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Research article

The environmental performance of upcycling: A comparative life cycle assessment in the apparel industry

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ABSTRACT

To achieve a sustainable circular economy in the textile industry, the upcycling of post-consumer textiles is often recommended as a good solution. Yet, the actual environmental benefits of the upcycling processes remain to be further quantified. This study evaluates the environmental performance of the upcycling of discarded uniforms from Luxembourgish companies and institutions. Three upcycled accessories were selected for evaluation through the life cycle assessment (LCA) methodology, including 16 quantitative environmental indicators: (i) A hot-water bottle cover made from a fleece jacket; (ii) A laptop sleeve made from a pair of pants; (iii) A bike bag made from a high-visibility work jacket. These products are compared with three brand-new accessories of similar functionality made from primary materials. The study finds that the upcycling process has a substantially lower environmental impact across most categories compared to brand-new production. On average, upcycled accessories result in 87% fewer environmental impacts, with variations depending on the accessory and the specific impact category. Taking a closer look at climate change and water use indicators, avoided emissions reach up to 6.60 kg CO_2 eq. per kg of product for the laptop sleeve, and up to 1.92 m^3 of water use per kg for the bike bag. The analysis highlights that the energy demand of upcycling (especially electricity use) is a key factor influencing the results, given that electricity consumption and the transport stage (from the uniforms collection point to the upcycling center) are the main input flows to the upcycling process. A sensitivity analysis confirms that the environmental advantage of upcycling decreases from 87% at the reference lifespan to 74% when considering 50% lifespan reduction and 35% when considering 80% lifespan reduction for upcycled products. While the hot-water bottle cover and bike bag maintain substantially lower impacts than brand-new production even under the most conservative scenario, the laptop sleeve – the most energy-intensive product – exceeds brand-new impacts on average at 80% lifespan reduction, highlighting the critical importance of product durability and electricity source in determining the net environmental benefit of upcycling. Beyond its environmental scope, this study contributes to the broader sustainability agenda by providing quantified, product-level evidence in support of circular economy policy instruments – including Extended Producer Responsibility schemes and green financial incentives – and by illustrating how community-based upcycling initiatives can simultaneously deliver environmental and social co-benefits, in alignment with the UN Sustainable Development Goal 12 on Responsible Consumption and Production.

1. Introduction

1.1. Context and motivations

The textile and fashion industry is one of the most environmentally intensive sectors globally, estimated to be responsible for between 2% and 8% of global greenhouse gas emissions, 215 trillion litres of water consumed per year, and 9% of annual microfibre pollution to oceans [1]. The scale of this challenge is illustrated by the fact that the global textile industry currently operates at a circularity rate of just 0.3%, with over 99% of the approximately 3.25 billion tonnes of materials it consumes annually derived from virgin sources [2]. Synthetic fibres – particularly

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polyester derived from fossil fuels – alone account for 63% of raw materials used in textile production [2], underlining the systemic dependence on non-renewable resources that circular strategies such as upcycling seek to address. Furthermore, up to 30% of clothing produced annually remains unsold, further entrenching the cycle of resource extraction and waste [2]. The rise of fast fashion has further accelerated clothing consumption while shortening garment lifespans, further amplifying the sector's environmental impacts [3]: the number of uses per garment before discard has decreased by an estimated 36% over the past 15 years [1].

At the European level, textiles rank among the top four household consumption categories in terms of environmental and climate pressures, with EU citizens consuming on average 19 kg of clothing, footwear and household textiles per person in 2022, generating approximately 355 kg CO_2 eq. per person from the textile supply chain [4]. In response, the EU Waste Framework Directive now mandates that Member States establish separate textile collection systems from 2025 onwards [5], yet less than 35% of textile waste is currently collected separately in Europe, underscoring the urgency of developing effective end-of-life pathways such as upcycling. Beyond its environmental dimension, the textile industry's sustainability challenge is also social and economic: employing approximately 140 million people worldwide, the sector profoundly influences social wellbeing and community livelihoods, yet many workers face conditions characterised by low wages, excessive working hours, and limited social protections [2]. Circular strategies such as upcycling therefore carry the potential to simultaneously address environmental degradation and generate local employment and social value, particularly when implemented through community-based initiatives – aligning with the UN Sustainable Development Goal 12 on Responsible Consumption [6] and Production and the EU Strategy for Sustainable and Circular Textiles.

To address the growing issue of textile waste at the local level, HUT – Hëllef um Terrain, a Luxembourgish non-governmental organization dedicated to supporting vulnerable individuals and communities both within Luxembourg and internationally, launched the Lët'z Refashion initiative, which repurposes discarded clothing into new products through upcycling. Among the textile streams received by the initiative, personnel workwear from companies and public institutions constitutes a regular and practically relevant source of material. These garments frequently cannot be reused directly due to wear, branding elements, or security requirements, and they currently lack established recycling or repurposing pathways in Luxembourg. As a result, they are typically downcycled or disposed of, despite their potential for value recovery through upcycling. Their steady availability within the Lët'z Refashion collection system makes them a suitable case for examining the environmental performance of local upcycling practices.

This circular fashion approach could not only minimize textile waste but also reduce the environmental impacts associated with textile production [7–9]. Additionally, it aligns with countries' strategic priorities of fostering a circular economy (CE) and creating socio-economic benefits such as employment opportunities and community support, while promoting sustainable consumption and production practices [10]. Identifying environmental hotspots across the textile value chain is a prerequisite for targeting such circular economy interventions effectively; in this regard, lifecycle thinking consistently identifies fibre production and wet processing – notably dyeing and finishing – as the most environmentally significant stages, due to their reliance on fossil fuels and the generation of hazardous effluents [11]. Upcycling is one promising CE practice [12] for which the potential environmental benefits still need to be quantified. In fact, while several studies [8,13,14] advocate for a better valorisation of post-consumer textiles through upcycling to tackle fast fashion cycles and reduce the carbon and water footprint of these products [15–17], there is a lack of quantified studies to evaluate the actual ecological benefits of upcycling practices in the apparel industry.

In this context, a study is conducted to evaluate the environmental performance of the upcycling of recovered uniforms used by Luxembourgish companies and institutions that would otherwise be discarded. The life cycle assessment (LCA) methodology [18] is used for this purpose.

1.2. Research approach and objectives

This study aims to evaluate the potential environmental benefits of the upcycling process initiated by a clothing and accessories upcycling center in Luxembourg. A comparative life cycle assessment (LCA) is conducted, focusing on three upcycled accessories made from different pieces of used uniforms:

- a hot-water bottle cover made from a fleece jacket;
- a laptop sleeve made from a pair of pants;
- a bike bag made from a high-visibility work jacket.

To serve as a baseline for comparison, three brand-new accessories with similar functions, made from primary materials, are also considered. The study quantifies the environmental impacts of producing the upcycled accessories and calculates the avoided emissions compared to brand-new production. This assessment focuses exclusively on environmental aspects. While the social and economic dimensions of upcycling are acknowledged as important components of a holistic sustainability assessment, they fall outside the scope of the present LCA study and are identified as a priority avenue for future research. To do so, the study follows the LCA methodology in accordance with ISO 14040/44 [18], providing a comprehensive, life cycle-wide, and multi-criteria evaluation of environmental impacts. The key stages are:

- Goal and scope definition: The scope of the assessment is defined for both upcycling and brand-new production scenarios, including the functional unit (FU), which ensures fair comparison. The FU represents the quantified function or service of the product.
- Life cycle inventory: Input and output data for the upcycling process are collected to model the foreground inventory. This includes data on the materials from used uniforms, their origin, logistics, the upcycling process, and the resulting products, including waste and emissions. Background data from an LCA database (ecoinvent), which provides generic data on aspects such as energy production and material extraction, supplement the modelling.
- Life cycle impact assessment: Based on the inventory data, the potential environmental impacts are evaluated by quantifying the effects of resource use and emissions. These calculations are performed using an LCA software (SimaPro), following the European Commission's environmental impact assessment methodology (Product Environmental Footprint – PEF – 3.1), which assesses 16 indicators [19].
- Interpretation: Several analyses are conducted, including contribution analysis to identify the main sources of impact from uniforms, assessment of the impacts avoided through upcycling, and comparative analysis of scenarios.

2. Materials and methods

2.1. Goal and scope definition

2.1.1. Object of the study and functional unit

To assess the environmental performance of the upcycling scenario, three upcycled accessories, made by HUT – Hëllef um Terrain, are considered: (i) a hot-water bottle cover made from a fleece jacket, (ii) a laptop sleeve made from a pair of pants, and (iii) a bike bag made from a high-visibility work jacket. Pictures of the considered accessories are provided in Appendix A. For comparison to the baseline, three similar accessories made from new materials are used. The FU is "the production of 1 kg of accessory". This study focuses exclusively on environmental impacts based on the LCA framework. Economic and social aspects, including potential cost differences between upcycled and brand-new items, are not assessed and therefore fall outside the scope of this work.

2.1.2. System boundaries, inventory modelling and cut-off criteria

For the baseline (brand-new production), the system boundaries include the material extraction and processing needed to produce the brand-new accessory as well as the transportation of the product to Luxembourg where it is used. For the upcycling scenario, the system boundaries include the collection of the used uniform and the upcycling process itself, transforming the uniform intended for disposal into a new functional textile product. In accordance with the cut-off approach, which assigns the environmental impacts of a material or product to its original production phase, the impact of the uniform's production is fully attributed to the producer and not carried over into the upcycling process. Similarly, the avoided impacts associated with the remaining textile from the upcycling process, which is further used for padding and replace the use of primary materials, are not considered in the impact assessment. The system boundaries specific to each scenario studied are depicted in Fig. 1 and Fig. 2.

2.1.3. Inventory modelling

Specific data are collected for the upcycling process performed by HUT – Hëllef um Terrain, the upcycling center. For the corresponding brand-new production process, generic data from the ecoinvent database are used [20]. The system modelling "Allocation, cut-off by classification" of the ecoinvent database is used to model background processes. The inventory modelling is performed with the LCA software tool SimaPro (v9.6), using background processes from the 2024 version of ecoinvent (v3.10).

2.1.4. Data quality criteria

Data collected for the upcycling process are expressed per item and are based on information and measurements provided by the upcycling center. For the background process modelling, the most representative (e.g., geographically) ecoinvent datasets are used. Luxembourg data are used for the electricity source used for the upcycling process and thermal energy; European or Global datasets are used for the other processes, as detailed in the life cycle inventory.

2.1.5. Assumptions and implications

To ensure comparability, it is assumed that upcycled items have a lifespan equivalent to that of brand-new items. While this assumption simplifies the analysis, differences in durability between upcycled and new products could alter the results. For instance, if an upcycled product's lifespan is shorter, its environmental impact would effectively increase, as more units would need to be produced to fulfil the same FU over time. Further research should include durability testing to validate this equivalence.

2.2. Life cycle inventory (LCI) analysis

The brand-new production process is modelled using generic datasets from ecoinvent, based on the composition of products similar to the upcycled items (a hot-water bottle cover, a laptop sleeve, and a bike bag). These items were selected based on their popularity and high sales volumes in the market, ensuring they represent commonly sought-after products. The input flows (i.e., ecoinvent processes) considered to produce 1 kg of brand-new hot-water bottle cover, laptop sleeve and bike bag, respectively, are presented in Appendix B.

The brand-new hot-water bottle cover considered in the study is modelled as being made from 100% polyester, while the laptop sleeve and bike bag are assumed to be primarily composed of polyester and polyurethane, with quantities estimated. The datasets used for modelling include the production of polyester and the transportation processes (truck and ship), which are representative of the global market (GLO) or "rest-of-the-world" (RoW).

Data for the upcycling process were collected directly from the upcycling center's operations, including:

- Material inputs (e.g., fleece jacket, winter pants).
- Process parameters (e.g., electricity use for sewing machines).

The end-of-life uniforms are collected from Luxembourgish companies and public institutions. For the LCA, a maximum distance of 30 km travelled by a light truck (3.5–7.5 t) is assumed to transport the uniforms from the collection point to the Lët'z Refashion center for upcycling. This distance is a conservative upper bound, as typical collection distances in a small territory such as Luxembourg are generally much shorter.

The upcycling process for all three accessories is straightforward and requires only basic sewing and assembly skills. Staff at the Lët'z Refashion center carry out the design, cutting, and sewing operations, which do not involve advanced technical expertise or complex machinery. This ensures that the process is accessible and locally feasible.

Also, note that in the Lët'z Refashion initiative, donated workwear is first inspected, and only items that are clean, dry, and free from visible soiling are accepted for upcycling. The initiative does not apply industrial washing, sterilisation, or disinfection procedures (e.g., autoclaving or chemical sanitisation), as the upcycled products are not intended for applications requiring hygienic or sterile conditions. Because no cleaning or sanitising step is performed in practice, this process was not included in the LCA inventory.

As mentioned in Section 2.1., these foreground data were collected for each item and in accordance with ISO 14044:2006. Based on the data collected, the production model is scaled to 1 kg of upcycled items. The input and output flows considered to produce 1 kg of upcycled hot-water bottle cover, laptop sleeve and bike bag are presented in Appendix B.

The remaining textile during the upcycling process is further used for padding and is excluded under the cut-off approach. Upcycled accessories have a lifespan considered equivalent to that of brand-new accessories. The assumption of lifespan equivalency between upcycled and brand-new items ensures functional comparability in accordance with ISO 14040/44 standards. This approach simplifies the analysis while accounting for limited data on durability differences and variability in use conditions.

The complete LCI data with associated ecoinvent processes are available in Appendix C.

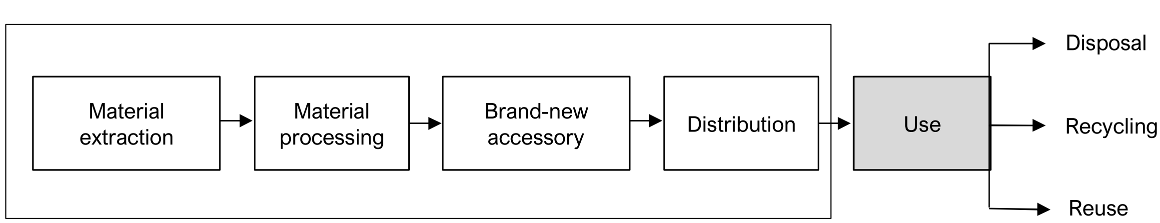

Fig. 1. System boundaries of the brand-new production process. The black frame represents the system boundaries while the grey boxes are the system components that are not considered in the assessment.

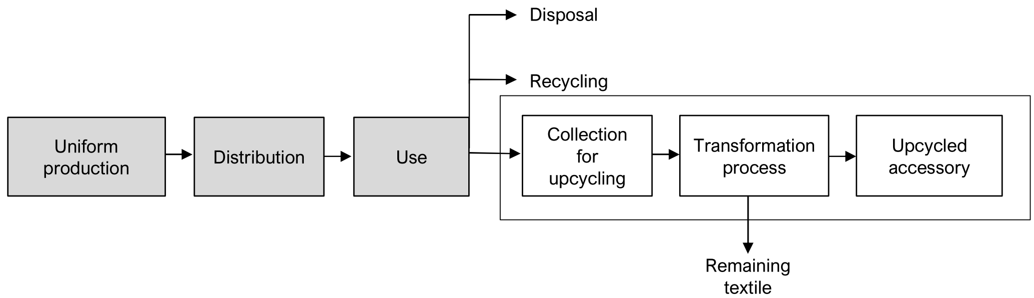

Fig. 2. System boundaries of the upcycling production process. The black frame represents the system boundaries while the grey boxes are the system components that are not considered in the assessment.

2.3. Life cycle impact assessment (LCIA) methodology

The environmental impacts were calculated using the Environmental Footprint (EF) 3.1 method [19], developed by the European Commission.

3. Results and interpretations

3.1. Overall LCIA results

Fig. 3 shows graphically, for each impact category of the EF 3.1 method, the total emissions of 1 kg of accessory produced either through the brand-new pathway or through upcycling. Based on those emissions values, the avoided impact of upcycled production compared to brand-new production as well as the impact reduction rate is determined (Table 1).

The numerical results associated with the graphs presented in Fig. 3 are available in Appendix D.

A graphical representation of the avoided emissions for climate change and water use impact categories is provided in Appendix E. Finally, Fig. 4 represents the relative impact of upcycling and brand-new production i.e., the percentage of contribution to the maximum of impact per impact category.

To simplify the naming of the three accessories considered, particularly in tables and graphs of results, the terms “cover”, “sleeve” and “bag” are used to refer to the hot-water bottle cover, the laptop sleeve and the bike bag, respectively.

The results presented in Fig. 3, Table 1 and Fig. 4 show that the production of 1 kg of accessories (representing the three upcycled items studied) results in significantly lower environmental impacts through the upcycling process compared to the baseline, i.e., brand-new production. Specifically, as seen in Fig. 3, upcycling shows lower impacts across all 16 impact categories, with the exception of ionising radiation for the upcycled laptop sleeve. Table 1 further illustrates that, on average, the overall environmental impact of upcycling is 87% lower than brand-new production (with reductions of 93% for the hot-water bottle cover, 73% for the laptop sleeve, and 96% for the bike bag). These reductions vary between 53% and 99%, depending on the impact category and the accessory (excluding ionising radiation). Fig. 4 further highlights that the brand-new production of 1 kg of accessory generates, on average, eight times more environmental impact than upcycled production.

Focusing on key categories such as climate change and water use, the upcycling process avoids significant emissions. For instance, it prevents 5.89 kg CO_2 eq./kg of hot-water bottle cover, 6.60 kg CO_2 eq./kg of laptop sleeve, and 4.44 kg CO_2 eq./kg of bike bag (Appendix E). In terms of water use, it saves 1.53 m^3 /kg for the hot-water bottle cover, 1.56 m^3 /kg for the laptop sleeve, and 1.92 m^3 /kg for the bike bag (Appendix E).

These findings align with the literature, such as Stanescu [17] and Bijoya and Zunjarrao [21], which emphasize the clear environmental benefits of textile waste upcycling, including reductions in pollution (air, water, and soil) from waste disposal and the decreased need for virgin raw materials. More broadly, these results are consistent with the wider LCA literature on textile circularity, which confirms that extending the service life of textiles through circular strategies generally yield the lowest environmental impacts compared to conventional disposal routes [9,22]. While reuse and upcycling are distinct circular economy strategies, both share the common principle of avoiding virgin material production; in that regard, it is worth noting that [23], using a comparable EF-based LCA methodology, found that the overall environmental impact of a new t-shirt is approximately 70 times larger than that of a reused equivalent, further contextualising the scale of avoided impacts demonstrated in the present study.

Among the brand-new products, representative of global production, the bike bag shows the highest overall impact across 14 of the 16 impact categories. The exceptions include climate change (biogenic sources), human toxicity (cancer effects), land use, ozone depletion, and photochemical ozone formation. The elevated impacts of the bike bag are attributed to the greater use of polyurethane (flexible foam), which has higher associated impacts than nonwoven polyester. For example, polyurethane production results in 7.59 kg CO_2 eq./kg compared to 6.4 kg CO_2 eq./kg for polyester. The bike bag also likely contains a higher quantity of polyurethane compared to the laptop sleeve. It is important to note that the impact results of brand-new accessories can vary depending on the materials and quantities used, providing only an estimation of the avoided impacts through upcycling.

In contrast, among the upcycled products, which represent local production in Luxembourg, the laptop sleeve shows the highest impact across all categories compared to the hot-water bottle cover and bike bag, which have similar impacts. This is primarily due to the higher electricity consumption required for producing 1 kg of the laptop sleeve (5.11 kWh/kg) compared to the hot-water bottle cover (1.20 kWh/kg) and the bike bag (0.69 kWh/kg). The higher electricity demand, combined with Luxembourg's electricity mix (which includes imported electricity from Belgium, where over 25% is generated from nuclear power), explains the high impact on ionising radiation. This is linked to uranium residue treatment from nuclear power, which increases emissions in this category [24].

While the results highlight the clear benefits of upcycling, several limitations should be considered:

- *Lifespan assumptions*: This study assumes that upcycled accessories have the same lifespan as brand-new products. If the lifespans of the upcycled and brand-new products differ, the impacts would change accordingly. For example, if the upcycled product has half the lifespan of a brand-new product, its environmental impact per FU would double, as production would need to be doubled to provide the same service over time in a linear economic model.
- *Electricity mix variability*: The modelled electricity mix for upcycling reflects Luxembourg's grid, which includes imports from neighbouring countries with varying carbon intensities. Variations in the

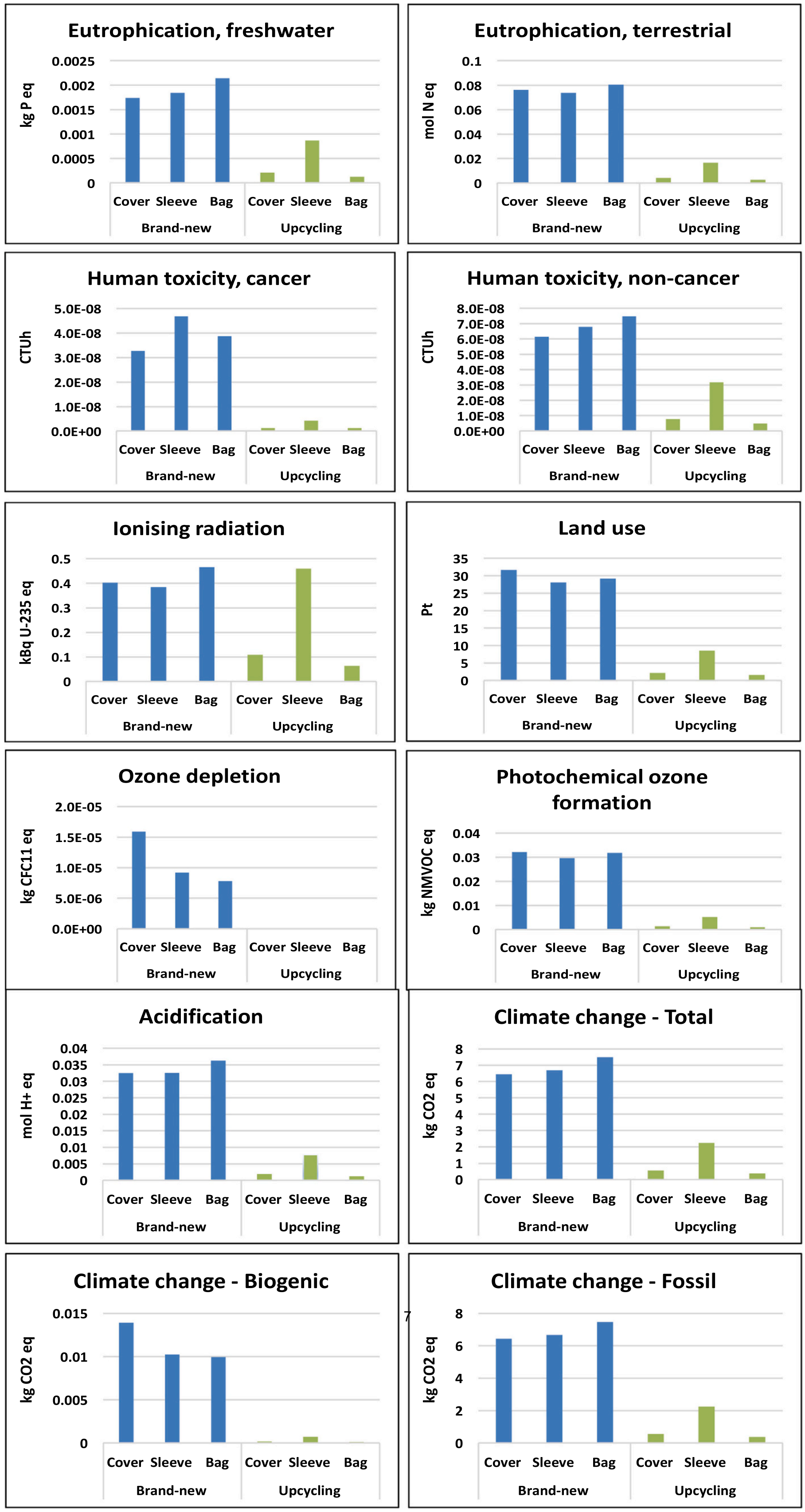

Fig. 3. Total emissions expressed per FU, for each scenario (upcycling and brand-new production) and for each impact category (EF 3.1 method) – graphical representation.

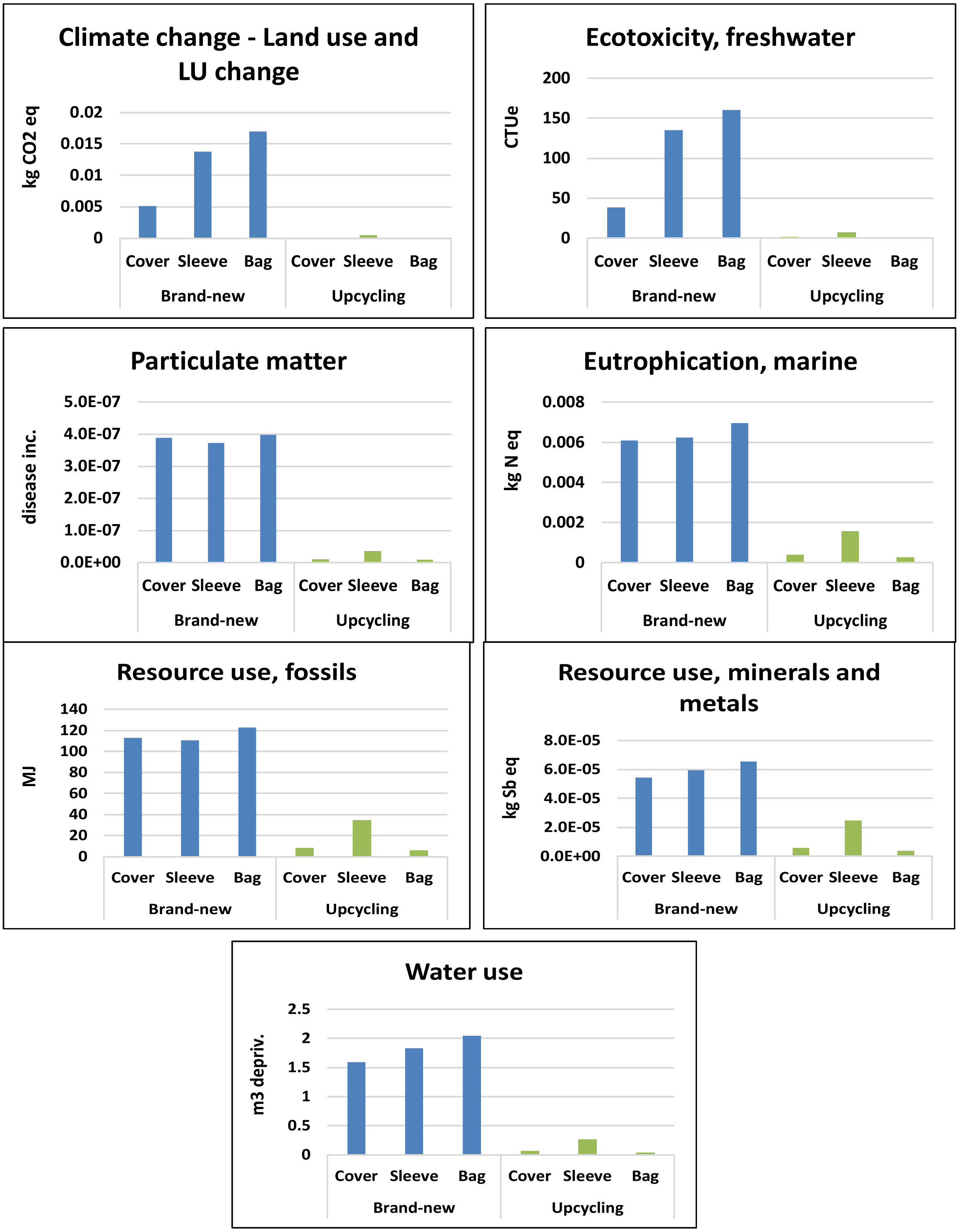

Fig. 3. (*continued*).

electricity mix (e.g., renewable-heavy vs. fossil-heavy grids) may affect the absolute emissions from the upcycling process. However, given the dominance of virgin material production impacts in the brand-new scenario, such variability would have a limited effect on the relative differences between the two scenarios.

- *Transport distances*: Transport emissions are based on an average distance of 30 km per trip. Longer transport distances for upcycling (e.g., rural collections or cross-border logistics) could increase relative impacts. Nonetheless, these emissions remain minor compared to the resource extraction and manufacturing impacts of brand-new items.
- *Complex upcycling processes*: This study focuses on relatively simple upcycling cases involving minimal additional processing. If more complex processes were included, such as dyeing, additional cleaning steps for uniforms, or greater transportation distances [15], the environmental impacts of upcycling would likely increase. Future research could explore these scenarios to provide a more

Table 1
Avoided impact and impact reduction rate (%) of upcycling compared to brand-new production per accessory and per impact category.

Impact categories	Unit	Avoided impact			Impact reduction rate (%)		
		Cover	Sleeve	Bag	Cover	Sleeve	Bag
Acidification	mol H+ eq	-0.031	-0.025	-0.032	-94%	-76%	-96%
Climate change (total)	kg CO2 eq	-5.89	-4.44	-6.60	-91%	-66%	-95%
Climate change - Biogenic	kg CO2 eq	-0.014	-0.010	-0.010	-99%	-93%	-99%
Climate change - Fossil	kg CO2 eq	-5.87	-4.42	-6.58	-91%	-66%	-95%
Climate change - Land use and LU change	kg CO2 eq	-0.005	-0.013	-0.016	-98%	-97%	-99%
Ecotoxicity, freshwater	CTUe	-36.8	-127.8	-157.5	-95%	-95%	-99%
Particulate matter	disease inc.	-3.79E-07	-3.38E-07	-3.67E-07	-98%	-91%	-98%
Eutrophication, marine	kg N eq	-0.006	-0.005	-0.006	-94%	-75%	-96%
Eutrophication, freshwater	kg P eq	-0.002	-0.001	-0.002	-88%	-53%	-94%
Eutrophication, terrestrial	mol N eq	-0.072	-0.057	-0.073	-95%	-78%	-97%
Human toxicity, cancer	CTUh	-3.15E-08	-4.24E-08	-3.70E-08	-96%	-91%	-97%
Human toxicity, non-cancer	CTUh	-5.36E-08	-3.62E-08	-6.52E-08	-87%	-53%	-93%
Ionising radiation	kBq U-235 eq	-0.294	0.075	-0.332	-73%	20%	-84%
Land use	Pt	-29.5	-19.5	-26.4	-93%	-70%	-94%
Ozone depletion	kg CFC11 eq	-1.59E-05	-9.14E-06	-7.77E-06	-99%	-99%	-99%
Photochemical ozone formation	kg NMVOC eq	-0.031	-0.025	-0.029	-96%	-83%	-97%
Resource use, fossils	MJ	-104	-76	-110	-92%	-69%	-95%
Resource use, minerals and metals	kg Sb eq	-4.84E-05	-3.49E-05	-5.90E-05	-89%	-59%	-94%
Water use	m3 depriv.	-1.53	-1.56	-1.92	-96%	-85%	-98%
Average impact reduction					-93%	-73%	-96%

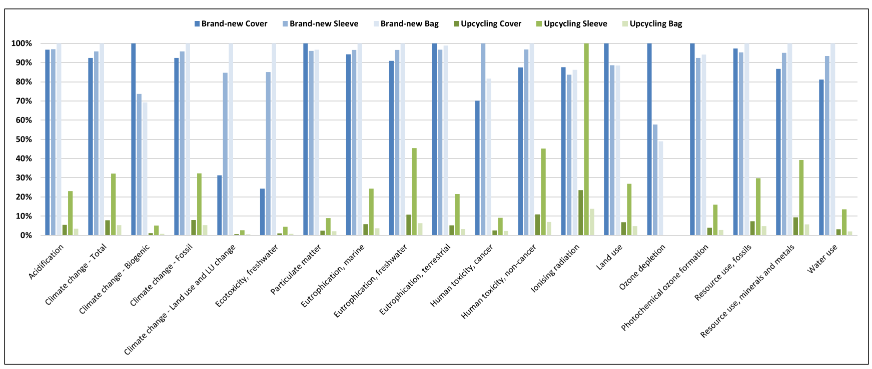

Fig. 4. Overview of the relative impact for each scenario (upcycling and brand-new production) and each impact category.

comprehensive understanding of upcycling's environmental performance across a broader range of applications.

3.2. *Focus on climate change*

Fig. 5 illustrates the greenhouse gas (GHG) emissions (in kg CO_2 eq.) per FU, comparing the emissions from brand-new production with those from the upcycling process, along with the main contributing processes for each.

As highlighted in section 2.3.1, emissions from brand-new production are significantly higher than those from upcycling for all three accessories studied. Specifically, brand-new production emissions are 3

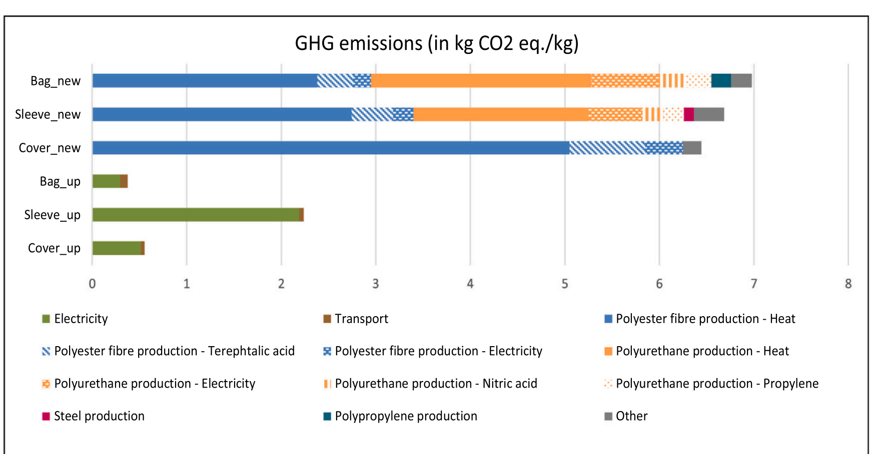

Fig. 5. Absolute GHG emissions expressed in kg CO_2 eq. per FU (1 kg of accessory produced) for each scenario (upcycling and brand-new production). *In the Y axis title, [accessory]_new refers to the brand-new accessory, [accessory]_up refers to the upcycled accessory.*

times higher for the laptop sleeve, 12 times higher for the hot-water bottle cover, and 19 times higher for the bike bag. The bike bag has the highest emissions at 6.98 kg CO_2 eq./kg, followed by the laptop sleeve at 6.68 kg CO_2 eq./kg, and the hot-water bottle cover at 6.44 kg CO_2 eq./kg. These high emissions from primary production are mainly driven by the production of polyester fiber and polyurethane (used in the laptop sleeve and bike bag), which accounts for 94–97% of total GHG emissions. This finding is consistent with comparable LCA studies, which identify fibre production as the primary environmental hotspot across circularity strategies for synthetic garments [9,25]. The heat required for these primary textile production processes is the largest contributor to emissions, making up 72–81% of the total impact. Additionally, electricity and chemicals (such as terephthalic acid for polyester, and nitric acid and propylene for polyurethane) contribute significantly to the emissions from polyester fiber and polyurethane production (11% and 14%, respectively). Minor contributors include steel (used for the laptop sleeve zipper) and polypropylene (used for bike bag buckles), accounting for less than 3% of total GHG emissions.

In contrast, accessories produced through the upcycling process exhibit much lower GHG emissions: 0.37 kg CO_2 eq./kg for the bike bag, 2.24 kg CO_2 eq./kg for the laptop sleeve, and 0.55 kg CO_2 eq./kg for the hot-water bottle cover. These emissions primarily result from the electricity required to operate sewing machines during the upcycling process, which uses discarded uniforms as input (0.69 kWh/kg for the bike bag, 5.11 kWh/kg for the laptop sleeve, and 1.20 kWh/kg for the hot-water bottle cover). Since the upcycling process takes place in Luxembourg, the Luxembourgish electricity mix is applied in the model. The associated emissions are largely due to electricity imports from Germany, which accounts for approximately 45% of Luxembourg's electricity consumption [24]. Germany's electricity production is around 35% reliant on fossil fuels, particularly lignite, natural gas, and hard coal [24,26]. Additionally, electricity imports from other countries such as the United Kingdom, the Netherlands, and the Czech Republic, which also rely on fossil fuel-based electricity generation, contribute to the overall emissions. As discussed in section 2.3.1, the upcycled laptop sleeve exhibits higher emissions per FU due to the more energy-intensive nature of its upcycling process. Finally, the transportation step (covering the 30 km distance between the collection point for used uniforms and the Lët'z Refashion center where upcycling takes place) makes only a minor contribution to the total GHG emissions of the upcycling scenario.

3.3. Sensitivity analysis

A sensitivity analysis was conducted to assess the influence of product lifespan on the environmental performance of upcycled accessories. Two reduced-lifespan scenarios are presented in Table 2 and detailed in Table 3, corresponding to a 50% and an 80% reduction in lifespan relative to the baseline assumption – requiring twice and five times as many upcycled products respectively to deliver the same functional unit over time. As expected, shortening the lifespan increases the environmental impacts per functional unit across all impact categories, since more products would be required over time to deliver the same service – resulting in impacts 100% and 400% higher than the baseline upcycling scenario.

At the reference lifespan, the overall average impact reduction across all three products and all categories is 87%, with the hot-water bottle cover, laptop sleeve, and bike bag achieving average reductions of 93%, 73%, and 96% respectively. At 50% lifespan reduction, the overall average impact reduction decreases to 74%, with the cover, sleeve and bag achieving average reductions of 86%, 45%, and 92% respectively – all three products retaining lower environmental impacts than brand-new production across all impact categories, except for ionising radiation for the laptop sleeve (+139%), discussed further below. At 80% lifespan reduction, the results diverge significantly across products. The hot-water bottle cover and bike bag retain clearly lower average impacts than brand-new production, with average reductions of 65% and 79% respectively. The cover exceeds brand-new production only for ionising radiation (+35%), while all other categories remain substantially lower. The bag remains lower than brand-new production across all impact categories, including ionising radiation (-19%), confirming the robustness of its environmental advantage even under this extreme scenario. However, the laptop sleeve reached an average impact that is 37% higher than brand-new production at 80% lifespan reduction, with 11 out of 19 impact categories exceeding brand-new impacts, including climate change (+68%), eutrophication freshwater (+136%), human toxicity non-cancer (+133%), ionising radiation (+498%), resource use minerals and metals (+107%), and resource use fossils (+56%). Categories for which the sleeve still retains an advantage at this extreme scenario include ozone depletion (−98%), ecotoxicity freshwater (−73%), water use (−27%), and particulate matter (−53%). For the laptop sleeve – the most energy-intensive product, consuming 5.11 kWh/kg of electricity – the environmental advantage over brand-new production is maintained up to approximately 66% lifespan reduction

Table 2
Sensitivity analysis results for reduced lifespan scenarios (50% and 80%) for each upcycled accessory.

Impact categories	Unit	50% reduction in lifespan			80% reduction lifespan		
		Cover	Sleeve	Bag	Cover	Sleeve	Bag
Acidification	mol H+ eq	3.75E-03	1.55E-02	2.39E-03	9.39E-03	3.88E-02	5.97E-03
Climate change	kg CO2 eq	1.11E+ 00	4.49E+ 00	7.50E-01	2.77E+ 00	1.12E+ 01	1.87E+ 00
Climate change - Biogenic	kg CO2 eq	3.47E-04	1.43E-03	2.22E-04	8.68E-04	3.59E-03	5.55E-04
Climate change - Fossil	kg CO2 eq	1.11E+ 00	4.48E+ 00	7.49E-01	2.77E+ 00	1.12E+ 01	1.87E+ 00
Climate change - Land use and LU change	kg CO2 eq	2.29E-04	8.86E-04	1.75E-04	5.72E-04	2.22E-03	4.37E-04
Ecotoxicity, freshwater	CTUe	3.67E+ 00	1.46E+ 01	2.63E+ 00	9.17E+ 00	3.64E+ 01	6.57E+ 00
Ecotoxicity, freshwater - inorganics	CTUe	2.87E+ 00	1.16E+ 01	1.96E+ 00	7.18E+ 00	2.90E+ 01	4.90E+ 00
Ecotoxicity, freshwater - organics	CTUe	7.96E-01	2.97E+ 00	6.67E-01	1.99E+ 00	7.42E+ 00	1.67E+ 00
Particulate matter	disease inc.	1.94E-08	7.06E-08	1.71E-08	4.85E-08	1.77E-07	4.28E-08
Eutrophication, marine	kg N eq	7.63E-04	3.15E-03	4.89E-04	1.91E-03	7.87E-03	1.22E-03
Eutrophication, freshwater	kg P eq	4.12E-04	1.74E-03	2.46E-04	1.03E-03	4.34E-03	6.15E-04
Eutrophication, terrestrial	mol N eq	7.98E-03	3.29E-02	5.13E-03	2.00E-02	8.22E-02	1.28E-02
Human toxicity, cancer	CTUh	2.42E-09	8.58E-09	2.26E-09	6.06E-09	2.14E-08	5.65E-09
Human toxicity, non-cancer	CTUh	1.53E-08	6.34E-08	9.75E-09	3.83E-08	1.58E-07	2.44E-08
Ionising radiation	kBq U-235 eq	2.17E-01	9.19E-01	1.28E-01	5.43E-01	2.30E+ 00	3.20E-01
Land use	Pt	4.32E+ 00	1.70E+ 01	3.14E+ 00	1.08E+ 01	4.26E+ 01	7.85E+ 00
Ozone depletion	kg CFC11 eq	2.05E-08	8.30E-08	1.40E-08	5.14E-08	2.07E-07	3.51E-08
Photochemical ozone formation	kg NMVOC eq	2.57E-03	1.02E-02	1.84E-03	6.44E-03	2.56E-02	4.61E-03
Resource use, fossils	MJ	1.70E+ 01	6.91E+ 01	1.13E+ 01	4.24E+ 01	1.73E+ 02	2.83E+ 01
Resource use, minerals and metals	kg Sb eq	1.18E-05	4.92E-05	7.27E-06	2.95E-05	1.23E-04	1.82E-05
Water use	m3 depriv.	1.28E-01	5.33E-01	8.05E-02	3.21E-01	1.33E+ 00	2.01E-01

Table 3
Relative environmental performance of upcycled accessories compared to brand-new production across baseline and reduced lifespan scenarios for upcycled products (% difference per impact category and average; positive values in red indicate higher impacts then brand-new production).

Impact categories	Baseline (equal lifespan)			-50% upcycled lifespan			-80% upcycled lifespan		
	Cover	Sleeve	Bag	Cover	Sleeve	Bag	Cover	Sleeve	Bag
Acidification	-94%	-76%	-96%	-88%	-52%	-93%	-71%	19%	-82%
Climate change	-91%	-66%	-95%	-83%	-33%	-89%	-57%	68%	-73%
Climate change - Biogenic	-99%	-93%	-99%	-98%	-86%	-98%	-94%	-65%	-94%
Climate change - Fossil	-91%	-66%	-95%	-83%	-33%	-89%	-57%	68%	-73%
Climate change - Land use and LU change	-98%	-97%	-99%	-96%	-94%	-99%	-89%	-84%	-97%
Ecotoxicity, freshwater	-95%	-95%	-99%	-90%	-89%	-98%	-76%	-73%	-96%
Particulate matter	-98%	-91%	-98%	-95%	-81%	-95%	-88%	-53%	-89%
Eutrophication, marine	-94%	-75%	-96%	-87%	-49%	-92%	-69%	26%	-81%
Eutrophication, freshwater	-88%	-53%	-94%	-76%	-6%	-87%	-41%	136%	-68%
Eutrophication, terrestrial	-95%	-78%	-97%	-90%	-55%	-93%	-74%	12%	-83%
Human toxicity, cancer	-96%	-91%	-97%	-93%	-82%	-94%	-81%	-54%	-85%
Human toxicity, non-cancer	-87%	-53%	-93%	-75%	-7%	-86%	-37%	133%	-65%
Ionising radiation	-73%	20%	-84%	-46%	139%	-68%	35%	498%	-19%
Land use	-93%	-70%	-94%	-86%	-39%	-89%	-66%	52%	-72%
Ozone depletion	-100%	-100%	-100%	-100%	-99%	-100%	-100%	-98%	-100%
Photochemical ozone formation	-96%	-83%	-97%	-92%	-65%	-94%	-80%	-14%	-85%
Resource use, fossils	-92%	-69%	-95%	-85%	-37%	-90%	-62%	56%	-76%
Resource use, minerals and metals	-89%	-59%	-94%	-78%	-17%	-88%	-46%	107%	-71%
Water use	-96%	-85%	-98%	-92%	-71%	-96%	-80%	-27%	-90%
Average impact reduction	-93%	-73%	-96%	-86%	-45%	-92%	-65%	37%	-79%

for climate change, beyond which the energy intensity of the upcycling process outweighs the avoided production burden. This threshold is slightly higher for other categories such as water use (~71%). Consequently, the overall average impact reduction across all three products drops to 35% at the 80% lifespan scenario, compared to 87% at the reference lifespan – a significant reduction, yet still indicating a net environmental benefit at the system level when all three products are considered together.

A specific note is warranted regarding ionising radiation, which is the only category where the laptop sleeve already exhibits higher impacts than brand-new production at the reference lifespan (+20%). As discussed in Section 3.1, this is attributable to the sleeve's high electricity consumption combined with Luxembourg's electricity mix, which includes significant nuclear power imports from Belgium – a source for which uranium residue treatment generates substantial ionising radiation impacts. This structural characteristic means that ionising radiation is the first and most sensitive category to respond to lifespan reductions: at 50% lifespan reduction, the sleeve's ionising radiation impact reaches + 139% above brand-new, while at 80% reduction it reaches + 498%. The full set of sensitivity results for lifespan variations ranging from −10% to −80% is provided in Appendix F.

4. Conclusion and perspectives

The results of this LCA study demonstrate that the upcycling of uniforms into new accessories through the Lët'z Refashion initiative significantly reduces the environmental impacts compared to brand-new production, based on the overall assessment of environmental impact categories using the EF 3.1 methodology. The upcycled products analyzed (hot-water bottle cover, laptop sleeve, and bike bag) have, on average, 87% lower impacts across various environmental categories, including climate change and water use. The reduction in CO_2 emissions, ranging between 53% and 99% depending on the accessory and impact category, highlights the potential of upcycling, as a promising circular economy strategy, to contribute to Luxembourg's national efforts to mitigate climate change.

Energy use, particularly electricity consumption, is identified as the main source of impact within the upcycling process, especially for more energy-intensive products like the laptop sleeve. Nonetheless, these impacts are still significantly lower than those associated with the production of brand-new items from primary materials, which are dominated by the energy and resources required for producing synthetic textiles like polyester and polyurethane.

This study also assessed the robustness of the results with respect to product durability through a lifespan sensitivity analysis. The overall average impact reduction across all three products decreases from 87% at the reference lifespan to 74% when the upcycled products' lifespan is reduced by 50% and 35% when the lifespan is reduced by 80%, compared to brand-new products. While the hot-water bottle cover and bike bag maintain clearly lower impacts than brand-new production even at 80% lifespan reduction (average reductions of 65% and 79% respectively), the laptop sleeve – whose high electricity consumption makes it particularly sensitive to durability assumptions – reaches an average impact 37% higher than brand-new production at this extreme scenario, with its environmental advantage maintained only up to approximately 66% lifespan reduction for climate change. These findings confirm that the conclusions are not dependent on optimistic durability assumptions for two of the three products studied, while underlining that product durability and electricity source are key parameters in determining the net environmental benefit of upcycling. Future work should complement this approach with empirical durability testing and user-based lifespan data to further refine the assessment.

This analysis supports the argument that upcycling not only reduces waste but also plays an important role in reducing environmental impacts across the product lifecycle. The environmental benefits demonstrated here for local upcycling initiatives highlight the potential for broader implementation in reducing the environmental footprint of the textile industry. These results are consistent with global estimates suggesting that doubling garment utility through circular strategies could reduce GHG emissions by up to 44% at the sector level [1], and with scenario analyses conducted at a global scale showing that ambitious circular strategies could reduce textile industry environmental impacts by 35–50%, while even moderate interventions yield reductions of 17–20% [2]. The present study thus provides micro-scale, quantified evidence in support of such projections, further underlining the systemic potential of local upcycling initiatives such as Lët'z Refashion. The recent mandating of separate textile collection across EU Member States [5] is expected to significantly increase the availability of post-consumer textile streams suitable for upcycling, reinforcing the practical relevance of such initiatives. Taken together, these results support the case for green financial incentives and political actions to foster upcycling practices. In particular, the [27] proposal for a mandatory and harmonised Extended Producer Responsibility (EPR) scheme for textiles across all EU Member States [27,28] represents a key regulatory lever that could redirect textile waste streams towards local upcycling centres like Lët'z Refashion. However, it is important to note that the simplicity of the cases studied here does not fully capture the potential additional complexity and variability in other upcycling scenarios [12].

While this study focuses exclusively on environmental impacts, it is worth noting that local upcycling initiatives such as Lët'z Refashion also carry broader sustainability implications that extend beyond the scope of the present LCA. From a social perspective, such centres generate direct local employment and foster community engagement, embodying a model of circular production that prioritises social inclusion alongside environmental performance [2]. From an economic perspective, the quantified avoided impacts reported here provide an evidence base for calibrating emerging policy instruments: as EPR schemes redirect financial responsibility for end-of-life textile management towards producers, the demonstrated efficiency of local upcycling in avoiding environmental burdens supports the case for directing collected funds towards initiatives with proven environmental returns.

In all, the contribution of this study is primarily methodological rather than technological. First, it demonstrates how CE loops based on textile upcycling can be consistently modelled within a full LCA framework, allowing the quantification of potential environmental impact savings compared to brand-new production. The study provides a transparent and reproducible approach for assessing upcycling scenarios that are often qualitatively discussed but rarely quantified in detail. Second, the study focuses on short and local CE loops, using primary foreground data from an operational upcycling center. While the case study is situated in Luxembourg, the methodological approach is transferable to other regions and industries. The results are therefore not intended to be directly extrapolated, but rather to illustrate the environmental relevance of local upcycling systems and to provide a replicable framework that can be adapted to different geographical contexts, scales, and textile streams.

Further research could explore more complex upcycling systems and account for differences in product lifespan between upcycled and brand-new items (or validate this equivalency through empirical testing or sensitivity analysis). Nevertheless, this study provides strong evidence that upcycling is a promising strategy for reducing the environmental impacts of textiles (not only in terms of waste generation but also the need for virgin raw materials) while promoting sustainable production and consumption. In terms of contribution to the field of sustainability, this study advances knowledge across three dimensions: environmentally, by providing one of the first quantified, product-level LCA assessments of apparel upcycling under the EF 3.1 methodology; socially, by illustrating how community-based circular initiatives can deliver co-benefits beyond waste reduction; and economically, by grounding emerging policy discussions in measurable environmental performance data. Taken together, these contributions position upcycling as a multidimensional lever for sustainable development, aligned with EU policy objectives and global sustainability frameworks such as the SDGs. Future research should further strengthen this evidence base by explicitly incorporating social and economic indicators into the assessment.

CRediT authorship contribution statement

Marie-Sophie Roderich: Formal analysis, Investigation, Software, Writing – original draft, Writing – review & editing. **Ana-Luisa Teixeira:** Funding acquisition, Project administration, Validation. **Michael Saidani:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Enrico Benetto:** Funding acquisition, Supervision, Validation.

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.

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Appendix A. : Pictures of the three upcycled accessories considered in the study

Fig. A.1. Fleece jacket upcycled into a hot-water bottle cover

Fig. A.2. Pants upcycled into a laptop sleeve

Fig.A.3. High-visibility work jacket upcycled into a bike bag

Appendix B. : Life cycle inventories of new and upcycled items

Table B.1
LCI of the production of 1 kg of brand-new items

Brand-new	Hot-water bottle cover	Laptop sleeve	Bike bag
Polyester (kg)	1	0.57	0.48
Polyurethane (kg)		0.38	0.48
Steel (kg)		0.05	
Polypropylene (kg)			0.05

Table B.2
LCI of the production of 1 kg of upcycled items

Upcycling	Hot-water bottle cover	Laptop sleeve	Bike bag
Input flows			
Fleece (kg)	2.24		
Winter jacket (kg)		2.86	
High-visibility work jacket (kg)			4.59
Sewing thread (kg)	*Neglected*	*Neglected*	*Neglected*
Electricity (kWh)	1.20	5.11	0.69
Transportation (kgkm)	67	86	1.38
Output flows			
Offcuts used for padding (kg)	*1.24*	*1.86*	*3.59*

Appendix C. : Detailed LCI accociated with ecoinvent background processes

Table C.1
LCI of 1 kg of brand-new hot-water bottle cover

Flow	Unit	Value	Background process or elementary flow
Input			Name
Polyester	kg	1	Textile, nonwoven polyester {GLO}| market for textile, nonwoven polyester | Cut-off, U
Output			
Hot-water bottle cover (new)	kg	1	

Table C.2
LCI of 1 kg of brand-new laptop sleeve

Flow	Unit	Value	Background process or elementary flow
Inputs			Name
Polyester	kg	0.52	Textile, nonwoven polyester {GLO}| market for textile, nonwoven polyester | Cut-off, U
Polyurethane (for padding)	kg	0.38	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U
Steel (for zipper)	kg	0.05	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Polyester (for zipper tape)	kg	0.05	Textile, nonwoven polyester {GLO}| market for textile, nonwoven polyester | Cut-off, U
Output			
Laptop sleeve (new)	kg	1	

Table C.3
LCI of 1 kg of brand-new bike bag

Flow	Unit	Value	Background process or elementary flow
Inputs			Name
Polyester	kg	0.48	Textile, nonwoven polyester {GLO}| market for textile, nonwoven polyester | Cut-off, U
Polyurethane (for padding)	kg	0.48	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, U
Polypropylene (for buckles)	kg	0.05	Textile, nonwoven polypropylene {GLO}| market for textile, nonwoven polypropylene | Cut-off, U
Output			
Bike bag (new)	kg	1	

Table C.4
LCI of 1 kg of upcycled hot-water bottle cover

Flow	Unit	Value	Background process or elementary flow
Inputs			Name
Fleece	kg	2.24	*Cut-off*
Sewing thread	kg	< <	*Neglected*
Electricity	kWh	1.20	Electricity, low voltage {LU}| electricity, low voltage, residual mix | Cut-off, U
Transportation	kgkm	67	Transport, freight, lorry 3.5–7.5 metric ton, EURO6 {RER}| market for transport, freight, lorry 3.5–7.5 metric ton, EURO6 | Cut-off, U
Output			
Hot-water bottle cover (upcycled)	kg	1	
Offcuts (for padding)	kg	1.24	*Cut-off*

Table C.5
LCI of 1 kg of upcycled laptop sleeve

Flow	Unit	Value	Background process or elementary flow
Inputs			Name
Winter jacket	kg	2.86	*Cut-off*
Sewing thread	kg	< <	*Neglected*
Electricity	kWh	5.11	Electricity, low voltage {LU}| electricity, low voltage, residual mix | Cut-off, U
Transportation	kgkm	86	Transport, freight, lorry 3.5–7.5 metric ton, EURO6 {RER}| market for transport, freight, lorry 3.5–7.5 metric ton, EURO6 | Cut-off, U
Output			
Laptop sleeve (upcycled)	kg	1	
Offcuts (for padding)	kg	1.86	*Cut-off*

Table C.6
LCI of 1 kg of upcycled bike bag

Flow	Unit	Value	Background process or elementary flow
Inputs			Name
High-visibility work jacket	kg	4.59	*Cut-off*
Sewing thread	kg	< <	*Neglected*
Electricity	kWh	0.69	Electricity, low voltage {LU}| electricity, low voltage, residual mix | Cut-off, U
Transportation	kgkm	138	Transport, freight, lorry 3.5–7.5 metric ton, EURO6 {RER}| market for transport, freight, lorry 3.5–7.5 metric ton, EURO6 | Cut-off, U
Output			
Bike bag (upcycled)	kg	1	
Offcuts (for padding)	kg	3.59	*Cut-off*

Appendix D. : Total emissions (numerical values) of upcycling and brand-new production

Table D.1
Total emissions expressed per FU (1 kg of accessory produced), for each scenario (upcycling and brand-new production) and for each impact category (EF 3.1 method) – numerical representation

Impact category	Unit	Brand-new			Upcycling		
		Cover	Sleeve	Bag	Cover	Sleeve	Bag
Acidification	mol H+ eq	3.25E-02	3.25E-02	3.36E-02	1.88E-03	7.76E-03	1.19E-03
Climate change	kg CO2 eq	6.44E+ 00	6.68E+ 00	6.98E+ 00	5.54E-01	2.24E+ 00	3.75E-01
Climate change - Biogenic	kg CO2 eq	1.39E-02	1.03E-02	9.65E-03	1.74E-04	7.17E-04	1.11E-04
Climate change - Fossil	kg CO2 eq	6.42E+ 00	6.66E+ 00	6.95E+ 00	5.53E-01	2.24E+ 00	3.75E-01
Climate change - Land use and LU change	kg CO2 eq	5.09E-03	1.38E-02	1.63E-02	1.14E-04	4.43E-04	8.74E-05
Ecotoxicity, freshwater	CTUe	3.86E+ 01	1.35E+ 02	1.59E+ 02	1.83E+ 00	7.29E+ 00	1.31E+ 00
Particulate matter	disease inc.	3.89E-07	3.73E-07	3.76E-07	9.71E-09	3.53E-08	8.57E-09
Eutrophication, marine	kg N eq	6.09E-03	6.23E-03	6.46E-03	3.82E-04	1.57E-03	2.45E-04
Eutrophication, freshwater	kg P eq	1.73E-03	1.84E-03	1.91E-03	2.06E-04	8.68E-04	1.23E-04
Eutrophication, terrestrial	mol N eq	7.62E-02	7.37E-02	7.54E-02	3.99E-03	1.64E-02	2.57E-03
Human toxicity, cancer	CTUh	3.27E-08	4.67E-08	3.81E-08	1.21E-09	4.29E-09	1.13E-09
Human toxicity, non-cancer	CTUh	6.13E-08	6.79E-08	7.01E-08	7.66E-09	3.17E-08	4.88E-09
Ionising radiation	kBq U-235 eq	4.03E-01	3.84E-01	3.96E-01	1.09E-01	4.60E-01	6.39E-02
Land use	Pt	3.16E+ 01	2.80E+ 01	2.80E+ 01	2.16E+ 00	8.52E+ 00	1.57E+ 00
Ozone depletion	kg CFC11 eq	1.59E-05	9.18E-06	7.78E-06	1.03E-08	4.15E-08	7.02E-09
Photochemical ozone formation	kg NMVOC eq	3.21E-02	2.96E-02	3.02E-02	1.29E-03	5.11E-03	9.21E-04
Resource use, fossils	MJ	1.13E+ 02	1.11E+ 02	1.16E+ 02	8.49E+ 00	3.46E+ 01	5.67E+ 00
Resource use, minerals and metals	kg Sb eq	5.43E-05	5.95E-05	6.26E-05	5.89E-06	2.46E-05	3.63E-06
Water use	m3 depriv.	1.59E+ 00	1.83E+ 00	1.96E+ 00	6.42E-02	2.67E-01	4.03E-02

Appendix E. : Avoided Carbon emissions and water use by items

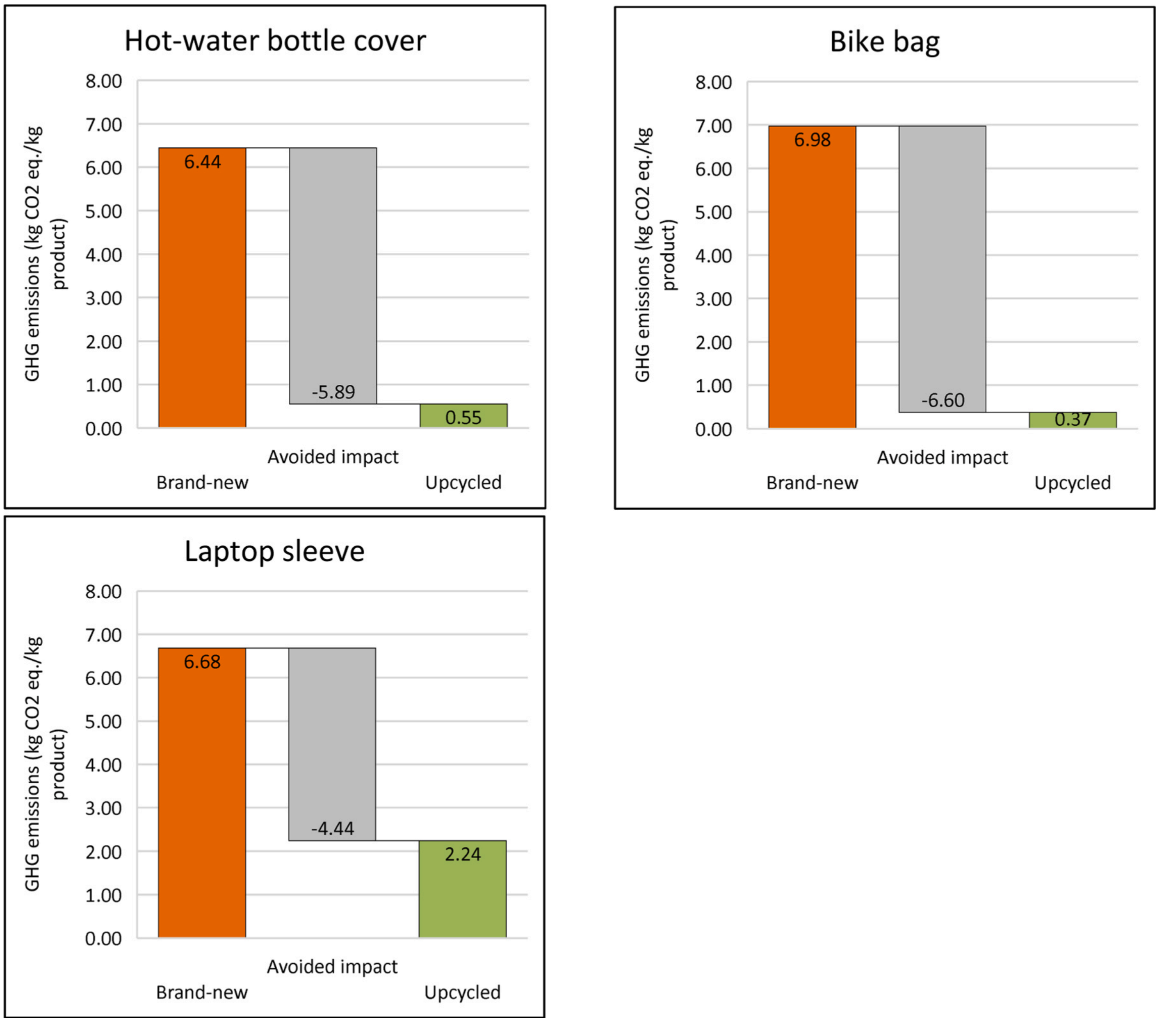

Figure E.1. Avoided GHG emissions (in kg CO2 eq./kg product) of the upcycled production compared to the brand-new production

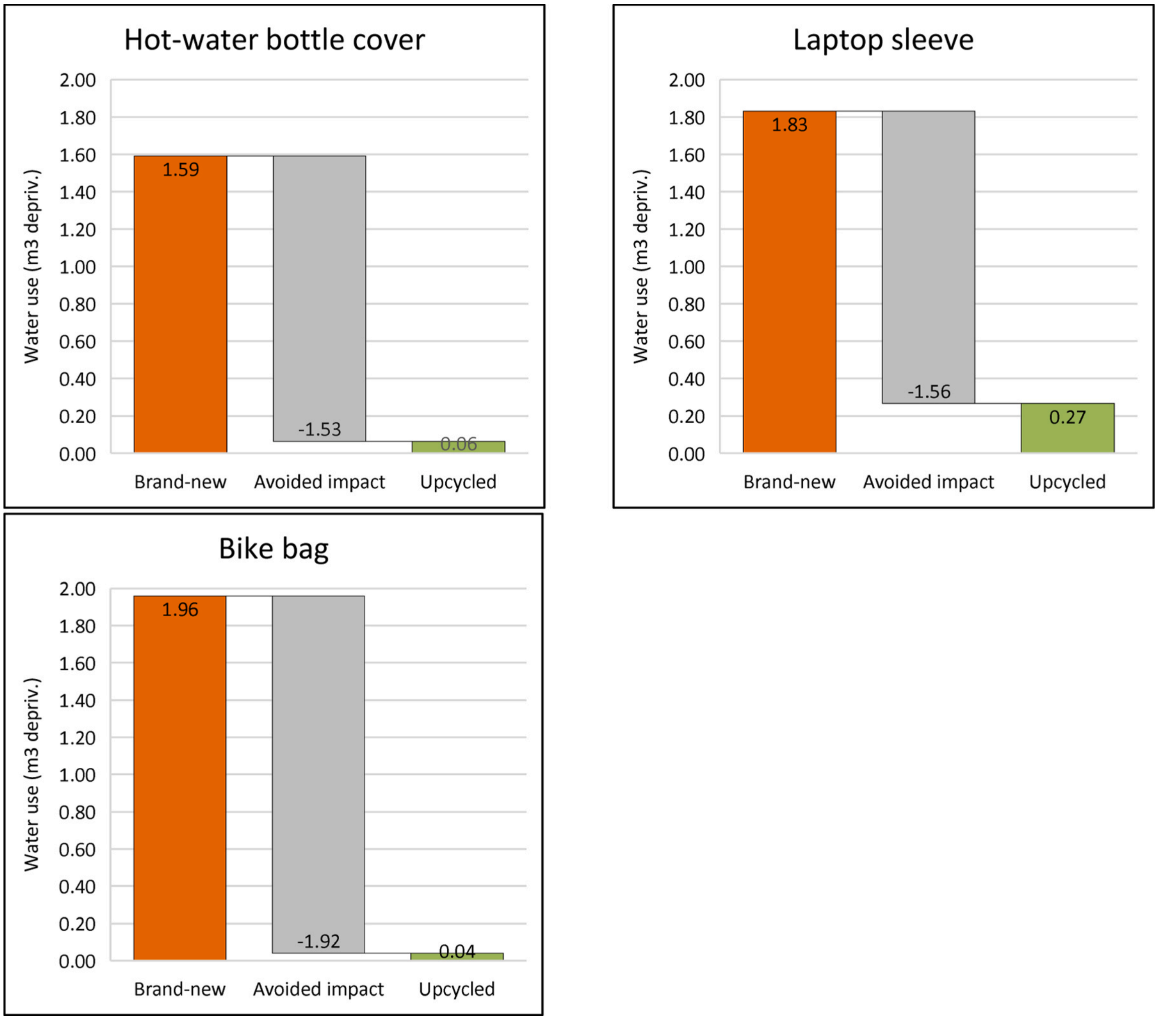

Figure E.2. Avoided water use (in m3/kg product) of the upcycled production compared to the brand-new production

Appendix F. : Sensitivity Analysis

Table F.1
Sensitivity analysis of environmental impacts for the hot-water bottle cover, showing variations in impact results for lifespan reductions between 10% and 80%

Impact categories	Unit	Baseline	Lifespan reduction (%) - Hot-water bottle cover							
			-10%	-20%	-30%	-40%	-50%	-60%	-70%	-80%
Acidification	mol H+ eq	1.88E-03	2.09E-03	2.35E-03	2.68E-03	3.13E-03	3.75E-03	4.69E-03	6.26E-03	9.39E-03
Climate change	kg CO2 eq	5.54E-01	6.15E-01	6.92E-01	7.91E-01	9.23E-01	1.11E+ 00	1.38E+ 00	1.85E+ 00	2.77E+ 00
Climate change - Biogenic	kg CO2 eq	1.74E-04	1.93E-04	2.17E-04	2.48E-04	2.89E-04	3.47E-04	4.34E-04	5.79E-04	8.68E-04
Climate change - Fossil	kg CO2 eq	5.53E-01	6.15E-01	6.92E-01	7.91E-01	9.22E-01	1.11E+ 00	1.38E+ 00	1.84E+ 00	2.77E+ 00
Climate change - Land use and LU change	kg CO2 eq	1.14E-04	1.27E-04	1.43E-04	1.63E-04	1.91E-04	2.29E-04	2.86E-04	3.81E-04	5.72E-04
Ecotoxicity, freshwater	CTUe	1.83E+ 00	2.04E+ 00	2.29E+ 00	2.62E+ 00	3.06E+ 00	3.67E+ 00	4.59E+ 00	6.12E+ 00	9.17E+ 00
Ecotoxicity, freshwater - inorganics	CTUe	1.44E+ 00	1.60E+ 00	1.80E+ 00	2.05E+ 00	2.39E+ 00	2.87E+ 00	3.59E+ 00	4.79E+ 00	7.18E+ 00
Ecotoxicity, freshwater - organics	CTUe	3.98E-01	4.42E-01	4.98E-01	5.69E-01	6.64E-01	7.96E-01	9.95E-01	1.33E+ 00	1.99E+ 00
Particulate matter	disease inc.	9.71E-09	1.08E-08	1.21E-08	1.39E-08	1.62E-08	1.94E-08	2.43E-08	3.24E-08	4.85E-08
Eutrophication, marine	kg N eq	3.82E-04	4.24E-04	4.77E-04	5.45E-04	6.36E-04	7.63E-04	9.54E-04	1.27E-03	1.91E-03
Eutrophication, freshwater	kg P eq	2.06E-04	2.29E-04	2.58E-04	2.94E-04	3.43E-04	4.12E-04	5.15E-04	6.87E-04	1.03E-03
Eutrophication, terrestrial	mol N eq	3.99E-03	4.43E-03	4.99E-03	5.70E-03	6.65E-03	7.98E-03	9.98E-03	1.33E-02	2.00E-02
Human toxicity, cancer	CTUh	1.21E-09	1.35E-09	1.52E-09	1.73E-09	2.02E-09	2.42E-09	3.03E-09	4.04E-09	6.06E-09
Human toxicity, non-cancer	CTUh	7.66E-09	8.52E-09	9.58E-09	1.09E-08	1.28E-08	1.53E-08	1.92E-08	2.55E-08	3.83E-08
Ionising radiation	kBq U-235 eq	1.09E-01	1.21E-01	1.36E-01	1.55E-01	1.81E-01	2.17E-01	2.72E-01	3.62E-01	5.43E-01

(continued on next page)

Table F.1 (*continued*)

Impact categories	Unit	Baseline	Lifespan reduction (%) - Hot-water bottle cover							
			-10%	-20%	-30%	-40%	-50%	-60%	-70%	-80%
Land use	Pt	2.16E+ 00	2.40E+ 00	2.70E+ 00	3.08E+ 00	3.60E+ 00	4.32E+ 00	5.40E+ 00	7.19E+ 00	1.08E+ 01
Ozone depletion	kg CFC11 eq	1.03E-08	1.14E-08	1.28E-08	1.47E-08	1.71E-08	2.05E-08	2.57E-08	3.42E-08	5.14E-08
Photochemical ozone formation	kg NMVOC eq	1.29E-03	1.43E-03	1.61E-03	1.84E-03	2.15E-03	2.57E-03	3.22E-03	4.29E-03	6.44E-03
Resource use, fossils	MJ	8.49E+ 00	9.43E+ 00	1.06E+ 01	1.21E+ 01	1.41E+ 01	1.70E+ 01	2.12E+ 01	2.83E+ 01	4.24E+ 01
Resource use, minerals and metals	kg Sb eq	5.89E-06	6.55E-06	7.37E-06	8.42E-06	9.82E-06	1.18E-05	1.47E-05	1.96E-05	2.95E-05
Water use	m3 depriv.	6.42E-02	7.13E-02	8.02E-02	9.17E-02	1.07E-01	1.28E-01	1.60E-01	2.14E-01	3.21E-01

Table F.2
Sensitivity analysis of environmental impacts for the laptop sleeve, showing variations in impact results for lifespan reductions between 10% and 80%

Impact categories	Unit	Baseline	Lifespan reduction (%) - Laptop sleeve							
			-10%	-20%	-30%	-40%	-50%	-60%	-70%	-80%
Acidification	mol H+ eq	7.76E-03	8.63E-03	9.70E-03	1.11E-02	1.29E-02	1.55E-02	1.94E-02	2.59E-02	3.88E-02
Climate change	kg CO2 eq	2.24E+ 00	2.49E+ 00	2.80E+ 00	3.21E+ 00	3.74E+ 00	4.49E+ 00	5.61E+ 00	7.48E+ 00	1.12E+ 01
Climate change - Biogenic	kg CO2 eq	7.17E-04	7.97E-04	8.96E-04	1.02E-03	1.20E-03	1.43E-03	1.79E-03	2.39E-03	3.59E-03
Climate change - Fossil	kg CO2 eq	2.24E+ 00	2.49E+ 00	2.80E+ 00	3.20E+ 00	3.74E+ 00	4.48E+ 00	5.61E+ 00	7.47E+ 00	1.12E+ 01
Climate change - Land use and LU change	kg CO2 eq	4.43E-04	4.92E-04	5.54E-04	6.33E-04	7.39E-04	8.86E-04	1.11E-03	1.48E-03	2.22E-03
Ecotoxicity, freshwater	CTUe	7.29E+ 00	8.10E+ 00	9.11E+ 00	1.04E+ 01	1.21E+ 01	1.46E+ 01	1.82E+ 01	2.43E+ 01	3.64E+ 01
Ecotoxicity, freshwater - inorganics	CTUe	5.81E+ 00	6.45E+ 00	7.26E+ 00	8.29E+ 00	9.68E+ 00	1.16E+ 01	1.45E+ 01	1.94E+ 01	2.90E+ 01
Ecotoxicity, freshwater - organics	CTUe	1.48E+ 00	1.65E+ 00	1.86E+ 00	2.12E+ 00	2.47E+ 00	2.97E+ 00	3.71E+ 00	4.95E+ 00	7.42E+ 00
Particulate matter	disease inc.	3.53E-08	3.92E-08	4.41E-08	5.04E-08	5.88E-08	7.06E-08	8.83E-08	1.18E-07	1.77E-07
Eutrophication, marine	kg N eq	1.57E-03	1.75E-03	1.97E-03	2.25E-03	2.62E-03	3.15E-03	3.94E-03	5.25E-03	7.87E-03
Eutrophication, freshwater	kg P eq	8.68E-04	9.65E-04	1.09E-03	1.24E-03	1.45E-03	1.74E-03	2.17E-03	2.89E-03	4.34E-03
Eutrophication, terrestrial	mol N eq	1.64E-02	1.83E-02	2.06E-02	2.35E-02	2.74E-02	3.29E-02	4.11E-02	5.48E-02	8.22E-02
Human toxicity, cancer	CTUh	4.29E-09	4.76E-09	5.36E-09	6.13E-09	7.15E-09	8.58E-09	1.07E-08	1.43E-08	2.14E-08
Human toxicity, non-cancer	CTUh	3.17E-08	3.52E-08	3.96E-08	4.53E-08	5.28E-08	6.34E-08	7.92E-08	1.06E-07	1.58E-07
Ionising radiation	kBq U-235 eq	4.60E-01	5.11E-01	5.74E-01	6.56E-01	7.66E-01	9.19E-01	1.15E+ 00	1.53E+ 00	2.30E+ 00
Land use	Pt	8.52E+ 00	9.47E+ 00	1.07E+ 01	1.22E+ 01	1.42E+ 01	1.70E+ 01	2.13E+ 01	2.84E+ 01	4.26E+ 01
Ozone depletion	kg CFC11 eq	4.15E-08	4.61E-08	5.19E-08	5.93E-08	6.91E-08	8.30E-08	1.04E-07	1.38E-07	2.07E-07
Photochemical ozone formation	kg NMVOC eq	5.11E-03	5.68E-03	6.39E-03	7.31E-03	8.52E-03	1.02E-02	1.28E-02	1.70E-02	2.56E-02
Resource use, fossils	MJ	3.46E+ 01	3.84E+ 01	4.32E+ 01	4.94E+ 01	5.76E+ 01	6.91E+ 01	8.64E+ 01	1.15E+ 02	1.73E+ 02
Resource use, minerals and metals	kg Sb eq	2.46E-05	2.73E-05	3.08E-05	3.51E-05	4.10E-05	4.92E-05	6.15E-05	8.20E-05	1.23E-04
Water use	m3 depriv.	2.67E-01	2.96E-01	3.33E-01	3.81E-01	4.44E-01	5.33E-01	6.66E-01	8.89E-01	1.33E+ 00

Table F.3
Sensitivity analysis of environmental impacts for the bike bag, showing variations in impact results for lifespan reductions between 10% and 80%

Impact categories	Unit	Baseline	Lifespan reduction (%) - Bike bag							
			-10%	-20%	-30%	-40%	-50%	-60%	-70%	-80%
Acidification	mol H+ eq	1.19E-03	1.33E-03	1.49E-03	1.71E-03	1.99E-03	2.39E-03	2.98E-03	3.98E-03	5.97E-03
Climate change	kg CO2 eq	3.75E-01	4.17E-01	4.69E-01	5.36E-01	6.25E-01	7.50E-01	9.37E-01	1.25E+ 00	1.87E+ 00
Climate change - Biogenic	kg CO2 eq	1.11E-04	1.23E-04	1.39E-04	1.59E-04	1.85E-04	2.22E-04	2.77E-04	3.70E-04	5.55E-04
Climate change - Fossil	kg CO2 eq	3.75E-01	4.16E-01	4.68E-01	5.35E-01	6.25E-01	7.49E-01	9.37E-01	1.25E+ 00	1.87E+ 00
Climate change - Land use and LU change	kg CO2 eq	8.74E-05	9.71E-05	1.09E-04	1.25E-04	1.46E-04	1.75E-04	2.18E-04	2.91E-04	4.37E-04
Ecotoxicity, freshwater	CTUe	1.31E+ 00	1.46E+ 00	1.64E+ 00	1.88E+ 00	2.19E+ 00	2.63E+ 00	3.29E+ 00	4.38E+ 00	6.57E+ 00
Ecotoxicity, freshwater - inorganics	CTUe	9.81E-01	1.09E+ 00	1.23E+ 00	1.40E+ 00	1.63E+ 00	1.96E+ 00	2.45E+ 00	3.27E+ 00	4.90E+ 00
Ecotoxicity, freshwater - organics	CTUe	3.33E-01	3.70E-01	4.17E-01	4.76E-01	5.56E-01	6.67E-01	8.34E-01	1.11E+ 00	1.67E+ 00
Particulate matter	disease inc.	8.57E-09	9.52E-09	1.07E-08	1.22E-08	1.43E-08	1.71E-08	2.14E-08	2.86E-08	4.28E-08
Eutrophication, marine	kg N eq	2.45E-04	2.72E-04	3.06E-04	3.49E-04	4.08E-04	4.89E-04	6.11E-04	8.15E-04	1.22E-03
Eutrophication, freshwater	kg P eq	1.23E-04	1.37E-04	1.54E-04	1.76E-04	2.05E-04	2.46E-04	3.07E-04	4.10E-04	6.15E-04
Eutrophication, terrestrial	mol N eq	2.57E-03	2.85E-03	3.21E-03	3.66E-03	4.28E-03	5.13E-03	6.41E-03	8.55E-03	1.28E-02
Human toxicity, cancer	CTUh	1.13E-09	1.25E-09	1.41E-09	1.61E-09	1.88E-09	2.26E-09	2.82E-09	3.76E-09	5.65E-09
Human toxicity, non-cancer	CTUh	4.88E-09	5.42E-09	6.09E-09	6.97E-09	8.13E-09	9.75E-09	1.22E-08	1.63E-08	2.44E-08

(*continued on next page*)

Table F.3 (*continued*)

Impact categories	Unit	Baseline	Lifespan reduction (%) - Bike bag							
			-10%	-20%	-30%	-40%	-50%	-60%	-70%	-80%
Ionising radiation	kBq U-235 eq	6.39E-02	7.10E-02	7.99E-02	9.13E-02	1.07E-01	1.28E-01	1.60E-01	2.13E-01	3.20E-01
Land use	Pt	1.57E+ 00	1.74E+ 00	1.96E+ 00	2.24E+ 00	2.62E+ 00	3.14E+ 00	3.93E+ 00	5.23E+ 00	7.85E+ 00
Ozone depletion	kg CFC11 eq	7.02E-09	7.80E-09	8.78E-09	1.00E-08	1.17E-08	1.40E-08	1.76E-08	2.34E-08	3.51E-08
Photochemical ozone formation	kg NMVOC eq	9.21E-04	1.02E-03	1.15E-03	1.32E-03	1.54E-03	1.84E-03	2.30E-03	3.07E-03	4.61E-03
Resource use, fossils	MJ	5.67E+ 00	6.30E+ 00	7.08E+ 00	8.10E+ 00	9.44E+ 00	1.13E+ 01	1.42E+ 01	1.89E+ 01	2.83E+ 01
Resource use, minerals and metals	kg Sb eq	3.63E-06	4.04E-06	4.54E-06	5.19E-06	6.06E-06	7.27E-06	9.08E-06	1.21E-05	1.82E-05
Water use	m3 depriv.	4.03E-02	4.47E-02	5.03E-02	5.75E-02	6.71E-02	8.05E-02	1.01E-01	1.34E-01	2.01E-01

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