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# Strategies to reduce environmental impacts from textiles: Extending clothing wear life compared to fibre displacement assessed using consequential LCA

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ABSTRACT

This study compared two strategies for reducing the environmental consequences of garments: changing fibre types or increasing the number of wears per garment to avoid manufacturing new garments. Scenarios were quantified using multi-indicator consequential life cycle assessment, and sensitivity was determined to test the robustness of the results. Increasing the number of wears per garment resulted in lower impacts across all indicators and fibre types. Conversely, changing fibre types resulted in changes to co-product systems and in trade-offs between environmental impacts, limiting the effectiveness of this strategy to reduce garment environmental impacts. Consistent environmental improvements were achieved by maximising the actual wear life of garments and minimising unnecessary garment purchases, not by changing fibre types. Strategies focused on reducing impacts from textiles and garments should focus on maximising consumer garment use as the highest priority to reduce environmental impact using fibre types and garment designs most suited to long life.

## 1. Introduction

The global trend towards increased per capita production and consumption of apparel, accompanied by reduced utilisation, decreases the sustainability of the clothing industry. Garment manufacture and sales have been decoupled from population growth, resulting in more garments per person and fewer wears per garment lifetime (Niinimäki et al., 2020). Since the early 1980s, the production of synthetic fibres has increased more than six times, a rate 3.6 times that of the global population growth rate. Over the same period, the increase in cotton production has approximately matched population growth (1.0 ×), whereas wool production increased at less than half the rate of population growth (0.4 ×) (Industrievereinigung Chemiefaser e. V. 2020a, b; The World Bank Group 2020). This suggests that a shift in market share towards synthetic fibres and away from natural fibres has occurred in unison with the increased per capita demand for fibre. The use phase, as well as the upstream life cycle phases of fibre production and garment manufacturing, can be hotspots for environmental impacts such as climate change, fossil energy use, water consumption and toxicity. These hotspots include the consumption of water and pesticide emissions associated with cotton production (Chapagain et al., 2006; Cotton Inc. 2016); the release of methane from sheep flocks, via enteric fermentation, in the production of wool (Wiedemann et al., 2020); greenhouse gases (Thomas et al., 2012) and energy use associated with manufacturing and garment laundering (Roos et al., 2015); and the water consumed (Gooijer and Stamminger 2016; Laitala et al., 2017), and nutrients (Levi Strauss and Co. 2015) and microplastic particles (Carney Almroth et al. 2018; Henry et al., 2019; de Falco et al. 2020) emitted during garment wear-wash cycles. For this reason, the increased per capita production of fibre is expected to increase environmental impacts per garment wear across a diverse range of indicators.

Sustainable garment production and consumption require comprehensive knowledge of the practices and policies that reduce pollution, minimise reliance on fossil fuels, and reduce negative impacts on natural

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resources, at each phase of the product life cycle. Such knowledge would support a wide range of global initiatives. For example, awareness of sustainable practices is one of many targets needed to advance sustainable global production and consumption (UNDESA 2020), and the use of the Product Environmental Footprint (PEF) method to revise EU (European Union) Ecolabel criteria for textiles and footwear is anticipated (EC DGE 2020). The Higg Materials Sustainability Index (MSI) (SAC 2017) has been widely used to assess the environmental impacts of material types (Laitala et al., 2018) in various contexts. Its uses include setting industry targets, such as the recommendation that 30% of cotton should be replaced by polyester over the next decade (GFA 2017), as well as informing material impact databases (Textile Exchange 2020), that in-turn inform brands and consumers around sustainable garment production and selection (Sustain Your Style 2020). However, these systems utilise attributional life cycle assessment (aLCA) databases that are, in some instances, supported by non-transparent and limited datasets (Watson and Wiedemann 2019). Further, using aLCA datasets and methodology has been questioned when the purpose is decision-making (Tillman 2010; Plevin et al., 2014; Ekvall 2019) because this analysis methodology does not aim to determine the impact of a change. The Norwegian Consumer Authority recently prohibited using the Higg MSI to communicate environmental claims to consumers because it was misleading (NCPA 2022). This shows that both the environmental impacts and the methods used to assess these impacts are coming under increasing scrutiny. The research community, therefore, has a role to play in using the most appropriate methodological approaches to provide decision makers with the information needed to reduce impacts across garment life cycles.

In earlier work, we used aLCA to assess the full life cycle impacts of a wool sweater (Wiedemann et al., 2020), and have shown the importance of increasing the number of wears per garment life cycle among use phase garment wear and care scenarios to reduce environmental impacts (Wiedemann et al., 2021). Consequential life cycle assessment (cLCA) was then used to show the farm stage impacts of wool may contrast with those obtained using aLCA primarily because cLCA considered the effect of products displaced by wool system co-products (Wiedemann et al., 2018). Similarly, we have used cLCA to show that an expansion or contraction of cotton production may produce effects contrasting with what would be inferred from aLCA because cLCA considered indirect products and processes (Nguyen et al., 2021). The present research used

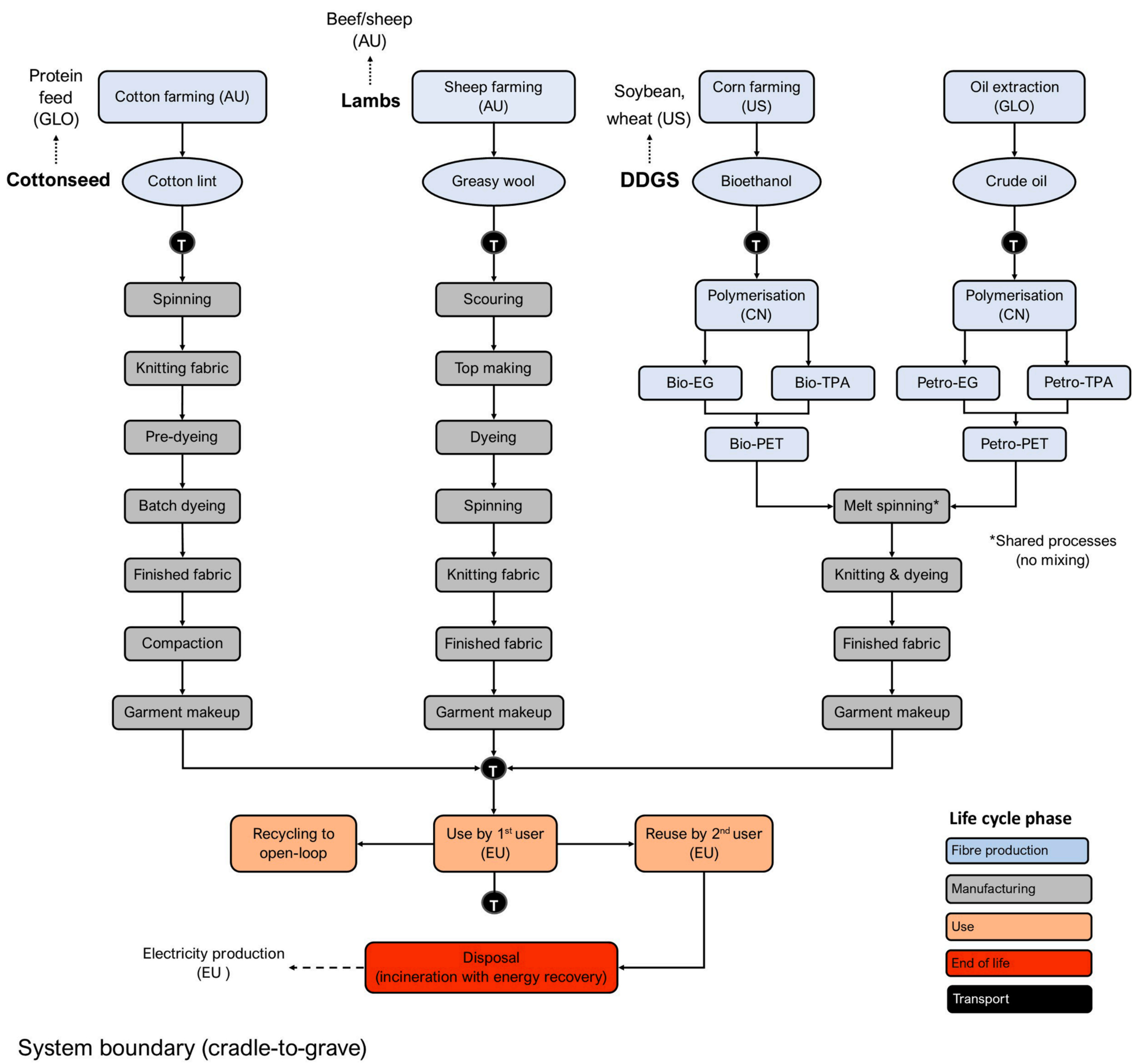


**Fig. 1.** A cradle-to-grave system boundary production of a sweater used in the EU showing major life cycle phases and co-products.

cLCA to explore options to reduce the environmental impact of garments by (1) quantifying the environmental consequences of choosing a sweater made from natural fibres in the form of cotton, wool, or PET from a bio-based feedstock in the EU market rather than a functionally equivalent sweater manufactured from fossil feedstock PET fibres, and (2) by quantifying the environmental impact of increasing the number of wears per garment life cycle to avoid the requirement for new PET garments. This enabled the two approaches to be compared for their ability to reduce impacts.

## 2. Materials and methods

### 2.1. Scope

The study investigated the comparative life cycle environmental impacts of wearing a sweater made from contrasting fibre types (cotton, wool, and bio-based- and petroleum-PET, i.e., bio- and petro-PET). A sweater (synonyms: sweatshirt, jersey, jumper, pullover) is a pullover-style, outer garment, consisting of knitted fabric, that covers the upper part of the body including the arms. A cradle-to-grave system boundary (Fig. 1) was analysed using a cLCA approach consistent with international standards (ISO 2006, 2014). The system consisted of five life cycle phases: (1) fibre production, (2) manufacturing, (3) use, (4) end of life (EoL), and (5) transport. Cotton and wool fibre production occurred in Australia, and PET fibres were synthesised in China, using petroleum available domestically or imported bio-based monomers (e.g., bioethanol and isobutanol) produced from US corn. Manufacturing occurred in major textile areas in China; the garment was then transported to the EU for the use and EoL phases. The functional unit was one wear of a sweater in the EU.

### 2.2. Life cycle impact assessment

The 16 indicators (Supplementary Material, Section 2.1) of the PEF method (European Parliament and Council of the European Union 2022) and an additional indicator in the form of microplastic leakage (Peano et al., 2020) were applied. The cradle-to-grave impacts were characterised results (no PEF normalisation or weighting factors applied). Impacts were determined for (1) a conventional number of wears per garment life cycle, and (2) where the number of wears was extended by 50% greater, thereby substituting the requirement to manufacture and wear a polyester garment for the equivalent number of wears (Supplementary Material, Section 2). Sensitivity analyses were conducted on key parameters across all life cycle phases (Supplementary Material, Section 3).

### 2.3. Life cycle inventory

The foreground consequential life cycle inventory (cLCI) included primary data collected from industry (as part of previous research), and secondary data from relevant literature (e.g., textile manufacturing for cotton and synthetic sweaters, and the use and EoL phases of garments). The key inventory data and their sources are summarised in the Supplementary Material. The background cLCI for upstream processes such as electricity supply, fertilisers and chemicals production and associated transportation of these resources were sourced from the ecoinvent "consequential" database v3.6 (Wernet et al., 2016).

For natural fibre production, cLCI data were used for the contraction of Australian cotton fibre (Nguyen et al., 2021) and Merino wool (Wiedemann et al., 2018). Australian cotton production was considered a marginal cotton supplier because production is highly mechanised (like other major exporters, the United States and Brazil), and expected to be sensitive to major changes in the global market for cotton (Sabala and Devadoss 2021). Similarly, Australian sheep flocks were considered to be a marginal source of wool because the country is a major supplier (FAO 2022) whose production is sensitive to the price of related apparel fibres. For synthetic fibre production, bioethanol from US corn was assumed to be the primary feedstock to produce bio-based PET fibre (Mohanty and Swain 2019).

Manufacturing LCI data included processes from the production of yarn from natural fibres (e.g., cotton lint and greasy wool) or synthetic PET pellets, to fabric production, garment makeup and warehouse storage of the finished garment in China. It was assumed that major textile manufacturers located in Guangdong and Shandong were representative of the average Chinese textile industry (Wang et al., 2015).

Foreground data to develop an inventory for the laundering and wear of sweater garments by EU consumers were obtained from an industry survey and the literature. ecoinvent v3.6 background data for Europe (excluding Switzerland) for consequential processes was used to represent use phase electricity (low voltage) and water consumption.

The length of the use phase ($U$, in wears) was defined as the total number of times a garment was worn by a first ($L_1$) (Table 1) and subsequent ($L_2$) user, with 50% less wears for $L_2$ (Wiedemann et al., 2020):

$$U = L_1 + (L_2 \times R_r) \tag{1}$$

After use by the first user, garments were redistributed to either reuse, recycling or disposal (as textile waste) pathways. For the wool sweater, inventory data from Wiedemann et al. (2020) was used, while for cotton and polyester garments, survey data were used. Garments sold second hand, donated to charity and/or family/friends comprised the second life, defining the reuse rate. Garment recycling at home (e.g., cleaning cloths) was considered open-loop recycling. Garment waste was considered the portion of garments placed in the rubbish bin at home.

Sweaters disposed of as municipal waste were assumed to be incinerated for energy recovery, which was the dominant and marginal pathway for the treatment of municipal waste including textile waste in EU between 2010 and 2016 (Eurostat, 2020). The incineration efficiency was assumed to be 30%, which is within the range of a previous report (Astrup et al., 2015). The total energy recovery was based on the energy embedded in the products and was apportioned to electricity generation.

### 2.4. Handling co-products

Co-products were identified throughout all production stages and were handled using system expansion for major co-products (ISO 2006). Briefly, cottonseed and sheep meat were the most valuable co-products for the fibre production of cotton and wool, respectively (Wiedemann et al., 2018; Nguyen et al., 2021). For bio-PET, distillers' dried grains with solubles (DDGS), which was co-produced at a biorefinery during the production of bioethanol and isobutanol, were the most valuable product (Wang et al., 2011; US Grains Council 2012). Other less-valuable co-products in manufacturing, such as tip yarn and fibre waste, were treated as waste sent to municipal waste systems (e.g., landfill).

### 2.5. Market effects

The most important market effects occurred in the fibre production and use phases. At the fibre production stage within Australia, demand-driven decreases in the production of cotton fibre resulted in the expansion of regional crops (Nguyen et al., 2021), and decreased Merino wool production was replaced by red meat production (Wiedemann et al., 2018). Decreased demand for bio-PET was replaced by other regional crops: for example, in the US, corn contraction was replaced by wheat and soybean production (Wallander et al., 2011; Lark et al., 2015). At the global scale, the increased production of regional crops reduced production elsewhere to maintain the global supply: demand ratio. Similar market effects were identified in the global market for major co-products of cotton (Nguyen et al., 2021), Merino wool (Wiedemann et al., 2018) and bio-based PET (Wang et al., 2012; Muñoz et al., 2014). Market effects associated with bio-PET fibre production are

**Table 1**
Key inventory data for the use phase and EoL of sweaters in the EU.

| Parameter | Unit | Cotton | Polyester | Wool | Reference |
|---|---|---|---|---|---|
| Washing | | | | | |
| Washed, machine | % | 90.0 | 94.0 | 59.0 | Survey data |
| Washed, hand | % | 8.0 | 3.5 | 33.0 | Survey data |
| Washed, dry clean | % | 2.0 | 2.4 | 8.0 | Survey data |
| Washing machine load | kg | 5.9 | 2.6 | 1.6 | Laitala and Vereide (2010) |
| Water per machine load | L | 51.0 | 46.0 | 43.0 | Laitala and Vereide (2010) |
| Water, handwash per kg washed | L | 12.8 | 12.8 | 12.8 | Wiedemann et al. (2020) |
| Liquid detergent, per kg washed | kg | 0.024 | 0.024 | 0.019 | Laitala et al. (2017) |
| Powder detergent, per kg washed | kg | 0.023 | 0.023 | 0.023 | Laitala et al. (2017) |
| Washing temperature | °C | 60.0 | 44.1 | 30.3 | Laitala et al. (2018) |
| Energy, machine wash | kWh/kg | 0.185 | 0.177 | 0.138 | Laitala and Vereide (2010) |
| Energy, hand wash | kWh/kg | 0.36 | 0.36 | 0.41 | Energy Saving Trust (2013) |
| Energy, dry cleaning | kWh/kg | 0.59 | 0.59 | 0.59 | Troynikov et al. (2016) |
| Microplastics, machine wash | mg/kg | 0 | 46 | 0 | Peano et al. (2020). |
| Drying and ironing | | | | | |
| Dried, tumble drier | % | 12.4 | 12.4 | 0.0 | Derived from Laitala et al. (2017) |
| Dried, heated house | % | 36.0 | 36.0 | 41.1 | Derived from Laitala et al. (2017) |
| Dried, unheated house | % | 13.1 | 13.1 | 14.9 | Derived from Laitala et al. (2017) |
| Dried, line | % | 38.5 | 38.5 | 44.0 | Derived from Laitala et al. (2017) |
| Energy, drying heated house | kWh/kg | 0.81 | 0.10 | 0.37 | Laitala et al. (2017a) |
| Energy, drying machine | kWh/kg | 0.59 | 0.59 | 0.59 | Schmitz and Stamminger (2014) |
| Garment use | | | | | |
| Garment weight | g | 350 | 340 | 300 | This study |
| Wears 1st user ($L_1$) | wears | 85.5 | 79.5 | 78.0 | Survey data |
| Total wear lifetime ($U$) | wears | 121 | 109 | 108 | |
| Reuse rate ($R_r$) | % | 82.3 | 73.9 | 74.7 | Survey data |
| Days wear per wash | days | 3.7 | 4.4 | 5.2 | Laitala et al. (2018) |
| Total wash lifetime | washes | 33 | 25 | 21 | Calculated from survey data |
| End of Life (EoL) | | | | | |
| Open-loop recycling | % | 19.1 | 21.8 | 14.2 | Survey data (home use) |
| Closed-loop recycling | % | 0 | 0 | 5 | Wool - Wiedemann et al. (2022) |
| Municipal waste | % | 80.9 | 78.2 | 80.8 | Survey data (less closed-loop) |

summarised elsewhere (Supplementary Material, Section 1.3). At the use phase, wears were considered equivalent across all garment types (i.e., independent of fibre or newness).

### 2.6. Calculating consequential impacts

Impacts were calculated for the consequence of switching fibre from a natural fibre to PET ($I_{PET_{1.0}-x_{1.0}}$), both worn for a standard fibre-specific number of wears per garment lifetime:

$$I_{PET_{1.0}-x_{1.0}} = I_{PET_{1.0}} - I_{x_{1.0}} \tag{2}$$

Where $I_{PET_{1.0}}$ and $I_{x_{1.0}}$ are the full life cycle impact of a PET sweater and natural fibre sweater, respectively.

Impacts were also calculated for the consequence of extending the number of wears per garment lifetime by 50%, thereby substituting the requirement to manufacture and wear a polyester garment for the equivalent number of wears. The impact of the extended wears was calculated using the following formula:

$$I_{x_{1.5}-PET_{new}} = I_{x_{1.5_u}} - \frac{\left(U_{x_{1.5}} - U_{PET_{1.0}}\right)}{U_{PET_{1.0}}} . I_{PET_u} - \left(I_{PET_f} + I_{PET_m} + I_{PET_t} + I_{PET_e}\right) \tag{3}$$

Where $I_{x_{1.5}-PET_{new}}$ is the difference between the impact of wearing sweater of fibre type $x$ 50% more times than its standard fibre-specific lifetime (including first and second users) (i.e., $I_{x_{1.5}}$) and the impact of the wearing a new PET sweater (subscript *PET*) a number of times equivalent to the number of additional wears achieved for sweater $x$, plus the impacts upstream and downstream of the use phase for the new PET sweater. Subscripts *f, m, t*, u and *e* refer to the fibre production, manufacturing, transport, use and EoL phases, respectively. Parameter $U$ refers to the number of wears. Subscripts 1.5 and 1.0 refer to extended wears (by 50%) and a standard number of wears, respectively. The approach is shown schematically in Fig. 2.

## 3. Results and discussion

### 3.1. Reducing environmental impacts via extended garment use

The results showed increased wears per garment life had consistent benefits across all fibre types and indicators (Fig. 3, right). For example, the climate change impacts of all natural fibres were negative if the number of wears was increased by 50%: that is, greenhouse gas emissions would be avoided entirely primarily because emissions associated with the manufacture of a new petro-PET garment were averted. These results were consistent with research showing extending garment lifetime reduces full life cycle impacts (Levi Strauss and Co. 2015; Roos et al., 2017; Moazzem et al., 2018; Wiedemann et al., 2020; Monticelli and Costamagna 2022; Mölsä et al., 2022). In contrast, a change in fibre type not only involved trade-offs (as discussed below) but also induced changes in a large number of allied production systems (e.g., rice and meat for human consumption, as well as products that have multiple uses, such as soy and vegetable oil). The use of cLCA to evaluate the importance of indirect effects is a strength of this methodological approach (Styles et al., 2018; Schaubroeck 2022; Brandão 2022). This primary finding reduces confidence in the ability of a change in fibre type to achieve change in the desired direction and amount required to reduce the impact of garments.

While carefully considered design and the use of quality materials is necessary to enable garment physical durability, longevity is also determined by the quality of fit and perceived value (Laitala and Klepp 2020). These attributes can be aided by the ability of the consumer to use and care for garments competently (Fletcher 2017), such as airing wool garments (Laitala et al., 2017; Piippo et al., 2022), and using targeted detergents (Mukhtar Abdul-Bari et al. 2020) to reduce odours. Similarly, increased satisfaction may come from the utilisation of more timeless designs (Mont 2008). The implication is that increasing the number of wears per garment life is not only highly effective at reducing environmental impacts, but it is also a feasible practice that can be modified by targeting both product durability and intrinsic value (Laitala and Klepp 2020).

Increasing the number of wears per garment life would be a simple strategy to reduce the environmental impacts of garment demand, with relatively straightforward effects. If the increased wears displaced the same number of wears of a petro-PET garment, the benefits were typically greatest in those impact categories for which petro-PET had the greatest impacts (i.e., those causally linked to energy consumption)

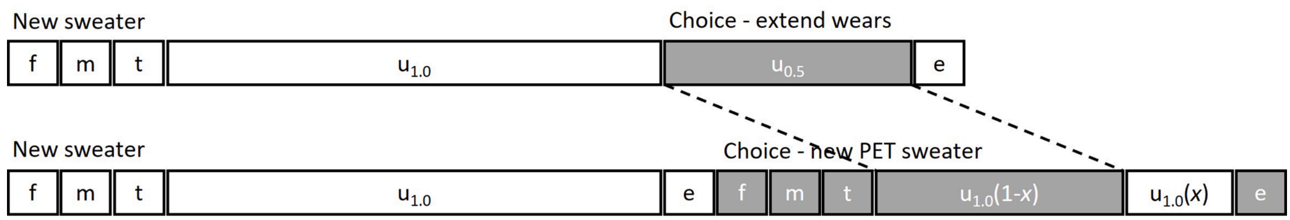


**Fig. 2.** Schematic representation of how the impact of choosing to wear a sweater 50% longer versus using a new PET sweater was modelled using cLCA. Boxes shaded grey were modelled to assess impacts, those shaded white were not. The dashed lines emphasise that the number of wears were equivalent across the two choices. Subscripts f, m, t, u and e refer to the fibre production, manufacturing, transport, use and end of life phases, respectively. The length of the u boxes is proportional to the number of wears. Subscripts 1.0 and 0.5 refer to a standard and an additional 50% of wears, respectively. Parameter x represents the proportion of the standard number of wears for a PET sweater remaining after it has been worn a number of times equivalent to the number of wears achieved by extending garment life 50%.

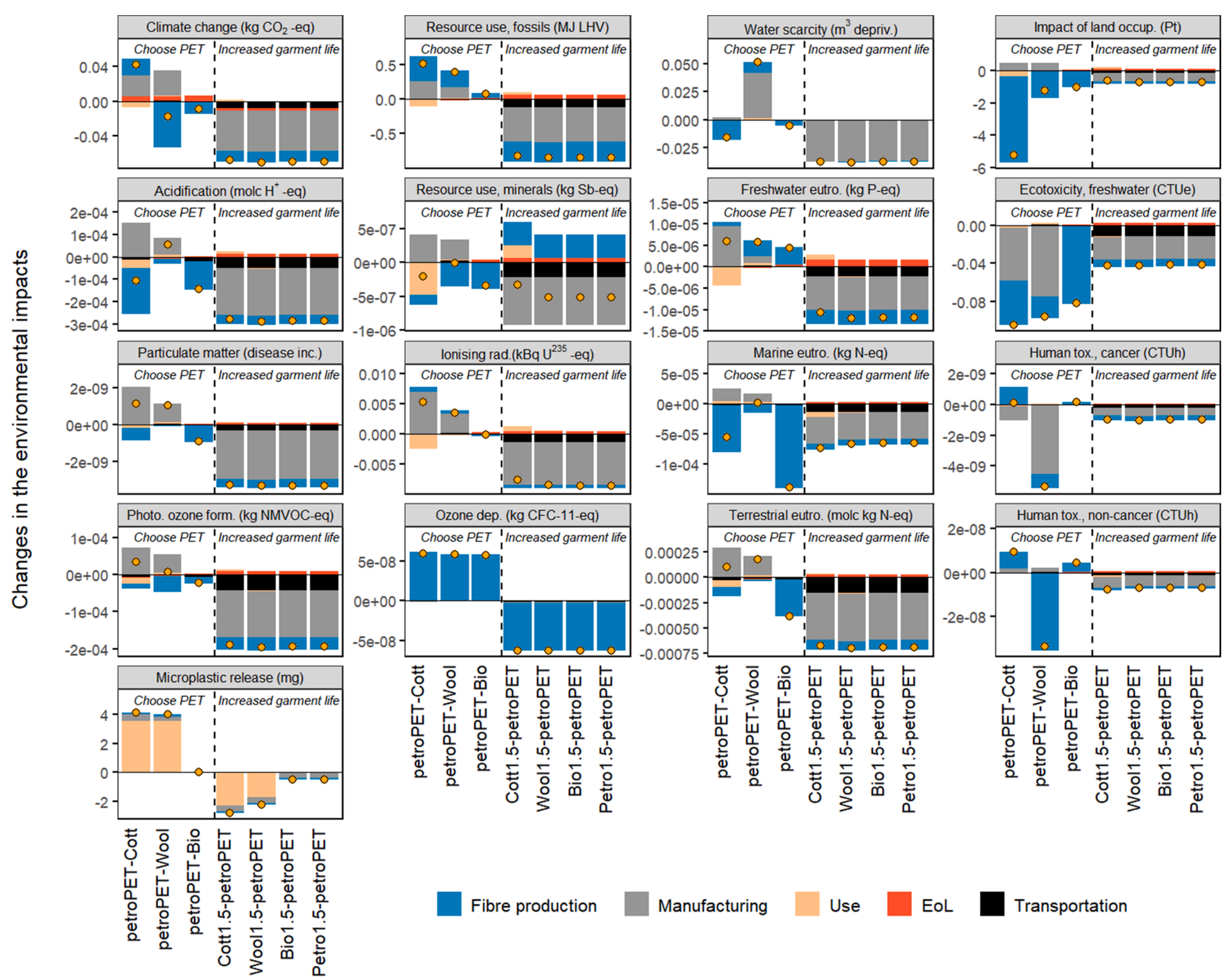


**Fig. 3.** Net impacts of choosing petro-PET over natural fibres for garments (fibre choice, left) or increasing active garment lifespan by 50% (and avoiding the production and wear of a PET sweater, right) across a set of 17 environmental indicators.

(Fig. 3). An important exception here was microplastic pollution, which remained high for PET garments throughout the extended wears period, confirming concerns raised elsewhere (Cobbing and Vicaire 2017). Increasing the number of wears per garment life, therefore, has the potential to mitigate some of the major impacts resulting from the increased per capita demand for garments and the shift in market share towards synthetic and away from natural fibres. This effect was more consistent than a switch between fibre types and, given the insensitivity of the trend to fibre type, is likely to be applicable in alternative systems (e.g., feedstocks, energy efficiency, EoL scenarios).

### 3.2. *Fibre choice involves trade-offs between impact categories*

The cLCA results showed no fibre choice minimised impacts across all indicators (Fig. 3, left). This contrasts with conclusions drawn using the more common aLCA approach. The aLCA approach is used in most sustainability indicators and rating schemes in the fashion industry to advocate for comparing garments on the fibre and material level, such as

Higg MSI and PEF. For example, the suggestion that 30% of cotton should be replaced by PET over the next decade (GFA 2017) to reduce environmental impacts, based on aLCA, would result in a smaller saving in water than expected, and at the expense of climate change, fossil fuel and micro-plastic pollution impacts (Fig. 3). If the perceived high 'material intensity' of wool (Kering 2022) were to reduce demand for this fibre, climate change and toxicity impacts would be avoided at the expense of resource use – fossil fuels, eutrophication (freshwater and terrestrial), water and microplastic impacts (Fig. 3). Obscuring trade-offs is an outcome of relying on a single score or single indicators, so contrasts between the present research and the above-cited fibre impact assessments were anticipated. Other reasons for the contrasts include the use of different system boundaries (cradle to factory gate for the Higg MSI), different impact categories and inventory data. Our study, which is relatively exhaustive in terms of the diversity of indicators and life cycle phases included, clearly shows that preferencing one fibre type over another requires a compromise between decreased impacts in one or more impact categories and increases in others.

Similar trade-offs existed for the choice of PET feedstock (i.e., petro- or bio-based), but there were few impact categories for which bio-PET showed lower environmental impacts (i.e., freshwater eutrophication, resource use – fossil fuels, ozone depletion and human non-cancer toxicity) (Fig. 3). With few exceptions (e.g., climate change EoL impacts), these contrasts were driven by increased fibre production impacts for bio-PET. Thus, we observed that initiating the life cycle of a PET garment with a biological system (i.e., agronomic production of biomass) rather than extracting fossil reserves (whose availability is due to the diagenesis of ancient biomass over millions of years), generally increased environmental impacts, rather than decreasing impacts. This is problematic, because use of fossil fuels can't be sustained indefinitely, and alternative approaches are needed.

In general, alternatives to petro-PET fibres showed higher impacts in categories for which the fibre production life cycle phase was the hotspot (Fig. 3). The clearest examples of this trend were marine eutrophication and the impact of land occupation, but other examples included water scarcity, acidification, terrestrial eutrophication and human non-cancer toxicity. The contrasts tended to be stronger for cotton than for wool because cotton production (as well as other crops that may expand in response to a decrease in cotton production) generally required more inputs (e.g., irrigation, fertiliser, pesticides). These observations are part of an overall trend whereby natural fibres tended to show higher impacts in categories that are 'land-based' and lower impacts from fossil energy and industrial process related impact categories. Land-based impact categories are those whose impact is sensitive to inventory items that are frequently rate-limiting inputs for primary production (i.e., water, nitrogen and phosphorous) or inversely proportional to yield (i.e., land occupation). There were exceptions to this generalisation. For example, petro-PET fibres had larger freshwater eutrophication impacts than natural fibres or bio-PET (Fig. 3) due to apparent large phosphorous emissions associated with petro-PET fibre production in the processes used, though this warrants further investigation. Conversely, petro- and bio-PET fibres showed large microplastic emissions and higher impacts in categories closely related to fossil energy consumption (particulate matter, photochemical ozone formation, ionising radiation) because the production of PET pellets and the dyeing processes were energy-intensive. The most obvious example of this was resource use (fossil fuels), and to a lesser degree, climate change (because sheep flock enteric methane emissions increased fibre production impacts for wool) (Fig. 3). The implication is that the set of impact categories chosen to assess the life cycle of a garment has the potential to bias the overall perception of fibre impacts. An indicator set with more land-based or less energy-based impact categories is likely to disadvantage natural fibres, and the converse may be true for synthetic fibres.

### 3.3. Hotspots when extending wears per garment

When increased garment life avoided the production of a new sweater made of petro-PET fibres, the hotspot was typically avoided material production and manufacturing impacts (Fig. 3, right). The petro-PET fibre production was a hotspot for ozone depletion, so increasing the number of wears rather than producing a new petro-PET sweater was effective at reducing this impact. Fibre production became a hotspot for resource use – minerals and metals impacts when garment lifespan was increased because the avoided production of purified terephthalic acid (PTA) needs to be replaced by other substitute product, however the magnitude of the scale of this increased impact was negligible. Increasing the number of wears for cotton or wool sweaters was effective at avoiding use phase microplastic emissions – this was the one exception to the generality whereby choosing to increase the number of wears per garment did not create use phase, end of life or transport (avoided) hotspots. Overall, the large, avoided material production and manufacturing impacts of increased wears per garment were sufficient that this treatment avoided impacts in net terms across all indicators (Fig. 3).

### 3.4. Further considerations

Sensitivity analyses were used to test the robustness of results (Supplementary material, Section 3). A major concern was the lack of publicly available data for PET textile manufacturing – the primary reference (van der Velden et al. 2014) is somewhat dated, especially because the industry has a recent history of increasing energy efficiency (Peters et al., 2021; Zhang et al., 2022). Energy-efficient PET manufacturing inventory data reduced impacts by ~20% for indicators closely linked to fossil energy use (climate change, particulate matter, ionising radiation, photochemical ozone formation). Similarly for the natural fibres, land-based and some toxicity indicators were sensitive to the choice of crop and source region (for cotton and bio-PET) and or system displaced by co-products (e.g., lamb displacing beef). The implication is that contrasting results will be obtained when systems of contrasting technology (e.g., products displaced), geography (especially for renewable raw materials) or timing (e.g., capturing recent trends in the decarbonising of grid electricity) are modelled, making the results presented here indicative rather than definitive. However, none of the changes invoked by the sensitivity analyses had an effect as pronounced or consistent as increasing the number of wears per garment life cycle by 50%.

In addition to concerns regarding the robustness of inventory data and sensitivity to assumptions, it is possible that the characterisation models behind the PEF indicators may not be appropriate to the systems being investigated. For example, the acidification and eutrophication characterisation factors are based on European models of emissions and transport (Seppälä et al., 2006; Posch et al., 2008; Struijs et al., 2010) that may be inappropriate in landscapes such as Australia characterised by relatively low population densities, low-input agriculture, low and variable rainfall, and distinct fluvial environments. For some indicators, country-scale characterisation factors exist but only for EU nations (acidification and terrestrial eutrophication). In contrast, for others, country-scale characterisation factors are grossly incapable of reflecting attributes that may change at spatial scales many orders of magnitude lower, such as the soil properties that underlie the LANCA impact of the land occupation method (Bos et al., 2020); these factors may have resulted in over-estimates of the environmental impact of natural fibres in this study. An additional problem common to land use inventories is that intensification (e.g., high stocking rates) would reduce apparent impacts but be an unsustainable practice (Wiedemann et al., 2020) – consequently, the LANCA indicator may not drive practice change in a desirable direction. For the AWARE water scarcity method, the human water consumption that underlies the characterisation factors is based on irrigation data that is up to 15 years old (Schmied et al., 2014;

Bontinck et al., 2021), and the livestock water consumption is based on animals per unit area, but the data source is not clear (Flörke et al., 2013), and there are concerns that the technique inaccurately models the role of responsible, regulated water management (Simmons et al., 2022). There are, therefore, concerns regarding the ability of the underlying model to reflect agricultural practices now and in the future. The implication is that for some indicators, there will be a need to refine the study results as the models become more globally applicable, and as the archetypes and spatial resolution of characterisation factors become more relevant.

### 3.5. Limitations

The main limitation of this study was the limited amount of high-quality primary data on consumer use habits throughout the lifetime of the garment and their disposal preferences at the garments' end-of-life. Despite utilising data from a major survey across Europe in this study, the authors acknowledge that garment use habits could vary substantially across different demographics from different geographical, cultural, and socioeconomical backgrounds. Nonetheless, the authors believe that this study is representative of the norm typical in a 'fast fashion' world, where trendiness, affordability, and convenience are highly prioritised over the preservation of garments. This limitation can also be seen as a requirement for further research. As outlined in this study, changing garment wear life is effective in reducing environmental impact, and more information is needed on the factors that govern and promote longer wear life.

There are also inherent limitations to the fundamentals of the background datasets obtained from LCA database packages. While the natural fibre cLCA datasets were based on primary data, this limitation was evident in the PET datasets. There were processes in the production of PTA that caused PET to have a net negative minerals and metals resource use in the consequential model. However, these datasets were obtained from non-transparent database processes, preventing examination of these processes for accuracy. This highlights a need for further research to provide more robust cLCA datasets for petro-PET and bio-PET.

While the focus of this study was contraction of cotton and wool, alternative scenarios could be examined that resulted in increased demand for cotton or wool. This would require an examination of expansion scenarios which may yield a different outcome. This presents opportunities for further studies.

## 4. Conclusions

Increased wears per garment life had consistent benefits across all fibre types and indicators. The implication is that increasing the number of wears per garment life would be a simple and straightforward strategy to reduce the environmental impacts of garment demand. In contrast, the results showed no fibre choice minimised impacts across all environmental impacts. That is, fibre choice required a compromise between decreased impacts in one or more impact categories and increases in others. Unlike increased wears per garment life, a change in fibre type was also sensitive to the choice of indicator, whereby impacts from natural fibres were high for land related indicators and impacts associated with fossil fuel were high for synthetic fibres, respectively. By maximising the number of wears, and minimising unnecessary purchases, designers, manufacturers, retailers and consumers can work to consistently reduce the environmental impacts of garment life cycles and this should be a key focus of efforts to reduce the environmental impacts from garments.

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## Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

## CRediT authorship contribution statement

**Stephen G. Wiedemann:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Simon J. Clarke:** Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Quan V. Nguyen:** Methodology, Software, Formal analysis, Data curation, Writing – review & editing, Visualization. **Zhong Xiang Cheah:** Formal analysis, Data curation, Writing – review & editing, Visualization. **Aaron T. Simmons:** Methodology, Writing – review & editing.

## Declaration of Competing Interest

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

## Data availability

The data that has been used is confidential.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107119.

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