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Using LCA and Circularity Indicators to Measure the Sustainability of Textiles—Examples of Renewable and Non-Renewable Fibres

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Abstract: Reducing environmental impacts by increasing circularity is highly relevant to the textiles sector. Here, we examine results from life cycle assessment (LCA) and circularity indicators applied to renewable and non-renewable fibres to evaluate the synergies between the two approaches for improving sustainability assessment of textiles. Using LCA, impacts were quantified for sweaters made from fossil feedstock-derived and bio-based PET. These same sweaters were scored using four circularity indicators. Both sweaters showed similar fossil energy footprints, but the bio-PET raw material acquisition stage greenhouse gas, water and land occupation impacts were 1.9 to 60 times higher, leading to higher full life cycle impacts. These contrasts were principally determined by what raw material acquisition processes were considered outside the system boundary of the alternative feedstocks. Using circularity indicators, fossil-feedstock PET scored lowest (worst) because the feedstock was from a non-renewable source. These examples highlight the limitations of LCA: the renewability or non-renewability of raw materials is not fully considered, and contrasts in processes included within system boundaries can preclude equitable comparisons. For LCA to be suitable for quantifying sustainability, it should be complemented by circularity indicators capable of demonstrating the contrast between renewable and non-renewable raw materials, particularly in the case of textiles.

Keywords: apparel; bio-based; circular; fiber; footprint; synthetic; system boundary; PEF; textiles

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1. Introduction

A sustainable textile industry requires a supply of environmentally sustainable raw materials [1]. There has been growing interest in assessing and comparing textiles to determine the most sustainable fabrics and to enable a reduction in the overall environmental impacts from the textile industry [2–5]. Equitable comparisons are theoretically possible if all influencing factors can be assessed, and the most common method for making these comparisons is life cycle assessment (LCA). However, textiles from renewable and non-renewable raw materials capture fundamentally different processes within their system boundary. The assessment of renewable, natural fibres (e.g., wool, cotton) includes all impacts for the process of monomer production (i.e., the plant and animal processes involved and the agricultural system required to support these) [6,7]. By contrast, fossil feedstock-derived fibres do not include the biological processes required to generate the monomers used for textile production on account of these processes having occurred hundreds of millions of years ago. The life cycle of these fibres originated with fossil feedstock extraction [8], resulting in non-renewable raw materials having potentially lower impacts during raw material acquisition compared to renewable raw materials. The comparison of renewable and non-renewable fibres in LCA creates a conflict with international standards which state that 'systems shall be compared using the same … methodological considerations, such as ... system boundary ... ' [9] (p. 11). Furthermore, comparative assertions intended to be disclosed to the public require a 'description of the equivalence of the systems being compared' [9] (p. 30). In the European Union Product Environmental Footprint (PEF) scheme [10], the apparel and footwear category rules (PEFCR) [11] will be the first to compare products made from renewable and non-renewable raw materials. However, if LCA results (such as a PEF study) are reduced to a single score or simple label, there will be no way to convey such caveats.

Recently, the concept of circularity has received increasing attention from governments, the research community, companies and citizens [12]. The aim of circularity is to maintain the value of resources, products and materials in the economy for as long as possible and to minimise waste generation, thereby contributing to more sustainable, low carbon, resource-efficient and competitive economies [13]. Accordingly, anticipated environmental benefits of a circular textile industry include reduced use of virgin materials and the impacts associated with their production and reduced incineration/landfill emissions, resulting in reduced greenhouse gas (GHG) emissions via an increased number of wears per garment life [14–16]. Despite the emphasis on material recycling, a supply of virgin material inputs will continue to be needed in a circular economy [14]. Where renewable material inputs are used, there is a strong preference for regenerative, verifiably sustainable fibre production systems [17–20]. Conversely, reliance on virgin non-renewable material inputs is widely recognised as a major impediment to the sustainability of the fashion industry [14,20,21]. Within the PEF scheme, the circular footprint formula (CFF) is used to assign credits for recycling, the use of recyclate and energy recovery. This is a narrow conceptualisation of circularity focused on material fates. Duration of service (e.g., wears per garment life) is an important aspect of circularity that is captured elsewhere in a PEF study, but material attributes such as raw material renewability are not.

Circularity accreditation schemes often include requirements beyond slowing and closing material loops. Examples of these additional requirements include regenerative or organic certification for feedstocks from agricultural systems, phasing out toxic substances such as dyes [14,20,22], and phasing out polyester due to its emission of plastic microfibres [14,20]. There is also a strong push towards the use of renewable energy supplies [14,20]. These goals are well aligned with EU Green Deal strategies [23]. Implicit in these additional requirements is an acknowledgement that, in isolation, the recycling of raw materials is not sufficient for minimising the environmental impacts of product life cycles. By systematically quantifying the full life cycle impacts of a garment, from cradle to grave, LCA is well suited to identifying the environmental consequences of increasing material and product longevity as well as these additional requirements. This role of LCA increases the importance of carefully considering the implications of what processes are captured within a system boundary when LCA compares renewable and non-renewable material inputs, such as fibres derived from non-renewable (i.e., fossil) and renewable (e.g., from biological processes) feedstocks.

We hypothesise that LCA and circularity indicators are complementary tools because they are both concerned with assessing environmental impacts, with the former being concerned with reducing unsustainability, and the latter being concerned with a sustainable society [24,25]. To be sustainable, this society should avoid the accumulation of extracted substances in the lithosphere, avoid substances produced in the technosphere accumulating in the ecosphere, and avoid anthropogenic activities that impair the function of the ecosphere, and be accompanied by the efficient allocation of resources within and between societies [26]. Thus, where the raw material needs of a circular economy cannot be met by recycling, there should be a strong preference for renewable over non-renewable virgin raw materials. Here, we test the hypothesis that LCA and circularity indicators can deliver complementary sustainability assessments of a product life cycle using a pair of sweater (synonyms: pullover, jumper, jersey) case studies with contrasting raw material renewability. Virgin polyester made from fossil feedstock (PET-f, i.e., polyethylene terephthalate, where the subscript f refers to the petroleum feedstock) was contrasted with bio-based PET (PET-b) to explore the effects of fibre type renewability and recycling on (1) environmental impacts and (2) suitability for circular product life cycles. The aim was to identify how renewable and non-renewable fibres are handled in LCA and circularity assessment frameworks and to synthesise these findings, providing recommendations for improving comparisons between contrasting fibres by accounting for renewability.

2. Materials and Methods

2.1. Life Cycle Assessment

2.1.1. Goal and Scope

An attributional life cycle assessment (aLCA) approach was used to assess the environmental impacts of wearing a sweater made from PET-f or PET-b fibre. The method used was consistent with LCA standards [27]. The functional unit was one wear of a sweater in the European Union (EU). The garment was a long-sleeve pullover, suitable for mid-layer or outerwear, without a button or zipper. The garment mass was 340 g (the mass of a men's basic style crew neck sweater, 12-gauge, medium size is typically 330–350 g) (pers. comm. from a Chinese manufacturer of flat knit garments).

2.1.2. System Description and Boundaries

A cradle-to-grave system boundary was modelled, including all the life cycle stages from monomer formation, through to manufacturing, use and disposal of the garment (EoL), and all necessary transport (Figure 1).

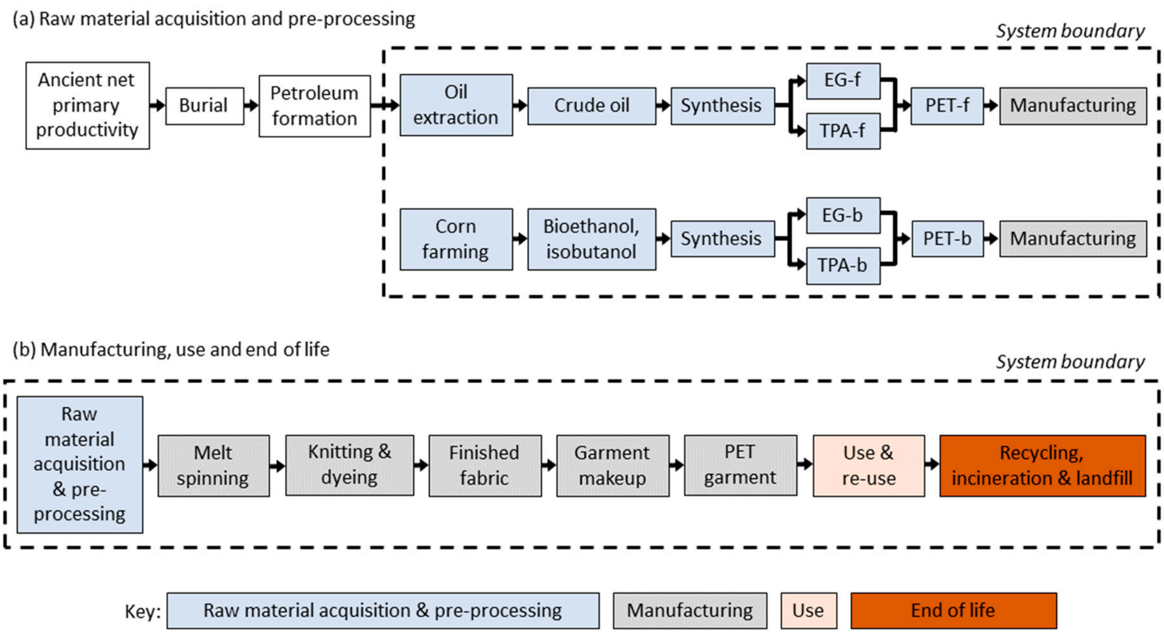

Figure 1. The system boundary of the full life cycle of a sweater used in the EU. The life cycle is shown in two parts to emphasise the processes involved in the (**a**) raw material acquisition and pre-processing and (**b**) the manufacturing life cycle stages.

For PET-f, the life cycle commenced with the extraction of crude oil from fossil reserves but excluded the petroleum formation process from ancient net primary productivity (e.g., marine phytoplankton, delta plants, lacustrine algae) and the subsequent diagenesis of these carbon-rich deposits. Crude oil from the global market was refined at a petroleum plant in China to yield purified terephthalic acid (TPA) and ethylene glycol (EG) which were polymerised to produce PET-f pellets. The manufacturing phase commenced with the transport of PET-f pellets to a manufacturing plant for melting and spinning to form PET-f fibre, followed by fabric and garment processing. Finished garments were transported by plane (8%) and ship (92%) to retailers in the EU [16]. Roundtrips by consumers, via a mix of cars and trains, transported garments from retailers to the place of garment use. The EoL phase took place in the EU and terminated with garments being recycled at home as rags or being incinerated or sent to landfill [10]. Heat and electricity generated by incineration avoided the production of natural gas and grid electricity, respectively. The recycling of PET garments as rags at home was assumed to avoid an equal mass of PET-f (as per the E*v term of the circular footprint formula [10]).

The PET-b feedstock was produced from bio-based TPA and bio-based EG [28,29], making the material 100 % bio-based. The system boundary for this case study began with the production of corn for bioethanol in the US, which is the major feedstock and origin for global bioethanol production [30]. Bioethanol was produced in a US biorefinery then transported to China by transoceanic tankers, via the Panama Canal, including ship-to-ship transfer and a stop in Malaysia [31]. It was assumed that in China a chemical plant produced TPA and EG and then used polymerisation to produce PET-b pellets. This polymerisation process is identical to that used to make PET-f, so the physical properties (including suitability for recycling) of PET from the contrasting sources were assumed to be the same [32]. Consequently, the subsequent system boundary was identical to that of a PET-f garment (except for biogenic carbon content). This assumed that differences in fibre physical (e.g., due to impurities [33]) and perceived quality were immaterial. The perceived value of a PET-b sweater may be different to that of a PET-f sweater (e.g., due to its provenance, relative rarity, or unfamiliarity), and this may have an influence on use phase parameter values (e.g., lifetime wears).

2.1.3. Life Cycle Inventory

The background life cycle inventory (LCI) data for the production of electricity, chemicals, fuel and diesel (used for transport), and infrastructure materials were derived from the ecoinvent v3.6 'attributional' database [34].

For the LCI of PET-f raw material acquisition, a global market petroleum unit process from the ecoinvent v3.6 'attributional' database [34] was used. This unit process accounted for the average onshore and offshore products and all losses of crude oil and petroleum associated with extraction and transportation (e.g., equipment leakage, evaporation loss and oil spills). The total losses were estimated to be 0.5 % of petroleum input to refineries based on a petroleum production attributional unit process in ecoinvent v3.6 database [34] (Table S1). For the PET-b raw material extraction and pre-processing phase, a unit process for US corn production from the ecoinvent v3.6 database [34] was used which included US-specific electricity, water and land use.

The foreground LCI data for PET garment manufacturing (Table S10) were the mean values in a review of manufacturer and peer-reviewed data [35,36]. Inventory data for the use phases of PET sweaters were based on wear and washing patterns obtained from a survey of German and UK consumers, supported by data from the literature on washing and drying machine use, and detergents (Table S14). The above-mentioned survey was also used to quantify disposal pathways.

Foreground transportation LCI data were obtained across the full garment life cycle (Tables S11–S13). Transport of materials associated with the raw material acquisition and pre-processing included the transport of petroleum from the global market (PET-f) and bioethanol and isobutanol from the US (PET-b). Other major transport activities included the transport of finished garments from China to the EU, the distribution to retailers [16], the transport of consumers to and from retail outlets [6] and the transport of garments to collection stations and incineration facilities [37].

Tables of foreground inventory data not presented here are available in the Supplementary Material. GHG emissions from the incineration of garments were estimated based on carbon storage in the material (Table S17).

2.1.4. Co-Production Allocation

For PET-f polymer production, there were multiple valuable co-products at refineries such as naphtha, diesel, fuel oil, hydrogen and gasoline. Impacts were allocated among these co-products by mass and energy in relation to emissions at the refinery level [38]. For the PET-b garment system, distiller's dried grains with solubles (DDGS) was the major biorefinery co-product during bioethanol and iso-butanol production from corn [39]. DDGS is commonly used as an animal feed, and economic allocation was applied to partition impacts between bioethanol or isobutanol and DDGS [40,41]. In the manufacturing phase, impacts relating to co-products such as recycled fibre, fabric and off-cuts at garment makeup were allocated based on mass. For the EoL phase, incineration of the disposed garments with energy recovery was assumed to produce electricity and heat, and the garment life cycle received credit for the avoided energy production (as per the circular footprint formula [10]).

2.1.5. Impact Assessment

A life cycle impact assessment was used to assess GHG emissions, fossil energy demand and water scarcity in SimaPro 9.1 [42].

GHG emissions were assessed throughout the whole life cycle based on the global warming potential with a 100-year time horizon (GWP_{100}). The GWP_{100} characterisation factors were 28 for methane (CH_4) and 265 kg CO_2-e for nitrous oxide (N_2O) [43]. Fossil energy demand was based on the inventory of purchased goods, services and transport distances, throughout a garment life cycle. Results are reported in megajoules (MJ) with lower heating values (LHV). Water stress was assessed using the water stress index (WSI) method [44] and reported in L-e per wear. Country- or regional-scale WSI characterisation factors were used for corn production in the US, manufacturing in China, and the use and EoL phases in the EU. We found that water footprint results were sensitive to routine updates to background inventory data. For this reason, (1) characterisation factors for water 'substances' and (2) modelling of water input, output and consumption in processes (e.g., hydroelectricity and cooling via heat transfer) were critically reviewed and revised where necessary. Land use impacts were assessed using LANCA characterisation factors modified by the European Commission's Joint Research Centre [45], based on previous research [46]. Impacts are reported in points (pt). The LANCA characterisation factors are based on characterisation models of soil quality. Consequently, the LANCA characterisation factors did not include marine landscapes, so land occupation impacts from offshore processes (such as oil extraction) were not included.

To assess model sensitivity to the possibility that fugitive, vented and flared methane emissions associated with oil and gas extraction [47–50] may be under-accounted in background inventory data, the three most important processes to the global petroleum process in ecoinvent v3.6 were identified (representing 76 % of production, Table S1). Global datasets were used to represent the mass of methane emissions per mass of oil and gas production as a percentage [51,52]. Methane emissions from the three most important ecoinvent processes were zeroed out, and then the calculated methane emission rate (2.28% kg CH_4/kg oil and gas) from the global datasets was applied to each. The dataset [51] for methane emissions is much higher than official data and includes emissions detected by satellite (4%). The latter excludes emissions over low and high latitudes and offshore. Because improvements in detection will likely increase the emission intensity, the calculated emission rate should be considered a non-conservative best estimate.

Impacts were determined using the CFF [53]. For PET garments, the EoL phase was credited with the avoided impacts of recycling garments as cleaning cloths, multiplied by a quality ratio, Q. Following the public version of the apparel and footwear PEFCR, Q = 0.75, 0.08 (estimated from prices), and 1.0 for recycled PET fibres, PET fabric as a wiper and PET as insulation [11]. Similarly, the EoL phase of each garment was credited with the avoided impacts associated with the incineration of garments and debited with the impacts of disposal as landfill. The allocation factor A, used to assign burdens and credits between the source and use of recycled materials, was set to 0.8 [53].

2.2. Circularity Indicators and Assessment Frameworks

Four circularity indicators were used to assess the circularity of fibre inputs:

- The Ellen Macarthur Foundation *Material Circularity Indicator* (MCI) [17];
- The World Business Council for Sustainable Development % *circularity* indicator [18];
- The Circular Materials Guidelines (CMG) feedstock content requirements [20];
- The Cradle to Cradle Certified™ Product Standard *Material Reutilization Score* (MRS) [22].

These four indicators were chosen because they each considered the renewability of material inputs. Within these indicators and assessment frameworks, the focus was on metrics that directly related to renewability. Because some indicators simultaneously assessed material attributes at both the initiation and end of a circular product life cycle, the scope was expanded to include EoL metrics wherever these were available. The indicators are described more fully in the Supplementary Materials. Representative values for all parameters were obtained from the peer-reviewed literature and an industry survey (Table S18). Some indicators were sensitive to whether renewable inputs were sourced from certified-sustainable agricultural systems. It was assumed renewable feedstocks were obtained from such sources, and the implications of this assumption were explored in the Discussion.

3. Results

3.1. Environmental Impacts Quantified Using LCA

The environmental impacts per wear of a PET-f sweater in the EU were 0.097 kg CO_2-e, 1.2 MJ of fossil energy demand, 0.5 pt for land occupation, 1.9 L-e for water stress and 2.9 L for freshwater consumption (Figure 2). The manufacturing phase was a hotspot for GHG emissions (60%) and fossil energy demand (49%). Both the manufacturing and use phases were hotspots (>30%) for land occupation and water stress (Figure 2). Accounting for fugitive, vented and flared methane emissions increased climate impacts for a PET-f sweater by 1.7% (results not shown).

Fossil energy demand associated with a PET-b sweater was similar to that of a PET-f sweater, but increased GHG emissions to 0.104 kg CO_2-e, water stress to 2.8 L-e, freshwater consumption to 3.9 L and land occupation to 1.6 pt, per wear (Figure 2). The increase was due to raw material acquisition and pre-processing phase GHG emissions, water consumption and land occupation 1.9, $\geq$25 and 60 times larger, respectively (Figure 2). The increase in GHG impact was more modest than freshwater and land occupation but nevertheless a material change, given the higher weighting typically allocated to climate change in product rating schemes [10]. Both the raw material acquisition and use phases were hotspots for water impacts. Of all the impacts reported here, uncertainty is largest for the water impacts associated with the raw material acquisition phase of the PET-b sweater because the availability and need for irrigation water is expected to vary across space and time in response to rainfall and the regulation of water supply networks.

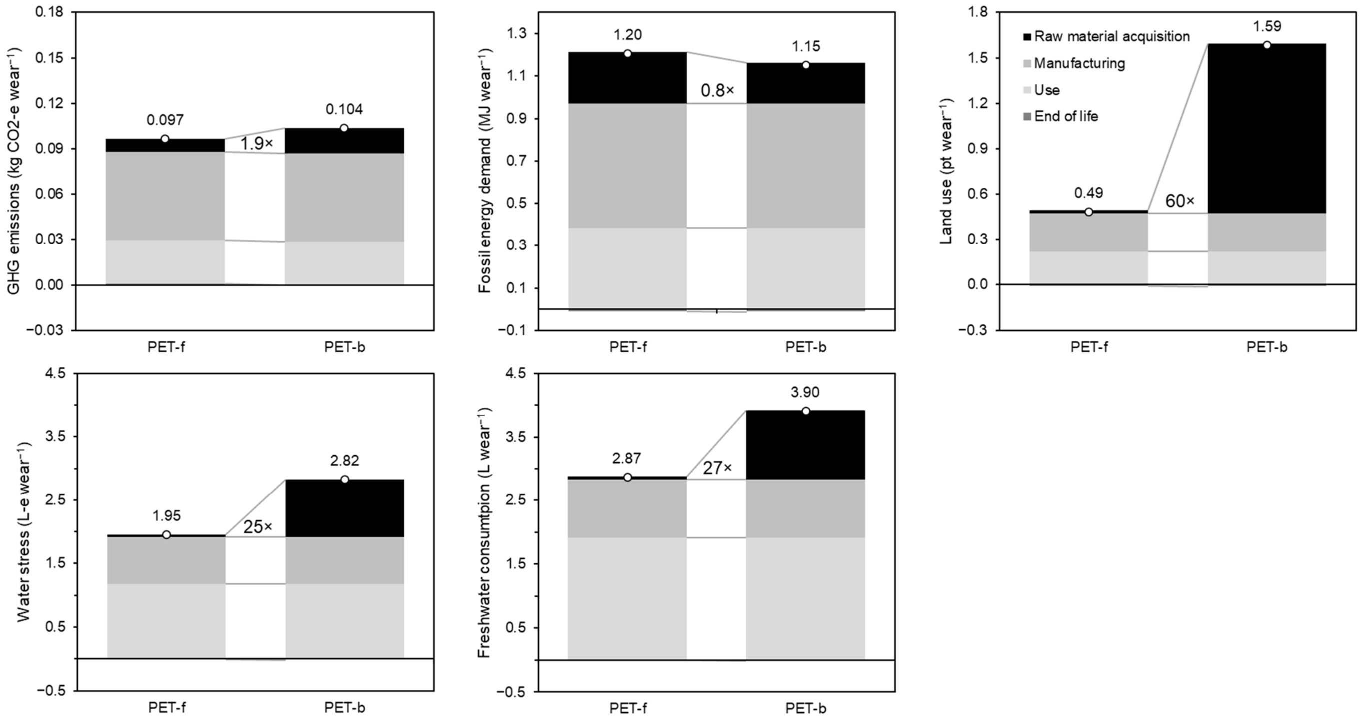

Figure 2. Greenhouse gas emissions, fossil energy demand, land occupation, water scarcity and freshwater consumption impacts per wear of a PET-f and PET-b sweater for each life cycle phase (legend shows grey shades assigned). Also shown are total impacts (circles) and multipliers showing the raw material acquisition phase impact for PET-b relative to PET-f.

3.2. Circularity Indicators and Assessment Frameworks

PET-f scored lower on all the indicators/assessment frameworks applied (Figure 3, Table 1). PET-f scored 0% on the % circularity indicator because the fibre represented neither circular in- or outflow (Table S18). PET-f received the lowest MCI score (0.10) because it was not a recycled/reused or sustainable input, and the latter attribute made it further ineligible to gain credit from energy recovery. PET-f received an MRS score of 67 ('gold') based on product recyclability alone. The MRS weighed output characteristics more heavily than input characteristics—if PET were from a recycled source (e.g., bottles) but not recyclable (e.g., due to the presence of other fibres) then the score would be 33 (not suitable for certification). PET-f received a CMG 'best' score for fibre recyclability potential as it is readily recyclable [21]. However, PET-f would not be considered a circular material under the CMG 'chemistry' category because it was derived from a fossil-based feedstock.

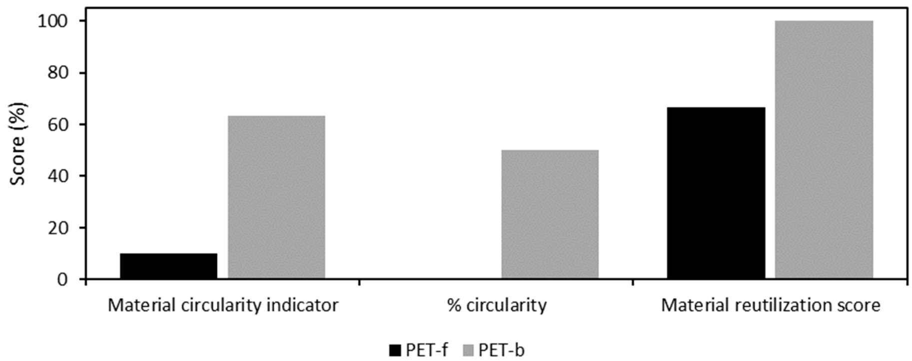

Figure 3. PET-f and PET-b garments scored using circularity indicators. The indicators are the Material Circularity Indicator [17], the % circularity [18], and the Material Reutilization Score [22]. The data used to derive the scores are provided as Supplementary Material.

Table 1. Assessment of PET-f and PET-b garments according to the Circular Material Guidelines [20].

Requirement No.	Requirement Name and Description	PET-f	PET-b
1A	Recycled and/or Reclaimed Content fibre content—This requirement is centred around incorporating recycled content in fibres.	Fail	Fail
1B—for products made partially from virgin cellulose and virgin protein-based materials	Renewable Sources—when non-recycled/reclaimed feedstock is from virgin natural sources	NA	NA
	Renewable Sources—when non-recycled/reclaimed feedstock is from virgin natural sources	NA	NA
1C	Recycled and Reclaimed Content—This requirement is centred around incorporating recycled or by-product fibres/yarns into fabric.	Fail	Fail
2	Fibre Recyclability Potential data	Best	Best

PET-b received an MCI score of 0.63, a % circularity score of 50% and an MRS score of 100. PET-b received a CMG 'best' score for fibre recyclability potential but would not be considered a circular material because it originated from an edible feedstock. PET-b scored high ('platinum') using the MRS because the material is potentially recyclable and because the fibres from biogenic sources are rapidly renewable (i.e., grown and harvested in cycles of less than 10 years).

4. Discussion

4.1. Approaches to Choosing More Sustainable Fibres

4.1.1. Option 1—ISO-Compliant Life Cycle Interpretation

The system boundary in cradle-to-gate or -grave LCA studies typically begins with a process in which raw material acquisition brings natural resources such as water, CO_2, land and minerals into the technosphere, but it may also involve the acquisition of materials within the technosphere (i.e., salvage such as urban mining and recycling). This follows international standards in LCA: depending on the goal and scope of the study, LCA assesses impacts from raw material acquisition to final disposal [27]. This boundary is practical—it identifies those processes over which the entity commissioning an LCA has operational or financial control or responsibility. However, initiating a system boundary with raw material acquisition omits the environmental processes that created these initial inputs [54]. For example, the LCA indicators used here omit the ancient water and nutrients required to create the biomass feedstock for fossil reserves [55], as well as the subsequent diagenesis that led to the formation of crude oil and natural gas [56]. A sustainable system should not allow the systematic accumulation of substances from the lithosphere in the ecosphere [26]. Consequently, the raw material acquisition process of a PET-f garment life cycle is not only treated inequitably by LCA when comparisons are made with renewable feedstocks but is also incompatible with sustainability principles. This was reflected in results obtained using the circularity indicators: PET-f was a consistently undesirable input because the fibre was obtained from a virgin feedstock that cannot be certified as sustainable. PET-f showed some degree of circularity based on EoL phase attributes only (i.e., recycling rate, recycling potential, recycling efficiency).

According to international standards in LCA [9], the 'interpretation phase' is the last of four phases in an LCA study. Along with the goal and scope phase, the interpretation phase frames the study. The ISO standard states that the appropriateness of the system boundary shall be considered as part of the interpretation process [9] (p. 25). We argue that the interpretation phase of an LCA study that compares renewable and non-renewable fibres should acknowledge the inequities that arise when an LCA study compares these fibre types using conventional system boundaries. The inequitable treatment of PET-f is an important issue because the results showed that renewable feedstocks often show high impacts on the raw material acquisition and pre-processing phase, which may translate to larger full life cycle impacts (Figure 2). This is consistent with other studies comparing renewable and non-renewable materials [57–59]. In these other studies, the raw material and acquisition and pre-processing phase is a hotspot for indicators that typically show higher impacts in biological systems (i.e., those closely related to water, nutrient and land footprints). The consistency of the present study with these observations increases the need for the interpretation phase of LCA studies to critically assess the appropriateness of system boundaries. Importantly, this suggests that the results of LCA are sensitive to indicator choice as well as weightings applied in the process of obtaining a single score.

An ISO-compliant LCA interpretation phase also requires that preliminary conclusions are consistent with aspects of the study including ' . . . predefined assumptions and values, methodological and study limitations, and application-oriented requirements' [9] (p. 27). An example of the latter would be identifying sustainable materials and processes for garment life cycles. As demonstrated by the approach presented here, a straightforward means of testing whether the environmental impacts delivered by an LCA study are consistent with possible sustainability objectives is to conduct the LCA in parallel with an assessment of material or product circularity using a circularity indicator. This is facilitated by common data requirements (e.g., relating to material sources and EoL pathways). Contrasts between LCA and results obtained from circularity indicators will be useful for framing the interpretation phase of an impact assessment, particularly the limitations of LCA that stem from inequitable system boundaries. In the present research, a comparison of Figures 2 and 3 shows that increased circularity may be associated with costs in the form of increased environmental impacts. In this example, the 'environmental cost of circularity' occurred at the raw material acquisition stage, with impacts per indicator up to 60× larger for the product with the more circular life cycle (PET-b).

4.1.2. Option 2—Select Raw Materials Based on Circular Product Life Cycle Criteria

In general, the circularity indicators favoured the use of recycled and renewable inputs in products whose materials could be recycled or biodegraded. The preference for renewable inputs sometimes came with a certification requirement. For the MCI and CMG, the certification requirement was to verify that the renewable materials were sustainably produced. Consequently, in the absence of such certification, the circularity scores and assessments for PET-b would be low or zero and often similar to that of PET-f (results not shown). The implication is that non-renewable material inputs are clearly undesirable, but in the absence of certification, inputs that would conventionally be considered renewable may be identified as undesirable. These certification schemes are focused on impacts relating to raw material acquisition, and toxic chemicals during pre-processing and manufacturing (the schemes are also focused on farming—there is no reference to certification schemes for rehabilitating land after extracting the oil feedstock for PET-f, for example). This focus de-emphasises the use phase, which may be a hotspot for impacts (Figure 2), thereby perpetuating an inequitable assessment of alternative fibres by focusing on upstream impacts [60]. More importantly, there is a risk of certification schemes 'throwing the baby out with the bathwater' by failing to recognise the role conventional non-certified agriculture can play in supplying renewable feedstocks. Certification may impede the supply of virgin renewable fibres or recycled fibres to circular product life cycles if the attainment of certification is costly to primary producers [61] or increases their perceived exposure to risk [62] or if it is impractical to separate certified materials from non-certified during transport and processing. Continued reliance on certification schemes may require greater investment in extension, programs on regenerative agriculture and financing arrangements to increase their social and economic viability [14]. It is prudent to question whether the costs of (and investment in) third party certification schemes are commensurate with their benefits. For example, a vendor declaration system (where a producer signs a document attesting to the conditions under which their goods were produced) could facilitate the supply of sustainable feedstocks at a much lower administration cost.

The circularity indicators also had criteria for preferred materials associated with the EoL phase. These included the proportion of material originating from sustainable biological cycles incinerated for energy recovery (MCI, C2C), the proportion of material compostable (MCI, WBCSD, C2C) and the proportion of material *potentially* (MCI, CMG, C2C) or *actually* (WBCSD) recycled. Recyclers prefer post-industrial PET textile waste or are experimenting with recycling post-consumer PET blends [21]. Consequently, circularity indicators that rely on *potential* circular EoL treatments are likely to return contrasting scores to indicators that require data on *actual* processing rates. Scoring materials and products on *potential* recycling and biodegradation rates are presumably designed to reflect processes under the control of an entity—this control may end once a garment is sold or disposed of. However, reducing the rigour of circularity indicators by not requiring *actual* data on EoL process reduces their relevance to the full life cycle of products and materials. As explained in the context of renewable and non-renewable feedstocks, a system boundary that does not consider all life cycle stages equally is prone to producing inequitable comparisons.

5. Conclusions

In a circular economy, selection of renewable and sustainable products and supply chains is paramount for reducing environmental impacts. LCA is a highly effective tool for determining environmental impacts across a range of indicators. However, it does not inherently take renewability or non-renewability into account. Moreover, because the system boundary for renewable monomers includes the primary processes that produced the monomer, while for fossil-fuel feedstocks it begins with extraction, the results presented here showed raw material acquisition phase LCA impacts up to 60 times higher for renewable relative to fossil feedstocks. We contend these results mislead sustainability assessment because renewability (a primary requirement according to sustainability principles) is not differentiated in LCA. Circularity indicators provided a system for quantifying the impact of renewability within a textiles supply chain and showed improved scores for bio-based PET compared to fossil-feedstock PET. Considering this, where renewable and non-renewable fibres are to be compared, we recommend that:

- LCA and circularity indicators are applied in parallel to help frame the interpretation phase of an ISO-compliant LCA;
- The interpretation phase of an ISO-compliant LCA study carefully considers the impact of system boundaries on life cycle impacts;
- Where possible, actual rather than potential rates (such as recycling and composting) be used to parameterise circularity indicators.

These recommendations address the shortcomings of LCA and circularity indicators, yet capitalise on their respective strengths in the process of selecting for low input, sustainable fibres for the circular economy.

Supplementary Materials: The data presented in this study are available as supplementary material at: https://www.mdpi.com/article/10.3390/su142416683/s1; Table S1: The global supply of crude oil for petroleum production; Table S2: Key inventory data for the production of PET-f in China; Table S3: Inventory data to produce corn at a US farm; Table S4: Key inventory data for the production of 1 kg bioethanol (95 % without water) from US corn; Table S5: Key inventory data for the production of bio-based ethylene oxide from bioethanol; Table S6: Key inventory data for the production of bio-based ethylene glycol from bio-based ethylene oxide; Table S7: Key inventory data for the production of bio-based isobutanol from US corn; Table S8: Inventory data for the production of 1 kg bio-based TPA; Table S9: Key inventory data for production of 1 kg bio-PET pellets; Table S10: Summary of the materials and energy use to manufacture synthetics garment from PET pellets; Table S11: Transportation of bioethanol and isobutanol from US to China; Table S12: Transportation of 1000 kg finished garments from China to the EU; Table S13: Inventory data for retail operations and consumer transport to and from retail outlets in the EU; Table S14: Key inventory data for the use phase of sweaters in EU; Table S15: Inventory for 1 kg of powder, tablet, liquid and handwash detergents used to wash garments in the EU; Table S16: Average disposal pathway of sweater garments in EU (UK and Germany); Table S17: Total carbon storage in 1 kg fabric/garments; Table S18: Key parameters and values for circularity indicators. References [6,16,18,20,22,25,30,31,34–36,40,43,63–88] are cited in the supplementary materials.

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