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Article

Does Use Matter? Comparison of Environmental Impacts of Clothing Based on Fiber Type

Kirsi Laitala [1,*], Ingun Grimstad Klepp [1] and Beverley Henry [2]

[1] Consumption Research Norway (SIFO), Oslo Metropolitan University; 0130 Oslo, Norway; ingun.g.klepp@oslomet.no
[2] Science and Engineering Faculty, Queensland University of Technology (QUT), Brisbane, QLD 4001, Australia; beverley.henry@qut.edu.au
* Correspondence: kirsi.laitala@oslomet.no; Tel.: +47-672-356-32

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Abstract: Several tools have been developed to compare the environmental impact of textiles. The most widely used are Higg Materials Sustainability Index (MSI) and MADE-BY Fiber Benchmark. They use data from production to evaluate the environmental impacts of textiles differentiated by fiber type. The use phase is excluded from both tools. This article discusses whether there is evidence that the use of textiles differs systematically between different fiber types and examines the consequences of comparing the environmental impacts of clothing based on differences in production of fibers alone without including differences in their use. The empirical material in this paper is based on analysis of rating tools and a literature review on clothing use. It shows that fiber content contributes to the way consumers take care of and use their clothing. When use is omitted, major environmental problems associated with this stage, such as spread of microplastics, are also excluded. This one-sided focus on material production impacts also excludes the importance of product lifespans, quality, and functionality. The consequence is that short-lived disposable products are equated with durable products. Comparing dissimilar garments will not help consumers to make choices that will reduce the environmental burden of clothing. We need an informed discussion on how to use all materials in the most environmentally sustainable way possible.

Keywords: sustainable clothing; fiber properties; clothing production; fashion consumption; maintenance; environmental sustainability tools; fiber ranking; material selection; LCA

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1. Introduction

Awareness of environmental impacts of clothing and other textiles is growing and several tools have been developed to assess and compare textiles. They use data limited to material production to evaluate the environmental impacts of textile differentiated by fiber type. This article discusses the consequences of comparing clothing based on differences in production of fibers or fabric without including garment use. When the use phase is left out, major aspects that contribute to the environmental impacts are also excluded, such as spread of microplastics, product lifespans, quality, and functionality.

Textiles constitute a substantial proportion of the global environmental burden. Fiber production has grown to 100 million tonnes [1] and it has been estimated that clothing is responsible for about 3% to 6.7% of global human-caused CO_2 emissions [2,3]. The value chain for production of textiles is long. Environmental impacts occur in all stages including fiber production due to agriculture, animal husbandry [4], and industrial synthesis, through a variety of processes such as spinning, weaving, sewing, and further to application of various properties such as color, waterproofing, flame retardants, etc. Textile production and consumption have high water and energy use, and occupy land suitable for food production [5,6]. Cotton cultivation globally consumes about 16.5% of all pesticides while it is grown on only 2.4% of the world's arable land [7]. The industry affects biodiversity [8] and pollution of waterways [5], and socio-economic challenges due to uneven distribution of wealth and poor labor conditions [9]. The use phase of clothing includes laundering and drying that contribute to high use of water, energy, and chemicals [10]. Estimates suggest that as much as 20% to 35% of all primary source microplastics in the marine environment are fibers from use of synthetic clothing [11–13].

A significant amount of effort is being directed towards reducing these environmental impacts. There exists national and international regulations related to use of harmful chemicals (such as REACH in EU [14]), various labelling schemes for indicating that the production has been more environmentally sustainable (EU ecolabel [15], the Nordic Swan [16]), organic [17] or produced in a social responsible way (Fair Trade) [18]. However, such labels are used less on textiles than on many other products such as food, detergents, or paper [19]. Clothes are commonly labelled only with their fiber content and lack information about properties such as strength, degree of pilling or colorfastness that affect use.

The increased interest in sustainability of textiles can be seen in the work conducted by the industry [20–22], as well as by governments/authorities of some countries [23,24]. It has also contributed to development of tools for sustainability comparisons of a range of products, an alternative approach to only ecolabelling a few products as "greener". Since fiber content is one of the few facts available on all garments, this is also the most frequent basis for comparison. Two of the most commonly used tools based on fiber content are the Higg Materials Sustainability Index (MSI) [25] and MADE-BY's Fiber Benchmark [26]. They evaluate the impact using life-cycle thinking from a cradle-to-gate perspective. The use phase is not included in these comparisons.

Despite the importance of use phase related to product lifespans and maintenance, the environmental impacts are compared only based on differences in production. Therefore, this paper discusses two questions: "Is there evidence that the use of textiles differs systematically between different fiber types?"; and "What are the consequences of comparing the environmental sustainability of clothing based on differences in production of fibers alone without including differences in their use?".

These questions will be answered based on an extensive survey of literature on the use phase of clothing. Initially, we will introduce the two most widely used fiber ranking tools mentioned above. In the results, Section 4, findings on the main practices of clothing use phase that determine environmental impacts are summarized. These include laundering and drying (energy and water consumption and release of microfibers), as well as laundering frequency and clothing lifespans. In Section 5, we discuss our research questions. We conclude with suggestions for further research.

2. Background

Life-cycle assessment (LCA) is a technique used to assess environmental impacts of products, processes or services [27]. Full LCA includes all stages of the lifecycle from raw material extraction, materials processing, manufacture, transport, use, repair and maintenance, recycling, and finally end-of-life ("cradle-to-grave" analysis) [28,29]. The measuring unit for product LCA, called the functional unit, is defined by the 'service delivered', a quantified performance achieved within a given period of time [27]. For example, the functional unit for assessment of paint could be the coverage of a certain area over a certain time ($m^2 \cdot$year), rather than just liters of paint. It links the emissions or resource to function, and makes it possible to compare products [30]. Unfortunately, many apparel and textile LCA studies have used units such as 'one garment' or 'kg of textile' in a specific fiber. If included, consumer use has often been assumed to be the same across all garments regardless of fiber, quality or purpose (e.g., socks vs. formal wear). Similarly the method of disposal has often been assumed equal for all garments, such as landfilling, without accounting for suitability for recycling or biodegradability.

Most assessments focus on fiber production stage, but a recent report that quantified the apparel industry's global environmental impacts across various indicators showed that the three life cycle stages with most impact were dyeing and finishing, yarn preparation, and fiber production (use phase was outside the scope of the study and thus excluded) [3]. The dyeing and finishing stage had the highest impact with regards to all indicators studied. For example, it contributed 36% of total greenhouse gas (GHG) emissions, followed by yarn preparation that constituted 28% mainly due to the energy intensive processing and high dependence on fossil-based energy. Fiber production constituted 15% of the total, which indicates that, for the climate change indicator, choosing fiber type as a basis for comparison gives less impact than would be the case if production stages with larger impact, dyeing, and finishing, as well as yarn preparation were chosen.

The importance of use phase relative to the production stage varies between the different environmental impacts. Based on the market share and consumption of textile products in EU-27, Beton et al. [31] showed that production and use phase dominate the environmental midpoint indicators evaluated. Distribution and end-of life only have minor roles. Use contributes over 60% of the indicators for human toxicity, freshwater and marine ecotoxicity, metal depletion, ionizing radiation as well as water depletion. Production dominates indicators for agricultural land occupation, terrestrial ecotoxicity, freshwater and marine eutrophication, as well as natural land transformation [31]. Their study did not take microplastic pollution into account.

Allwood, et al. [32] analyzed the importance of consumer practices for a cotton T-shirt and a viscose blouse for primary energy consumption. Elimination of tumble-drying and ironing, together with lowering the wash temperature from 60 °C to 40 °C, could lead to around 50% reduction in the global climate change impact of the product. The same study also shows that the material manufacture stage for cotton requires less energy than the later production stages, while the relationship is the opposite in the case of viscose.

As awareness of the potential detrimental impacts of textiles on the environment has increased, tools have been developed to help compare sustainability of textile fibers. The most widely used tools are the Higg Materials Sustainability Index (MSI) and the MADE-BY Fiber Benchmark. These ranking tools use knowledge of production processes to assess selected impact categories in cradle-to-gate analyses.

Ranking Tools

The MADE-BY Benchmark for Fibers was published in 2009 and has been updated several times since [26]. Currently it includes 27 fibers in five classifications from Class A (best) to Class E (worst). The Class A fibers are mechanically recycled polyester and nylon, organic flax and hemp, and recycled cotton and wool. Class E fibers include viscose (generic as well as bamboo), conventional cotton, nylon, rayon, elastane, and wool. Recycled products rate highly, as the recycled material is considered waste and does not bear any environmental burden from the first life. An additional category, 'unclassified', includes fibers that are not (yet) classified due to a lack of data.

Classification is based on six parameters (See Table A1 in the Appendix A). It is based on the production process of fibers from the origin of the raw material to fibers ready to be spun, and thus excludes all stages from spinning onwards. The unit of comparison is 1 kg of fiber ready to be spun. MADE-BY has also a wet processing benchmark that includes information about pre-treatment, dyeing, garment finishing, and printing stages [33]. The selected impact categories/parameters do not cover all environmental aspects, for example abiotic resource depletion (depletion of non-renewable resources, e.g., fossil fuels for preparation of synthetic fibers) is not included, nor biodegradability.

The Higg Index is a set of tools developed by the Sustainable Apparel Coalition (SAC) [25]. The Higg Index has, or is in the process of developing, tools for each step in the supply chain. An overview of what each of the tools covers is given in Table A2 in the Appendix A. The three Higg tools most directly relevant to a product are the Design & Development Module (DDM) [34], Materials Sustainability Index (MSI) [35], and the Product Environmental Footprint expected to launch at the end of 2018. The MSI is a cradle-to-gate material scoring tool that assesses and scores a material's impacts from the extraction or production of raw materials through to the material ready to be assembled into a final product. It combines scores for five impact categories: global warming, eutrophication, water scarcity, abiotic resource depletion, and chemistry (currently a qualitative score). MSI also feeds into the product environmental footprint that will add other stages of the supply chain.

Sustainable apparel coalition member companies (including brands, retailers, and manufacturers) are estimated to be responsible for more than one third of the apparel and footwear produced globally [36]. Therefore, the potential impact of the SAC Higg tool is large. SAC emphasizes limitations and the uncertainty in available data. However, the Higg Index has become important as a basis for other comparisons and evaluations such as the Pulse Score in the Pulse of the Fashion Industry report [20], as well as Preferred Fiber and Materials (PFM) Benchmark by Textile Exchange [37]. In these, it has been used to rank apparel. While the limitations in use of the cradle-to-gate MSI to compare apparel and textiles is specified by SAC, these shortcomings are not clearly presented and understood by users.

Both MADE-BY Fiber Benchmark and Higg MSI use fiber type as a starting point for comparison and neither includes finishing or use, or considers the product lifespan. The tools are under development and the underpinning data, assumptions and other critical information are not publicly available. However, because they already have, and potentially will be given, great influence, the prerequisites they are building on should be discussed. The science and understanding of environmental sustainability assessment has progressed substantially and it is critical that tools keep up with this new knowledge and do not perpetuate poor estimates and incorrect results. We will contribute through discussing the consequences of the use phase not being integrated into comparisons of apparel by looking at how fiber content affects the use of clothing.

3. Materials and Methods

This article collates previous empirical research on various fiber properties and consumer clothing behavior. In addition, it includes reanalyses of existing research data. Several sources have been used. Electronic databases ISI web of science® (Clarivate Analytics, Philadelphia, PA, USA), EBSCOhost® EBSCO Industries, Ipswich, MA, USA) Research Databases, and Google Scholar (Google, Mountain View, CA, USA) were searched. Search terms used included clothing, apparel, or fashion combined with use, laundering, drying, ironing, disposition, discard, or recycling in the title, abstract, keywords or the body of the articles. In addition, reference lists of the articles found were scanned through. Various textile handbooks have been used for collecting information about fiber material properties. Only studies discussing clothing use that include data relevant for modelling the use phase of clothing in LCA are included in the review. The review excludes other stages of the clothing production and distribution chain, as well as textiles other than for clothing, such as furnishing, bed textiles, towels and upholstery. Accessories, such as scarves, are included. The studies on consumer behavior are limited to those published after 1997, as current clothing practices are likely to differ from those of 20 years ago. Only studies in English, Norwegian, Swedish and Finnish are included. Details of the included studies can be found in reports by Laitala, et al. [38] and Henry, et al. [13]. The methods, Section 3, describe only data that has been reanalyzed specifically for this study.

One of the main sources is a global wardrobe audit conducted by The Nielsen Company [39]. The study consisted of an online survey of 467 adult respondents (90 min) across seven countries: Australia ($n = 56$), China ($n = 104$), Italy ($n = 51$), Japan ($n = 52$), South Korea ($n = 52$), UK ($n = 52$), and USA ($n = 100$) [39]. Respondents answered the same questions related to each of the clothing items they owned, including which materials they were made of, the age of the garments and maintenance practices. Unfortunately, the study did not separate between different man-made fibers such as viscose and polyester.

Another source that has been used for acquiring new data for this study is a Norwegian project where a wardrobe audit was conducted on all clothing going out of use from selected households. All 620 garments that went out of use during a half year were registered with the reason for disposal and lifespan of the disposed items. The study included 16 households with 35 family members in total—8 children, 3 teenagers, 16 women, and 9 men [40]. The material was reanalyzed to compare garments made of different fibers.

4. Results: Fibers Are Different in Use

This section presents data on the use phase that are relevant for fiber comparisons, based on garments made of different fibers. New data synthesis and reanalysis allows us to present results in a novel way relative to aspects that have environmental impacts, including maintenance and clothing lifespans. The differences in use are related to fibers functionality, and aesthetic and physical properties. To provide the context for this interpretation we will, therefore, firstly present key aspects of fiber properties.

4.1. Fiber Properties

Textile fibers have different properties that can be classified in following way [41,42]:

- Physical properties (length, fineness, moisture regain, etc.)
- Chemical properties (chemical composition, effects of acids, alkalis etc.)
- Mechanical properties (stiffness, tenacity, tensile strength, elasticity, etc.)
- Electrical properties (electrical conductivity and resistance)
- Thermal properties (thermal conductivity, flammability, melting point)
- Structural properties (micro structure, X-sectional, and longitudinal view)
- Biological properties (toxicity, bio-compatibility, microbial, and fungal resistance)
- Optical properties (reflectivity, transmittance, color)
- Acoustic properties (sonic velocity, sound absorption)
- Radiological properties (ability to protect from atomic/nuclear radiations)
- Environmental properties (UV stability, weathering, oxidation)
- Torsional property (torsional rigidity, breaking twist, shear modulus)

This list is not exhaustive but gives an indication of the variety of properties textile fibers have that influence their use. Table 1 lists the values for common textile fibers against a subset of properties that affect production techniques such as spinning and dyeing methods, as well as how the fibers behave during use.

Table 1. Typical properties of some common fibers.

Fiber	Fiber Length [42]	Diameter (μm) [42]	Moisture Regain at 65% RH (%) [42,43]	Elongation Strain to Failure (%) [42]	Dry Tenacity (N/tex) [44]	Flammability (Limiting Oxygen Index) [44,45]	Chemical Content/ Structure [46]
Cotton	10–50 mm	10–27	8.5	7	0.3–0.5	17–19	Cellulose
Jute	2 m	69	12–13.75	2.5			Cellulose
Flax (linen)	25 mm	15–20	8.75–12.0	1–3	0.4–0.6	17.4	Cellulose
Hemp	2.5 m	45	10–14	1–2			Cellulose
Silk	>10 m	12	11.0	25	0.2–0.5	23	Fibroin
Wool	25–355 mm	15–40	13.6	35	0.1–0.2	25–27	Keratin
Viscose (rayon)	filament	4–60	11.0	~25	0.1–0.3	16–18.7	Regenerated cellulose
Acetate	filament		6.5	20–45	0.1–0.2	18.5	Secondary cellulose acetate
Polyester	filament	15	0.4	15	0.3–0.9	22	Polyethylene gly-col terepthtalate
Polyamide (nylon)	filament	20	3.5–4.5	20	0.3–0.9	20	Polyhexa-methylene diamino-adipate
Acrylic	filament		1.5–2.5	25–45	0.2–0.5	17	Min. 85% polyacrylo-nitrile
Modacrylic	filament		0.4–3.5	25–45	0.1–0.3	26	35–85% acrylonitrile
Elastane (spandex)	filament		1–1.3	400–700	0.05–0.1		85% segmented polyurethane, polyether type

Table 1 shows for example that plant fibers are mainly composed of sugar based polymers (cellulose, hemicelluloses) combined with lignin and pectin. They have, therefore, many similar properties such as flammability and moisture regain, but vary in strength and size due to differences in molecular structure and fiber geometry.

Heat and moisture transfers influence the comfort of the wearer. Fibers that are hydroscopic in nature vary from those that are hydrophobic (e.g., polyester). Hydrophobic fibers absorb almost no water compared to most natural fibers that contain moisture up to more than 10% of their weight.

The limiting oxygen index (LOI) gives the amount of oxygen required to support combustion. The oxygen content of the earth's atmosphere is about 21%, and, therefore, fibers that have LOI below 21 burn readily (such as cotton and acrylic) whilst those with a values above this do not burn as easily (such as wool and modacrylic).

In addition to their physical and chemical properties, fibers have different aesthetic and tactile qualities. Textile materials are also a part of cultural or social practices, traditions, and value systems. These aspects will not be part of this article beyond noting that they also have consequences for use and contribute to the social or emotional lifespan of clothes as opposed to their technical lifespan.

4.2. Maintenance

Clothing maintenance consists of many actions that, in each case alone, seem small and environmentally rather insignificant. However, because they are repeated so often and by all people in the world, they will together constitute a significant environmental impact. While production of each garment takes place once, washing and subsequent practices such as drying and wrinkle removal will be repeated on a regular basis. The longer a garment is used, the more important this phase will be for the overall environmental impact of the garment [2]. Thus, the differences in environmental impacts, for example, related to different fibers, will be multiplied. Differences in lifespan of different fibers also has an important influence on the environmental impact of clothing maintenance but this aspect must be combined with the contribution due to 'frequency' of production for short compared to long lifespan garments. Hence, the 'production burden' of long lifespan garments is amortized over a much longer period of use.

4.2.1. Inherent Fiber Soiling Properties

Fibers have different chemical and physical properties that affect soil retention, odor formation, and ease of cleaning. Due to polyesters' oleophilic nature, oily stains easily stay on the fiber surface [47,48], whereas in cotton, the soil rather enters the inside the fiber lumen, as well as in the interfiber spaces [47]. Woolen fabrics are rather resistant towards water based soils due to the hydrophobic waxy, lipid coating chemically bonded to the fiber surface [49]. However, when staining first occurs, they are more difficult to get clean than the synthetic samples (higher soil retention). Cotton materials showed even more soiling, but tolerate more efficient washing and detergents than wool does [49]. The physical structure and finishes are also important [47,50–52].

Axillary odor following wear is lowest on wool, followed by cotton-based fabrics and highest on polyester [53]. It has even been shown in tests that the odor on polyester fabrics can increase up to a week after the garments was used, which did not happen with wool or cotton specimens [54]. After sportswear samples were used, polyester had the strongest odor, followed by chemically odor-control treated polyester, then cotton, and wool had the least smell [55]. It is easier to remove odorants from cotton than polyester fibers [56].

This shows that inherent fiber properties affect the soiling characteristics of garments. Cotton gets dirty easily, but can be washed efficiently and thus cleaned. Wool resists staining and develops less odor, but stains are difficult to remove. Soil on synthetic materials is quite easy to clean off. In the following sections, we investigate whether consumer studies confirm that these properties have an effect on consumers' laundering practices.

4.2.2. Cleaning Methods

There are several alternative methods for cleaning clothes. Even though use of washing machines is the dominant method, it is more common to wash laundry by hand in rural areas in developing countries [57]. Other alternative cleaning methods include airing, steaming, or dry-cleaning.

There are differences in which cleaning methods are chosen for various fibers. Garments made of silk, wool, and wool blends were over three times more likely to be dry-cleaned than garments of cotton or synthetics and their blends (Table 2). Women reported washing laundry by hand more often than men, which is also confirmed by other studies [58,59]. In contrast, men dry-clean a larger portion of their clothing than women, mainly formal or business clothing such as suits, ties, overcoats, coats, jackets and blazers. However, there are also large national differences, UK consumers did not see the same need to dry-clean woolen garments as the US respondents, and preferred to wash them instead, while Italian and Chinese were more likely to wash them by hand.

Table 2. Main washing methods for clothing made of different materials [39].

Washing Method by Fiber	Hand Wash	Machine Wash	Dry-Clean	Combination of Methods or Unknown
Cotton and cotton blends	8%	80.5%	6.5%	5%
Wool and wool blends	11%	35%	36%	18%
Synthetics and man-made materials	9.5%	71.5%	9%	10%
Silk	23%	25%	37%	15%

4.2.3. Dry-Cleaning

Dry-cleaning is a process of cleaning garments with the help of chemical solvents, pre-dominantly volatile organic solvents. Perchloroethylene (PERC, C_2Cl_4) is the most common solvent used, but it requires much more energy per kilogram of laundry compared to regular laundering (Tables 3 and 4). In addition to high energy consumption, the solvents used in dry-cleaning have negative health effects [60] and cause environmental hazards when not handled safely [61]. Professional wet cleaning is more energy efficient than regular laundering or dry cleaning and poses the least risk to human health and the environment of the cleaning methods listed in Table 3 [62].

Table 3. Estimated electricity usage of dry-cleaning and wet-cleaning processes/solvents [62].

Cleaning Process/Solvent	Electricity Use (KWh/kg Textiles)
GreenEarth® (decamethylcyclo-pentasiloxane D5)	1.195
Hydrocarbon	0.783
LCO_2	0.681
PERC	0.586
Wet cleaning	0.205

These different ways of cleaning textiles have varying environmental impacts and energy consumption. We have not found studies that document the relationship between their use and different fibers.

4.2.4. Washing Temperature and Program

The cleaning effectiveness of hand and machine washing depends on temperature, chemicals, amount of water and mechanical agitation. These four factors affect the laundry result (cleanliness) and wear of the garments. Both cleanliness and wear in turn affect the lifespan of garments. The washing temperature and washing cycle/program used have a great influence on the energy consumption of laundering. Cotton programs allow the whole capacity of the machine to be used, while gentler cycles are suited for smaller laundry loads. For example, for synthetics/easy care programs about half of the total load is usually used, and for the wool wash cycle it is usually recommended that around one-third of the maximum capacity of the machine is used [63].

In Europe, the average washing temperature is about 43 °C [64]. The lowest average washing temperatures (under 40°) are found in Spain and Portugal and the highest in Sweden, Norway, and Finland (above 46°) [65]. Most countries have lower average laundering temperatures than in

Europe. For example, the average temperature is about 31 °C in the USA [66], and about 18 °C in Japan [67]. It is difficult to estimate what the global average is, as various washing methods are used, and little is known about some, especially about hand laundering that is the dominant method in many rural developing areas. Therefore, in this article, we focus on figures of the developed countries.

The most reliable data on consumer behaviors come from two German studies Berkholz et al. [68] conducted a metering study in 100 German households. They measured the total electricity consumption for laundry washing in each household for one month (Table 4). The results show that a cotton cycle was the most commonly used, and that both cotton and synthetics were washed at higher temperature and heavier laundry load than wool and delicates such as silk. Kruschwitz, et al. [69] studied laundering habits of 236 German households during a 28-day test period. The households documented all 2867 washing cycles in a diary including weight of laundry and amount of detergents (Table 5).

Table 4. Washing programs and their parameters based on metering data from 100 households in Germany (Berkholz et al. [68] as cited in Tables 3 and 12 in Gooijer and Stamminger [70]).

Type	Temperature (°C)	Load Used (kg/cycle)	Energy Use per Load (kWh/cycle)	Energy Use per kg Laundry (kWh/kg)	Water Use per kg Laundry (L/kg)
Cotton	49.7	3.18	1.02	0.32	13.8
Mix	42.2	2.64	0.66	0.25	16.7
Easy care	39.3	2.8	0.67	0.24	15.7
Delicate	36.5	2.36	0.76	0.32	18.6
Wool	25	2.46	0.56	0.23	17.9

Table 5. Average wash load and temperature for different washing programs in Germany (*n* = 2763 wash cycles) (Table 5 and Figure 8 from Kruschwitz et al. [69]).

Washing Program	Number of Wash Cycles	Arithmetic Average Amount of Load with Standard Deviation (in kg per Wash Cycle)	Average Wash Temperature
Cotton	1967	3.4 ± 1.2	47.1
Synthetics	47	3.0 ± 1.0	44.1
Easy care	492	2.8 ± 1.3	38.8
Silk	1	-	20.0
Mix	74	3.7 ± 1.4	43.7
Wool	31	2.1 ± 1.1	30.3
Delicates	151	2.3 ± 1.2	34.6
Not specified	104	-	40.6

These studies show that both the washing temperature and program used vary between fibers. Even though the wool laundry load is smaller than the average load, the energy consumption per kg textiles is still less than the average. Water consumption per kilogram of textiles per laundry load is higher in delicates and wool wash cycles than other commonly used wash cycles (Table 4). However, water use in washing machines is highly dependent on: (i) the type of machine (vertical axis top loading machines use a lot more than horizontal drum types) [66,71]; (ii) the age of machine (new machines are more efficient due to stricter energy labelling requirements and improved automatic water level adjustment to fit the amount of laundry) [72,73]; (iii) maximum capacity of the machine [74]; and (iv) the selected program [68].

4.2.5. Microplastics

Microplastic particles, including the subset, microsynthetic fibers commonly referred to as microfibers, are now ubiquitous in aquatic and terrestrial ecosystems globally. Synthetic fibers are not readily biodegradable [75,76]. Estimates suggest that as much as 20% to 35% of all primary source microplastics in the marine environment are fibers from synthetic clothing, and the amount is increasing [11,12].

Microfibers can enter the environment through primary sources that include fibers shed from synthetic apparel and textiles during use and washing or through secondary sources, predominantly degradation and fragmentation of larger pieces of synthetic textile waste. Man-made fibers now constitute 70% of global fiber production [1].

The number of reliable peer-reviewed studies on microfiber loss from clothing is still small. We summarize the main findings from four published studies that have quantified microfiber shedding during washing. Browne et al. [77] quantified fibers lost in wastewater from washing blankets, fleeces, and shirts made from polyester. The authors concluded that a single polyester fleece garment can produce more than 1900 fibers per wash. Hartline et al. [78] tested five jackets to quantify microfiber shedding and test differences with washing machine type and garment age. The recovered microfiber mass per garment ranged from approximately 0 to 2 g, with the highest exceeding 0.3% of the unwashed garment mass. Microfiber masses from top-load machines were approximately seven times those from front-load machines.

Napper and Thompson [79] tested jumpers made of 100% polyester, 65%/35% polyester-cotton blend and 100% acrylic during several washing cycles and varying washing conditions. The amount of fibers shed by polyester and acrylic knits was highest during the first washes, while there were no significant changes for the polyester-cotton knit. For an average wash load of 6 kg, the acrylic sample had the highest release, over 700,000 fibers per wash, followed by polyester, almost 500,000 fibers. Polyester cotton blend had lowest release, 138,000 synthetic fibers. Pirc et al. [80] documented that during consequent washing cycles, the emissions initially decreased and then stabilized at approx. 0.0012% per unit weight. Release of fibers during tumble drying was approx. 3.5 times higher than during washing.

These studies show that textile, in addition to laundering conditions, characteristics such as how loose fibers are, fabric composition, garment construction, presence of insulation in garments such as jackets are all likely to influence fiber shedding during washing. The range in results and different units highlight the critical need for standardized testing protocols to define the magnitude of the problem and to quantify the effectiveness of mitigation strategies.

Man-made plant-based fibers are poorly understood as a source of potential persistent micro-particle pollution. In some studies, they have not been distinguished from petroleum-based plastic fibers, but recent studies have begun to identify fibers of cellulosic polymers separately from synthetic textile fibers [81–83].

The knowledge base on microplastics pollution is still new and there are many unanswered questions. It is however certain that synthetic fibers contribute significantly to the problem. Natural materials also lose fibers, but they are biodegradable in nature [84]. There is uncertainty about how microfibers from regenerated cellulosic fibers behave. Nevertheless, we know enough to say that the contribution to the spread of microplastics through laundry is dependent on properties of the textile and fiber.

4.2.6. Drying

Drying wet laundry requires energy that is either 'free' when the laundry is dried outdoors or in unheated rooms indoors, but comes at a cost if extra heating is required [85]. In general, drying laundry in a dryer uses more energy than washing the laundry in a washing machine [85]. Due to inherent properties of some fibers such as silk, wool and acetate, tumble-drying is usually not recommended.

As shown in Table 1, fibers have different abilities to take up moisture. Therefore, the moisture content in fibers varies after laundry, and different amounts of energy is required to dry them. In particular, many synthetics have a lower ability to take up moisture and less energy is needed to dry the same amount of laundry. However, they are more often dried in a dryer than many natural fibers such as wool and silk, that are preferentially air-dried as instructed by care label.

We did not find any literature on consumer practices related to drying of garments of specific materials. However, some examples for specific products were found. A recent survey showed that over 80% of American consumers use a tumble dryer to dry their t-shirts and jeans, while the share in Germany and Sweden was about 20%, and even less in Poland, 12% [86]. These products are mainly made of cotton. There are large differences between these countries in the ownership rates of clothes dryers, reported as 83% of USA households [87] compared to 16% of Polish households [85].

Methods used for drying vary greatly between countries and are dependent on the climate, economy, and culture. Textiles of different fibers differ in their likelihood of being dried with a dryer, which is the most energy-intensive form of drying. Because fibers vary in the amount of moisture they hold, energy use during tumble drying also differs with fiber type.

4.3. Number of Days in Use before Laundering

As we have previously shown, inherent fiber properties affect the soiling properties of garments, i.e., how easily textiles get dirty. In this section, we see if consumer studies confirm that these properties have an effect on laundering frequency during use.

A consumer survey in the UK showed that 97% of Britons wear at least some clothes more than once before laundering [88]. The items that are most frequently laundered after one use were swimwear, sportswear, and underwear. The items that were most often used more than once before laundering were jeans, trousers, and jumpers/cardigans (outer jackets/coats were not included in this question). In general, items worn next to skin are washed more frequently than outer garments.

Table 6 summarizes studies that report average number of wears between washing for specific garments [38]. This summary shows that the number of days in use before laundering varies between garment types, and between the same garment type made in different fibers. Some are generally washed after each use, while others are washed much less frequently.

Table 6. Number of days different garments are used before wash. Average estimate rounded to closest half day [38].

Garment	Norway [63,89] (3 Surveys)	Netherlands [89,90] (1–2 Surveys)	Greece [89]	Spain [89]	Other Countries	Average Estimate
Woolen sweater	8.9 (mode 10) >7.1 (mode > 10 days)	10.3				10
Cotton sweater	4.7 (mode 2)	6.9				5
Woolen undershirt or thin sweater	3.4 3.9 4.3	3.2	2.8	2.7	3.2 USA [91]	3
Cotton t-shirt	1.8 2.1 2.8	1.4 1.7	2.0	1.5	2.26 USA, Sweden, Germany and Poland [86]	1.5
Jeans	4.7 >5.7	3.3 4.2	3.0	3.6	9.5 Canada [92] 5.4 Australia [93] 8.9 Sweden [94] 8.24 USA, Sweden, Germany and Poland [86]	5.5
Blouse/shirt	1.9	1.6 2.0	2.0	1.6		2
Sports clothing	2.3	1.5				1.5
Thin socks	1.5	1.3	1.4	1.1		1.5
Wool socks					2.3 USA [91]	2.5
Underpants/briefs	1.2 1.3	1.1	1.2	1.1		1

Data in Table 6 show that the number of days between washing differs markedly between products of different fibers within the same product groups as well as between different types of garments. Comparison of similar wool and cotton products shows that woolen products were likely to be used about twice as long between washes than cotton products. In other words, consumers utilize the inherent properties of different fibers in relation to cleanliness to a certain degree.

4.4. Clothing Lifespans

The length of the period of clothing use is usually referred to as clothing lifespan or lifetime and often expressed in years, or sometimes number of wears, or number of washes. Recently, use of the term "duration of service" has become more common. Effective lifetime refers to the time the clothing is in active use, and can be shorter than the total use period when clothing is inactive and stored for periods of time. There are some differences in the way these terms are used. Long overall lifespan can mean either that the garment is used a lot and washed often, or the opposite, used and washed seldom but stored for a long time between uses.

Using real data on the actual service life of a product means that it can be determined how often a garment needs to be produced to fulfil a functional unit. If, for example, a functional unit of 10 years of wearing for a specific use area was assumed, a garment that lasts two years only needs to be manufactured five times, whereas a garment that lasts one year would need to be produced ten times [91]. Garments that remain unused do not contribute to any functional unit related to wearing.

Most Western consumers own a large amount of clothing, and do not necessarily remember when each item was acquired. Therefore, estimating the total length of lifespan as well as the active service life of garments that are used a lot is challenging.

Clothing lifespans have been discussed in some studies, but very little information is available on actual lifetimes and use times of clothing. For example Beton et al. [31] have estimated that all garments have a lifespan of 1–3 years based on expert opinions, but without referring to empirical research data. Results, expressed as average and the range of values, from various consumer studies on clothing lifespans are collected in Table 7 [38].

Table 7. Summary of garment lifespans in years from various studies and estimated average lifespan based on these data (only the period with one current owner is used, not the total age of preowned clothes) [38]

Garment Type	Wardrobe Audit Survey in Seven Countries [39]	Wardrobe Audit Interviews Norway (Textile Waste) [40]	Survey, Norway [95]	Online Survey, UK [96]	Survey, UK [97]	16 Households' Purchases, Netherlands [90]	Survey, Netherlands [98]	Survey (Germany, Poland, Sweden, & USA) [86]	Online Survey, Finland [99]	Total Lifespan, Average and Range
T-shirts	4.6	4.2		4.0	3.3	6.8		3–4	4.5	4.6 (3.3–6.8)
Blouses/shirts	4.6		5.6	3.3/4.3	3.6	7.2			5.7	4.8 (3.3–7.2)
Jumpers/sweaters	5.8		10.8 (wool)	4.5	3.7	7.1	6.17 (wool)			6.0 (3.7–10.8)
Suits	8.7									8.7
Jeans	3.9	4.3		3.8	3.1		2.45 (cotton)	3–4		3.5 (2.5–4.3)
Trousers/pants	4.9		4.4	5.4		6.2			5.3	4.7 (2.5–6.2)
Skirts	4.8	4.1		5.2		15.2				6.9 (4.1–15.2)
Dresses	4.5			4.7						7.1 (4.1–15.2)
Jackets/Blazers	5.3	4.0		6.5		11.5				6.8 (4.0–11.5)
Coats	6.3		6.4	6.2		11.6			7.6	7.0 (4.0–11.6)
Underwear briefs/boxers	2.5	4.4		2.4					3	3.1 (2.4–4.4)
Bras	3.0									3.5 (3.0–4.4)
Socks	3.6 (incl. stockings)	2.9		2.4	1.8				2.3	2.6 (1.8–3.6)
Average of all garments	4.7	4		3.3						4

Some consumer groups are more likely to keep their clothing longer than average, including men, older people, people on low incomes, and people in higher social grades. Socks, tights, and stockings as well as knickers and underpants have the shortest expected lifespans, while swimwear, jackets, blazers, and coats have the longest expected lifespans [96].

Survey data from seven countries [39] included the question, "When did you buy this clothes item or accessory?". Some garments were brand new while others were likely to be disposed of soon. We therefore assumed that the total lifespan is about double the average age of garments currently in use. The results for various types of garments are given in Table 8.

Comparison of garments made of different fibers showed that garments made of silk had the longest lifespans, 9.4 years (mainly based on the high proportion of men's ties). This was followed by cashmere clothing (6.7 years), wool blends (6.6 years), synthetics (6.3 years), 100% wool (5.3 years), cotton blends (4.2 years), merino wool (4.0 years), and finally the shortest lifespans were reported for 100% cotton garments with 3.6 years.

Table 8. Breakdown of garment ages based on fiber content [39]

Garment Category	Cotton and Blends	Synthetic/Man Made	Wool and Blends	Silk
Suits – jacket + trouser/skirt	7.0	6.6	9.7	-
Pants/trousers (casual/everyday)	4.2	5.1	4.8	-
Jackets/blazers (work/formal)	4.3	4.9	5.7	-
Overcoats/coats/raincoats (casual/everyday)	5.8	8.4	5.3	-
Jumpers/pullovers/sweaters/cardigans	5.6	6.5	6.0	-
Shirts/blouses/tops (casual/everyday)	3.8	6.2	6.0	8.5
Singlets/tanks (women's)	3.0	2.2	2.6	3.1
Ties (men's)	9.5	12.8	9.3	14.5
Socks/stockings	3.3	4.2	5.5	4.3
Underwear briefs/boxers	2.2	3.2	3.9	3.5

These studies have estimated the lifespan in years, but the active use is of interest for being able to apply the functional unit in LCA calculations. The UK Waste and Resources Action Programme (WRAP) has prepared a clothing longevity protocol with the aim of improving the sustainability of clothing across its life-cycle. They estimated use frequencies of five different garment examples [97]. According to their assumptions, jeans have the highest wearing frequency of 75 wears per year, followed by socks (50 wears), knitwear (50 wears), t-shirts (25 wears), and finally shirts (16 wears). They indicated that each clothing item is worn 12 h per wearing day, but this will also vary depending on how many times a day the user changes clothing. For example, sportswear is likely to be worn shorter periods per instance of wear, mainly during the activity [97].

Consumers' economical situations affects the amount of clothing owned and the length of clothing lifespans. Results from a survey in UK indicated that high active use of clothing correlated with factors around quality and value for money, low active use with factors such as fashion and branding. People with low income reported longer clothing lifespans [96].

Fiber content is also connected to clothing lifespans. In Norway, we asked what is the oldest garment that survey respondents still had in active use [100]. The average age of such garments was 15.8 years, but 14% of respondents had garments that that were over 30 years old and still in use. Garments in wool, such as sweaters, national costumes and suits, were most common amongst the oldest garments. A weakness of this information is that it does not say anything about how much each garment is used, so this question does not provide information about technical durability. However, the answers show that technical life is not the dominant parameter for longevity. This is also an important result of the Fletcher's "craft of use" project [101].

Research on reasons for clothing disposal can help in understanding the various drivers that shorten clothing lifespans [102]. We have found six studies that report disposal data quantitatively, expressed as a percentage of clothing by reasons for discarding items of clothing [103–108]. The distribution between the different reasons for disposal varied between these studies. Clothing being worn out or otherwise damaged was the major reason in four of these studies, followed by size and fit issues that were the most important reason in one study and second most important reason in three studies. Fashion, taste related issues, and being bored with clothing items was given as the main reason in one of the studies (that focused on young female students), and second most common reason in three studies. The other less frequently given disposal reasons included among other things, situational reasons such as lack of storage space. None of the studies analyzed clothing disposal reasons based on the fiber content.

The 2012 Nielsen survey also asked where the respondents were going to dispose of garments when they stopped using them. A higher proportion of wool garments were planned to be delivered for reuse (50%) than cotton (42%) or synthetics (44%) (Table 9). Synthetics were more likely to be binned (39%), while cotton products were more commonly recycled at home (i.e., used as rags). When comparing the reuse of cotton and wool, wool is 19% more likely to be delivered for reuse (through charities, family, friends, or sold) than are cotton products.

Table 9. Responses to the question "Which of the following would you use to dispose of this clothes item or accessory when no longer wanted?" Answers were divided according to fiber content [39].

Fiber Content	Donate to Charity	Donate to Family/Friends	Bin	Recycle at Home	Sell	Other	Don't Know	Total for Reuse
Cotton and blends	29%	11%	32%	14%	2%	6%	7%	42%
Wool and blends	27%	20%	31%	9%	4%	3%	7%	50%
Synthetics	28%	13%	39%	8%	3%	5%	6%	44%
Silk	28%	15%	32%	9%	4%	6%	7%	47%

There are conceptual and methodological challenges in studying the lifespan of clothing, but even larger challenges in establishing functional unit based thinking. At the same time, lifespan is often the most decisive variable in terms of reducing environmental impacts, and functional units are crucial for providing a basis for product comparison. Therefore, it is interesting to explore whether there are simple indicators that can be used as a unit to measure this. A possible indicator for longer lifespan is the physical strength of the garments. This can be measured in properties such as tensile or tear strength, resistance to abrasion or pilling, color fastness, and so on. Such a parametric requires that all clothes are tested and/or that it is established whether different fibers have different characteristics. However, using physical strength as the only indicator for lifetime disregards the fact that life span is also determined by social, emotional, and aesthetic factors.

Price is another possible indicator for lifespan. It is likely to impact the lifespan because consumers are likely to make more effort in choosing a suitable product when they have to use a larger portion of their income to purchase it. Thus, expensive clothing becomes a better more thoughtful purchase, regardless of whether the garment actually is technically better than cheaper alternatives. The converse is that people with low income are 'forced' more often to select clothing carefully, use it carefully, and to take better care of it. Therefore, cost should be seen related to income and is not an adequate indicator for lifespans on its own. This aspect should be studied further.

As already shown, clothes made of different fibers vary in lifespan, but comparisons should only be made between similar products, such as between t-shirts in cotton and wool. At the same time, individual differences are largely related to how long or how often the garments are used, and there is not a direct connection between garments' fiber content, price, or physical strength. We know more about the connection between fiber content and lifespans. Garments, while sold as a product, are lived as a process, and their durability depends on the way they are appreciated and included in the user's wardrobes.

5. Discussion: Comparing Apples and Oranges

Maintenance of clothing involves many different parameters. We have shown how washing temperature, dry-cleaning, number of days in use before laundering, washing machine program selection as well as drying method vary for different fibers. Therefore, it is possible to calculate different environmental contributions per fiber, because clothes made of diverse fibers are maintained differently.

The contribution of textiles to the spread of microplastics and other pollution related to plastics is significant. This is also directly related to use, because fibers loosen during laundering. This recently identified environmental impact category is not included in the two tools we have initially presented, nor in LCA software tools. Spread of microplastic pollution from clothing and textiles is a fiber-specific problem. Petrochemical based fibers spread microplastics, while current research indicates that natural fibers do not. More research is needed on the contribution of additives such as finishes, and on the role of man-made cellulosic fibers.

There is a fundamental and urgent need for standardized procedures for sampling, quantifying, and monitoring microplastic prevalence in habitats and for methods for impact assessment on ecosystem and human health in order to assemble robust data for mitigation responses and then to monitor the effectiveness of those responses. The Sustainable Apparel Coalition's Higg Index provides a possible avenue for including chemical impacts of microfibers when data become available, but preliminary evaluation indicates that physical impacts would require a new approach to develop a suitable indicator for the range of microplastic particles and fibers entering terrestrial, freshwater, and marine ecosystems.

The Global Fashion Agenda's Pulse report presents a cradle-to-gate environmental impact analysis based mainly on the MSI, and gives a ranking clearly identifying natural fibers as the least sustainable and synthetics, particularly recycled polyester and some other non-conventional materials, as the best choice for the environment [20,21]. Recommendations in the Pulse report do not take into consideration all the reservations around ranking garments on material scores alone [35]. This report has been widely read and referred to, but also criticized, inter alia, for favoring polyester and not addressing growth in production and consumption [109].

As we have seen, finishing treatments are not included as default in fiber comparisons. It is possible they are excluded because they are many and complicated, or because they are assumed to be similar for all fibers. Post treatments are also different for different fibers. For example, wool has inherent properties that other materials try to obtain through the use of environmentally hazardous chemicals, for example low flammability (brominated flame retardants) [110] and low odor intensity (triclosan and various kinds of silver salts) on synthetic and cellulosic materials [111]. Other examples include the treatment of synthetic fabrics through mechanically or chemically wearing down to mimic the cotton's soft "comfortable" surface and treating wool to resist shrinkage in washing. The various finishing processes help to give the textile attractive use properties but each comes with some environmental impacts.

MADE-BY stops at raw material before it is spun to yarn and, therefore, stops before spinning, dyeing, knitting, weaving, and various finishes before final assembly. MSI includes further steps up to material that is ready to be assembled into a final product. In relation to discussions about closing circular loops, recycled materials may appear to be better than they are in reality, as long as all the processes that need to be repeated are not counted in the scoring. All the different processes from raw materials to finished products in textile production require the use of chemicals, energy, and often also water, and lead to waste production. As we discussed in Section 1, fiber production only constitutes about 15% of the total CO_2 emissions [3].

Analysis shows that clothing lifespan is an extremely complex factor to measure. We do not have consensus on a standardized measuring unit, but the different studies operate with years, days, and times of use or laundering. At the same time, this is a parameter that is most important for environmental impacts. A t-shirt used once and then discarded to landfill has 100 times greater production-burden environmental impact than a t-shirt used 100 times before being discarded.

Many clothes can even be used much longer. These inequalities, for example between different fibers, can add up to several hundred-fold difference. At the same time, it is very complicated to try to foresee what will have a long and intense use phase.

Both maintenance and lifetime also raise questions about how to access representative data. It is possible to investigate the expected life, as the studies referenced have done. It is also possible to investigate how long existing clothes have been used. The two methods or survey questions both provide important information, but one is hypothetical and forward-looking, and the other is summarizing and directed backwards. Both can be investigated empirically.

There is also a third way to approach the question and that is to ask what lies within best practice. How long could a potential lifespan of a garment be? Example of maintenance with current practice indicates that a wool sweater is used twice as long as one made from cotton before washing. However, the different characteristics of the fiber would enable the difference to be greater. According to tests conducted by manufacturer WoolPrince, it is possible to wear a wool button-down shirt for 100 days before washing [112,113]. Likewise, it is possible to recycle post-consumer polyester garments, although this is usually not done. The best practices for washing frequency, cleaning method, etc. can be studied empirically and will be a good measure of potential improvements in both consumer use and in production. Whether it is best practice or expected or current practice for different garments that are the most relevant information depends on what the survey will be used for.

We have illustrated the complexity by discussing the weaknesses in the two tools most commonly used for comparing textiles' environmental impact today. MADE-BY emphasizes that they see the limitations of their ranking approach, but think the simplification ensures the user-friendliness of the tool and its workability as well as supporting progress and positive impact towards the larger environmental strategy [26]. They emphasize that the simplification is necessary in order to move forward in using more sustainable fibers and to be able to measure progress. Similarly, the Higg MSI specifies that it does not provide a holistic view of the impacts involved with material production [35]. According to Ecotextile News [114], planned expansion of the Higg Index from designers and manufacturers to a consumer facing labelling will be possible through unique digital identities and smart labels on products. Such a labelling system could contribute to greater transparency and better information to consumers. However, at the same time, it makes it even more difficult to ensure that the tools are accurate and used properly and to avoid the risk of even greater perverse consequences from any possible bias that may be embedded in the tools due to simplifications and lack of sufficient real consumer data.

6. Conclusions: Use Phase Does Matter

We started this article with two questions. The first was "Is there evidence that the use of textiles differs systematically between different fiber types ?" We have shown that the answer to this question is 'yes', but with reservation.

Based on today's knowledge, it is possible to address inequalities in use. Clothes of different fibers are washed differently. For example, wool requires less energy and chemicals to be kept clean, compared to cotton. Cotton requires a more powerful wash, and often also uses energy for drying and wrinkle removal. Synthetic fabrics become dirty faster and are washed more frequently. Another clear difference is that synthetic clothing releases microplastic fibers during use and also contributes to the problem by forming microplastics in the end-of-use phase due to fragmentation to micro- and nano-sized plastic particles. Indicators to quantify impacts have not yet been developed, but non-biodegradable fibers could be given a qualitative environmental impact score for use and end-of-life phases to reflect the negative impacts of microplastics until consensus is reached on methods for inclusion in ranking tools.

The major reason for reservation is the shortage of robust information on consumer use. Realistic incorporation of the use phase should be based on equivalent functional units. Comparing garments without regard to their functionality and performance is problematic. This includes both technical, functional, and aesthetic aspects that affect care and lifespan. Knowledge around these aspects is still limited. This applies to both the questions about how the use should be measured (in years, hours, days, occasions, etc.) and how to handle the clothes functionality. Part of the problem is that there are so many different properties (e.g., resistance to odor, dirt, water repellency, air resistance, heat and moisture regulation, color fastness, pilling, etc.), and little focus on functional properties when selling clothes (except for athletic and performance wear). Before the tools can incorporate such aspects, empirical and theoretical development is needed.

The other question we asked was: What are the consequences of comparing the environmental sustainability of clothing based on differences in production of fibers alone without including differences in their use?

Here we provide a reminder that clothes can be used hundreds of times, last hundreds of years and be inherited for generations. At the same time, many clothes are used only once and sometimes not even that. The different fibers not only have different environmental impacts, but also different functionality. To compare clothes in different fibers without taking use into account is like comparing apples and oranges; they are fundamentally different and, therefore, not suited to comparison. The consequence is that disposable products are equated with lasting products. It generally requires less environmental and economic inputs to produce clothing for short lifespans. By not including lifetime and use, products with short life are favored; plastic and man-made cellulosic fiber clothes will be favored over those of natural materials which have higher environmental costs at the material production stage. The most effective solutions for reducing the environmental impacts from the production and consumption of clothing most likely lie within reducing consumption and making fewer and better clothes. It is a paradox that the tools can favor change in the opposite direction. A Pulse report that is based on the Higg MSI recommends increased use of recycled polyester, mainly to replace cotton [20].

LCA has been developed as a tool to support environmental improvements. However, when used as a tool for ranking different products it is important that analyses include all stages of the life cycle, and not just the production, or part of the production phase. Full life cycle assessment is what is required under ISO rules for any comparison using LCA.

Fiber ranking tools compare fibers based on assessment of part of the production stage of clothing. However, fiber content affects all stages of the life cycle of clothes, including their functionality, and the way consumers take care of and use their clothing, and should be taken into consideration. This opens up sustainability assessments to better products that last longer and have the potential to fulfil their purpose instead of products that just pollute a little less in production and that can perhaps be recycled but are not really coveted. The result is that recycled polyester 'wins' in the rating tools, while textile fibers that, in reality, have long life and low environmental impact in use 'lose', such as wool and silk. In order for the analysis to really rank environmental impacts and to really become 'environmental LCA', the use phase must also be taken seriously.

In addition, ideas of circular economy and green growth currently dominate discussions related to sustainable consumption. Even though resource efficiency has increased, they have not lead to reduction in total environmental impacts of textiles and clothing production [115,116]. Unfortunately, this will continue until the core of environmental problems, growth in quantity and decline in product lifetimes, are addressed. When using LCA on clothing, a critical need is systematically working to find good functional units. Where technical life is longer than the social life, we should find ways to get more users, e.g., through shared use and renting or borrowing of clothing. A good example of such a scheme is passing on children's clothing to smaller children. This is a common practice that helps to increase the overall wear time of the clothes. Before good functional units have been established, the number of times of use is probably the best target of usage, because it includes both technical and social life.

The number of people in the world is increasing rapidly, and we all deserve to eat well and be well-dressed. If we are to achieve this goal, we will need to reduce the total environmental impacts in ways that really make an impact.

All known textile materials have advantages and disadvantages across all stages of their life cycle including production and use. Good utilization of resources would be to exploit the attributes of the products where they have a positive advantage. Comparing clothes based on the environmental impact of the fiber production stage without discussing their usability for different purposes is to reduce diversity and turn the debate away from what really can background information is only available to members of the MADE-BY network.

Future Studies

For improving the fiber comparison tools based on LCA thinking, studying the following areas should be especially prioritized for each tool or impact:

- What does the tool lead to, how is it used, and is the ranking in line with the perceptions of materials found in industry and among consumers?
- Which life cycle stages could be incorporated the tool, and where knowledge gaps still remain?
- Will it affect the credibility of work not to include microplastic or other obvious major environmental challenges such as biodegradability?
- What is the best process for obtaining information on the number of times and/or hours that each garment is used during its lifespan (service life) in order to calculate the environmental impacts for functional units related to wear instead of per garment or kg textiles?
- Can a method be developed for measuring effective lifetime, where the unit is adapted to the clothes' function?
- Are there other parameters besides fiber content that can be used to effectively differentiate between textiles with different environmental impact, such as dyeing/finishing methods, price, or technical quality?
- How can best practice scenarios used in other contexts and material groups be adapted to give a good method for quantifying the use phase for clothes in LCA?
- How can systematization of clothing categories be used so that it becomes easier to compare between studies? Currently the divisions are based partly on garment types and partly on fiber content and this makes comparisons different. Categories should be made larger, but at the same time more precise, for example durables and consumables in different fibers.
- If fiber continues to be the basis for comparisons, how can we investigate whether environmental impacts of different types of finishing common to various types of fiber and fabric could be included, and how specific fiber type and properties—such as regular vs. longer cotton fibers (Pima, Egyptian etc.), or coarse vs fine wool—could be included.
- The need for further research on the relationship between fibers, especially recycled fibers, and microplastic shedding properties.

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Appendix A

Table A1. MADE-BY Impact parameters and their weight in final classification. The scores for each of the parameters have been divided into three classes: good, neutral, and bad, and final classifications are calculated based on that. The data is based on 'world average' when possible, but for some cases only regionally specific data has been available. When setting the aggregated toxicology score of each fiber, MADE-BY uses a worst case scenario based on the most toxic chemical input. The complete background information is only available to members of the MADE-BY network.

Impact Category Parameters	Description	Units of Measure	Weight
Greenhouse gases (GHG)	Carbon dioxide equivalents (incl. fossil emissions without subtracting embedded carbon in product sequestration)	Kg CO_2 eq/kg fiber	20%
Human toxicity	• Acute toxicity • Chronic toxicity • Reproductive hazard • Carcinogenicity	LD/LC for oral, dermal, inhalation and skin irritation level Chronic toxicity score and skin sensitization level. The State of California Proposition 65 list for developmental hazard IARC Group	20%
Eco-toxicity	• Acute aquatic toxicity to fish • Eco-toxicity potential	LC50 96 h Based on Material Safety Data Sheet (MSDS) information	20%
Energy input	Total energy use including feedstock	MJ/kg fiber	13.33%
Water input	Water input	Kg water/kg fiber	13.33%
Land use	Yield	Kg fiber/ha	13.33%

Table A2. Overview of Higg tools and modules (some yet to be published).

Tool Group	Tool Name and Measured Impacts
Facility tools	The Higg Facility Social & Labor Module (Higg FSLM) Facility workforce standards and those of value chain partners, external engagement on social-labor issues with other facilities or organizations, community engagement
	The Higg Facility Environmental Module (Higg FEM) measures: • Environmental management systems • Energy use and greenhouse gas emissions • Water use • Wastewater • Emissions to air (if applicable) • Waste management • Chemical use and management
Brand tools	Higg Brand & Retail Module (Higg BRM) measures the following environmental impacts: • Greenhouse gas (GHG) emissions • Energy use • Water use • Water pollution • Deforestation • Hazardous chemicals • Animal welfare Social impacts: • Child labor • Discrimination • Forced labor • Sexual harassment and gender-based violence • in the workplace • Non-compliance with minimum wage laws • Bribery and corruption • Working time • Occupational health and safety • Responsible sourcing

Table A2. *Cont.*

Tool Group	Tool Name and Measured Impacts
Product tools	Higg Materials Sustainability Index (MSI) includes five impact categories: • global warming • eutrophication • water scarcity • abiotic resource depletion • chemistry
	The Higg MSI Contributor
	Higg Design & Development Module (DDM)
	Higg Product Module (PM)

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