recycling are ambiguous. This study does not support the conclusion that textile recycling is preferable *in general* (Sandin & Peters, 2018). The results showed that for some impact categories, such as marine ecotoxicity or ionizing radiation, neither background uncertainty (coming from the LCI database) nor variations of scenario parameters changed the preferred scenario, which was the reference scenario (without recycling). This specific finding is context-dependent: for ionizing radiation, recycling

is unfavorable owing to the French electricity mix, which relies heavily on nuclear energy sources. The conclusion might be different if recycling were to occur in Germany or Portugal. However, for a specific context, this study suggests that textile recycling might never become beneficial, although large uncertainties are considered. At the other end of the spectrum, for other impact categories, such as global warming, the recycling scenario performs better in 100% of cases.

This conclusion stresses the necessity to perform a multicriteria analysis when assessing the environmental performance of textile recycling (Peters et al., 2019). In their literature review, Sandin and Peters (2018) noted that impact categories such as human toxicity or ecotoxicity were assessed in only 6 and 12 papers out of 41, respectively, while climate change was almost always assessed (39 papers). This choice can lead to misleading conclusions as to the potential environmental benefits of recycling, especially regarding some of the local impact categories investigated in this study (toxicity, ecotoxicity, marine eutrophication). Results suggest that terrestrial ecotoxicity is the most affected by the variability of the scenario parameters, i.e., the parameters that recycling companies and/or the LCA experts are likely to control the most, such as the product's replacement rate or the origin of the substituted product. When high uncertainty or variability is perceived for such parameters, our recommendation is to include at least a range of plausible values when local impact categories are assessed.

The replacement rate was found influential in several studies assessing the environmental impact of recycling systems, but without threatening the environmental benefits of recycling (Sandin & Peters, 2018). For example, Dahlbo et al. (2017) found that a replacement rate of 50% (1:2) did not change the superiority of the recycling scenario on climate change, terrestrial acidification, ozone formation and particulate matter formation. Similar results were obtained in this study and reinforced with an uncertainty analysis. Considering background uncertainty and replacement rate's variability (among others), Fig. 4 shows that the use of recycling fibers remains the preferred option for these impact categories. However, this conclusion does not hold for other impact categories, not investigated by Dahlbo et al. (2017) such as ecotoxicity, land use, toxicity. In this case, the variability of the replacement rate may threaten the recycling's environmental benefits (see Fig. 5).

4.3.2   Including Uncertainties in LCAs of Recycling Systems

Treating uncertainties when conducting an LCA study helps to improve the credibility and the reliability of the conclusions (Igos et al., 2019). On the environmental impact of textile recycling, the probabilistic approach adopted in this chapter allowed to reinforce and nuance some previous observations. For example, the results confirmed the trend of the recycling scenario's superiority for impact categories such as global warming and stratospheric ozone depletion (Liu et al., 2020; Spathas, 2017; Zamani et al., 2015; Shen et al., 2011). They verified the importance of some parameters, such as the replacement rate (Sandin & Peters, 2018), not only as an influential factor but also as one factor impeding confident decision-making when its variation range is unknown. Moreover, the uncertainty analysis conducted in Sect. 4.2.1 shed

more light on the water consumption category, nuancing conclusions drawn from the deterministic analysis. In this case, an inventory regionalization should be done to decrease the uncertainty related to specific background processes (water consumption in PVC production and wastewater treatment).

Nevertheless, accounting for uncertainty to aid decision-making with LCA is a complex task and there are limitations that should be considered. First, the uncertainty analysis did not account for all uncertainty types. For example, the choice of the allocation method was constant (cut-off), although it has been stressed as one influential factor in LCAs of textile recycling and in probabilistic LCAs (Spathas, 2017; Zamani et al., 2015; AzariJafari et al., 2018). A system expansion method would have included energy recovery from incineration as environmental benefits in the reference scenario, but also the environmental benefits of using recycled PE and PP in the recycling scenario (depending on the adopted perspective). The resulting changes are difficult to predict but would have likely affected categories such as global warming, acidification and fossil fuels scarcity. Second, there are different methods for uncertainty-statistics in comparative LCAs, other than the discernibility analysis used in this study (Mendoza Beltran et al., 2018). Mendoza Beltran et al. (2018) compared five methods and showed that they concurred with each other for a majority of impact categories, except for two of them, i.e., acidification and ionizing radiation. The comparison was performed on a different case study than textile recycling, i.e., different types of motor engines, but it showed that a different method could lead to slightly different results on a limited number of categories.

Finally, borrowing the terminology from of a well-known assessment framework (Rockström et al., 2009), an interesting future study could be to map for different open- and closed-loop scenarios in different countries the "safe operating space" of textile recycling. This analysis could help to better inform decision-makers of the contexts for which recycling is highly preferable from an environmental perspective, considering even larger variations and uncertainties than the ones in this study. Advanced statistical approaches could be used, such as explorative modelling and analysis. This approach integrate large uncertainties in computational experiments to provide insights for decision-making, such as identifying specific conditions that would cause some scenarios to perform poorly (Kwakkel & Pruyt, 2013).

5   Conclusions

This chapter investigated the environmental prevalence of textile recycling on a case of open-loop recycling, considering the influence of different parameters, uncertain background data and different impact categories. A probabilistic and parametric LCA was conducted and the main conclusions may be listed as follows:

- In comparison to a product manufactured with virgin materials, a product based on recycled textile fibers might have greater environmental impact, even when large background uncertainties are considered.
- Multicriteria assessment is highly recommended when assessing the environmental impact of textile recycling.

- Well-studied parameters such as the replacement rate or the substituted product's origin affected especially local impact categories such as terrestrial ecotoxicity.
- Other parameters such as distribution distances may influence or contribute greatly to the impact of recycling but not threaten its environmental benefits statistically, i.e., the confidence in the preferred scenario.
- A probabilistic analysis may contradict clear conclusions drawn from a deterministic analysis.

Overall, a general conclusion of this chapter is to not consider textile recycling more environmentally friendly than other options *in general*, but to assess it through a multicriteria quantitative assessment and preferably through a probabilistic approach. This conclusion does not mean that textile recycling should not be promoted and further developed because this study also showed its potential environmental benefits, e.g., on global warming. However, focussing on recycling only might not be sufficient to reach a sustainable, circular fashion industry (Keßler et al., 2021). More and more studies focus on the use phase of textile, accounting for parameters characterizing consumption behavior that are levers to reduce textile environmental impact from a systems perspective (Levanen et al., 2021; Keßler et al., 2021; Schmutz et al., 2021; Klug & Niemand, 2021).

Appendix

Table 5 Midpoint results of the comparative analysis

Impact categories	Units	Recycling scenario	Reference scenario
Global warming	kg CO_2 eq	9548	30,307
Stratospheric ozone depletion	kg CFC11 eq	0,004	0,019
Ionizing radiation	kBq Co-60 eq	506	78
Ozone formation, Human health	kg NOx eq	21	89
Fine particulate matter formation	kg PM2.5 eq	8	45
Ozone formation, Terrestrial ecosystems	kg NOx eq	22	91
Terrestrial acidification	kg SO_2 eq	19	107
Freshwater eutrophication	kg P eq	0,50	1,28
Marine eutrophication	kg N eq	0,27	0,39
Terrestrial ecotoxicity	kg 1,4-DCB	46,731	27,572
Freshwater ecotoxicity	kg 1,4-DCB	11	12
Marine ecotoxicity	kg 1,4-DCB	39	30
Human carcinogenic toxicity	kg 1,4-DCB	52	115
Human non-carcinogenic toxicity	kg 1,4-DCB	1225	3933
Land use	m2a crop eq	300	537
Mineral resource scarcity	kg Cu eq	14	22
Fossil resource scarcity	kg oil eq	3761	11,093
Water consumption	m^3	127	265

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