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Review

Review of Methodological Choices in LCA-Based Textile and Apparel Rating Tools: Key Issues and Recommendations Relating to Assessment of Fabrics Made From Natural Fibre Types

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Abstract: Life cycle assessment (LCA) is a key tool for determining environmental impacts for textiles and apparel and is the basis for the publicly available Higg Material Sustainability Index (MSI) developed by the Sustainable Apparel Coalition (SAC). This paper reviews and evaluates the Higg MSI with respect to rating of fabrics made from natural fibre types, with the aim of providing a constructive analysis of methodological issues identified by comparison with the International Standards and LCA guidelines. The major issues identified by the review were: (1) lack of sufficient guidance for comparative analysis and public disclosure; (2) incomplete system boundaries and the choice of functional unit; (3) the choice of attributional LCA methods and variable methods applied for handling multi-functionality; (4) use of generalised data and small datasets, without reported sensitivity or uncertainty; (5) exclusion of important impact categories, choice of LCIA methods and lack of coverage of non-LCA assessed issues; and (6) the choice of the weighting and normalisation approach. This review found that the provision of, and adherence to the appropriate standards and best practice in LCA would rectify most of these issues. To achieve the laudable aims of the Higg MSI, further development and refinement is needed to ensure robust information is provided to improve the sustainability of textiles.

Keywords: Sustainable Apparel Coalition; Higg MSI; Product Environmental Footprint; PEF; LCA; textile; apparel; environmental rating tool

1. Introduction

The textile industry is a vital contributor to global societies, providing clothing that is essential for humanity [1]. Fabric and textile production systems are many and diverse, ranging from supply chains that utilise natural fibres produced by smallholder farmers, to manufactured, fossil fuel derived synthetic fibres produced in large-scale factories. As a result of production, manufacturing, use and disposal, all textiles leave an environmental 'footprint' [2]. In a globalised economy, this footprint is rarely limited to the region of the world where the garment is sold, used and disposed of, but extends to countries that produce raw materials, manufacture and process textiles and garments. Textile production is resource intensive and gives rise to substantial environmental impacts from greenhouse gases, energy and water use, chemicals, microplastics and wastes [3–8]. The environmental impacts are determined by raw material type, manufacturing processes, the length of time that garments are used prior to disposal, garment care, and the end-of-life disposal methods used, some of which are partly determined by the consumer [9–11].

To understand and reduce these environmental impacts, a range of industry, government and non-government-organisations (NGOs) have invested in developing methods and systems to quantify impacts. Life cycle assessment (LCA) is a robust and well-established method that has been commonly applied to determine full supply chain impacts and report these relative to the final product [12]. The Sustainable Apparel Coalition (SAC) has developed a suite of LCA-based Product Tools including: the Higg Material Sustainability Index—-MSI, the Higg Design and Development Module–DDM and the Higg Product Module—PM) to enable the textile and apparel industry to measure the environmental impact of apparel production. The Higg DDM and PM both utilise the Higg MSI to determine supply chain impacts, making the Higg MSI the fundamental tool in the suite, and consequently the focus of this review. The Higg MSI is also publicly available and aims to enable users to "assess materials to understand impacts", and to "compare materials to make better choices" [13].

The Higg MSI produces a cradle to fabric score that assesses impacts from the extraction or production of raw material source, yarn formation method, textile formation, preparation and colouration for each type of fabric. Currently it assesses four LCA impact categories (global warming, eutrophication, water scarcity and abiotic resource depletion/fossil fuels) and one semi-quantitative impact category (chemistry). The score gives an overall rating of impacts of fabrics that are grouped by fibre type, and differences between fibre types are principally related to raw material source [13].

The Higg MSI has been used to promote dramatic changes in the type of fabric used in the apparel sector [14] and participation in the Higg MSI has been used as evidence to support environmental impact claims [15–18]. The Global Fashion Agenda [14] used the Higg MSI textile scores to recommend reducing conventional cotton textile production by 30% and substituting the demand with polyester textiles to reduce impacts from water use. While these applications are consistent with the stated goals of the Higg MSI, the ability of the Higg MSI to appropriately support such far-reaching conclusions must be tested by considering a range of methodological factors, together with the robustness and representativeness of the datasets compared to the LCA standards and guidelines.

To address this, the review aimed to i) examine the Higg MSI method, including the robustness and representativeness of the datasets used, compared to the LCA standards and guidelines with specific reference to fabrics based on natural fibres, and ii) assess the suitability of the Higg MSI to make comparative assertions between textiles or support claims of environmental sustainability. Examples have been provided for cotton and wool, as these are the major cellulosic and protein-based natural fabrics respectively. The review summarises a series of key issues and potential solutions related to these aims, to prompt improvement of the method, data and tools and to advance the goal of improving the sustainability of the global textiles industry.

2. Materials and Methods

The Higg MSI was assessed by reviewing the methods [19] and database [13] with comparison to the international LCA standards and guidelines, which form the basis for LCA and provide specific guidance where comparisons and public environmental disclosures are to be made, as is the case with the Higg MSI (Table 1). This systematic review followed a 3-step approach: (1) comparison of Higg MSI method to international LCA standards and guidelines to identify inconsistencies and issues (specifically each section of the Higg MSI was compared to the equivalent section in the LCA standards and guidelines), (2) classification of key issues that were expected to materially affect the robustness of the Higg MSI, and (3) a thorough analysis of these key issues, with the aim of providing recommendations for improvement. Examples were provided for scope and data related issues to demonstrate the significance of these issues for two major fabrics made from natural fibre. Examples of impact assessment related issues were not provided because of a lack of data, or a lack of transparency in the current methods.

Table 1. Standards, guidelines and product category rules referred to in the review.

Abbreviation	Standard/Guideline	Reference
ISO 14040	ISO 14040:2006, Environmental management—Life cycle assessment—Principles and framework	[20]
ISO 14044	ISO 14044:2006, Environmental management—Life cycle assessment—Requirements and guidelines	[21]
ISO 14025	ISO 14025:2006, Environmental labels and declarations	[22]
ILCD Handbook	International Reference Life Cycle Data System (ILCD)	[23]
PEF	EU Product Environmental Footprint (PEF) Guide	[24]
PEFCR guidance	EU Product Environmental Footprint Category Rules Guidance	[25]
T-shirt PEFCR	Product Environmental Footprint Category Rules (PEFCR) T-shirts	[26]
Higg MSI methodology	Sustainable Apparel Coalition (SAC) Higg Materials Sustainability Index (MSI) Methodology	[13]
IWTO Wool LCA	Guidelines for conducting a life cycle assessment of the environmental performance of wool textiles	[27]
SAC PCR Guidance	Sustainable Apparel Coalition Product Category Rule Guidance 2013	[28]
Footwear pilot PEF	The Footwear Product Environmental Footprint (PEF) Pilot-First Draft Product Environmental Footprint Category Rules (PEFCR) commissioned by SAC.	[29]

3. Results and Discussion

The methodological and practical issues were broadly categorised into the following areas: (1) guidance for comparative analysis and public disclosure, (2) choice of system boundaries and functional unit, (3) choice of LCA method and handling multi-functionality, (4) data quality, transparency; and handling of uncertainty, (5) exclusion of important impact categories, LCIA methods and coverage of non-LCA assessed issues, and (6) weighting and normalisation. In the following section these issues are discussed and recommendations to address them are provided.

3.1. Guidance for Comparative Analysis and Public Disclosure

Where results are made available for public comparison and promotion of one product and another, both ISO (via the 14020 series and Product Category Rules—PCRs and Environmental Product Declarations—EPDs) and PEF (via PEFCRs) provide a strong and clear structure for ensuring analyses are made 'on like terms' to fulfil requirements of Section 5.3 of ISO 14044. Similarly, the ILCD has prescriptive requirements for comparative studies to ensure equivalence between product systems being compared [30]. While the Higg MSI is not a sustainability certification scheme and does not claim to be ISO complaint, it was compared to ISO 14020 and 14040 series as they represent the most robust and scientifically rigorous standard for comparative LCA. Review of the Higg MSI methods [19] showed no process has been developed to parallel these systems (see Figure 1). ISO 14025 and product category rules (PCRs) are developed to provide detailed rules on how to model the life cycle of a product in a specific category. The results of an LCA that uses these PCR can then be used for an external Environmental Product Declaration (EPD). Effectively, PEFCRs are the PEF version of PCRs. PEF studies that are for external communication and comparison require more rigor than PEF studies for internal communication, and in the former, these need to be consistent with both the PEF guide and PEFCRs, while for the latter these can be completed based on only the PEF guide.

While it could be argued that the Higg MSI does not aim to provide the level of rigour of an EPD, and that disclaimers are made regarding the use of the data, the website and tool clearly encourages users to compare products to reduce impacts [13], and therefore promotes comparisons using a public platform. According to the SAC [19] in the future, the Higg MSI will be leveraged for the Higg Product Footprint Module (PM), thus any issues with the Higg MSI will flow onto the PM. The goal of the PM will be to create a consumer-facing product score which is aligned with the European Commission Product Environmental Footprint Category Rules (PEFCRs). It is contended that this requires a similar level of rigour to the established PCR system to ensure comparability between datasets and results. Moreover, the database has been used to promote comparisons between fabrics i.e., [14]. Additionally, textile companies have used the Higg MSI to compare fabrics made from different raw materials, and to make comparative environmental claims about fabrics [15–18,31–33]. The use of the Higg MSI as evidence to support environmental sustainability claims, considering the limitations, has been cited as a key concern because of the possibility of results being used for so-called 'green-washing' [34]; that is, non-substantiated and potentially misleading environmental marketing claims.

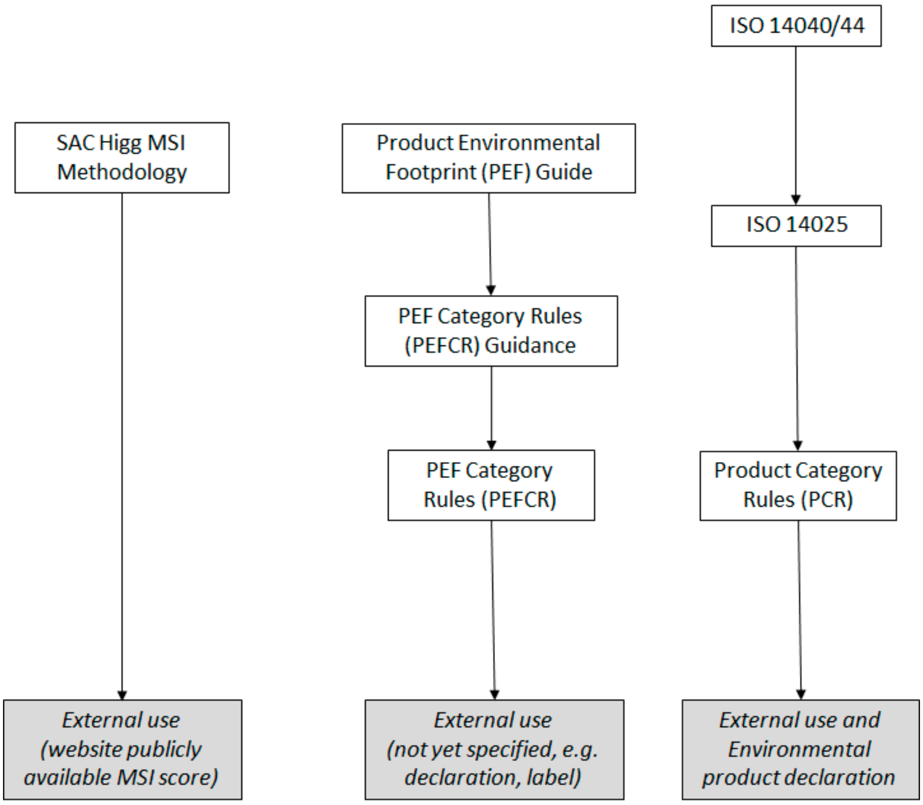


Figure 1. Comparison of Higg Material Sustainability Index (MSI), PEF method and the PCR concept based on ISO 14040/44 assessments for external use and declarations.

Considering the Higg MSI does not have equivalent requirements to PCRs, a review of the methods was conducted to assess compliance with the ISO 14044 requirements for comparative assertions. From this review, it was found that the Higg MSI guidelines function at a level that is unsuitable for public disclosures, because there is currently no robust way to ensure the Higg MSI scores are developed consistently. Partly this is because two data submission methods are permitted: with data being submitted either as process level inventories that enable modelling of impacts, or LCIA results that have been modelled independently (Section: The Higg MSI Data Submission Types, in [19]). The ability to submit LCIA data without requirement for standardisation of common variables such as allocation methods, which are commonly standardised in PCRs, potentially results in non-standardised comparisons. This results in an inconsistency with the ILCD because of the potential inconsistency with data submission (Section: Provisions, 6.10 Comparisons between systems, in [30]). It was therefore difficult to ascertain whether consistent choices were made around such issues as data quality requirements (ISO 14044, section 4.2.3.6.2) and equivalent system boundaries and methodological considerations, such as the choice of attributional or consequential LCA methods or specific method choices with respect to handling multifunctionality (ISO 14044, Section 4.2.3.7). Moreover, the following inconsistencies were noted with respect to compliance with ISO 14044; lack of comprehensive coverage of category indicators (ISO 14044, Section 4.4.5); requirement to perform category indicator by category indicator comparison (ISO 14044, Section 4.4.5); the use of weighing (ISO 14044, Section 4.4.5) and the lack of sensitivity and uncertainty analysis (ISO 14044, Section 4.4.5).

An example of the potential inconsistency with the Higg MSI arises from the acceptance of data in two forms, Type 1: data inputs/outputs at the process level, and Type 2: LCIA results that have been modelled by independent companies. Considering the latter option, it is not possible to ensure consistent methods (as required by ISO 14040, 14044, 14025, and PEFCR) using this approach.

These issues indicate the Higg MSI is not sufficiently developed to support comparative assertions with public disclosure. Considering the level of development of the Higg MSI currently, it would be more suitable if the Higg MSI was restricted for internal use only (i.e., no public disclosure). In addition, further development focusing on adoption of new, more specific guidance and adherence to this guidance, such as what is required in a PCR, is warranted.

3.2. Choice of System Boundaries and Functional Unit

The ISO 14044 defines the system boundaries for life cycle assessment as a set of criteria specifying which unit processes are part of a product system and thus determines which processes shall be included within the LCA [21]. The choice of system boundary is closely linked to the goal of the study. The functional unit is generally the unit that represents the function of the system and (particularly for cradle-to-gate LCA) represents the reference flow, or the product that crosses the system boundary. Thus, the two are interlinked. The Higg MSI applies a cradle-to-gate system boundary encompassing two out of four major lifecycle stages, that aims to include all impacts up to and including fabric manufacture (Figure 2).

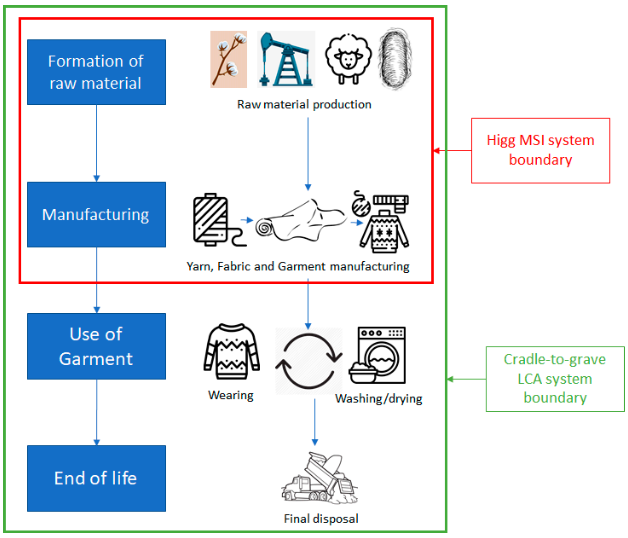


Figure 2. Comparison of the Higg MSI system boundary to a cradle-to-grave LCA system boundary.

A system boundary related challenges exist regarding the exclusion of the use phase and end-of-life in the Higg MSI, particularly in the context of a comparative analysis, where this choice requires careful consideration and justification. This must be done to ensure that the exclusion of life cycle stages, processes, inputs or outputs do not significantly change the overall conclusions of the study (ISO 14044, Section 4.2.3.3.1), to avoid the risk of unintended outcomes and burden shifting when comparisons are made. There has been no documented consideration and justification of this exclusion in the Higg MSI system, and this system boundary choice has been evaluated here with reference to the LCA literature.

Garment use has been demonstrated to contribute substantially to the environmental impacts of garments [35,36] because of the laundering requirements, and because of the duration of wear life. The review of Muthu [37] found that this stage contributed from 31–96% of total GHG life cycle impacts, and varied depending on fabric and garment type. Design choice, including choice of fibre type, choice of fabric structure, garment quality and makeup, and choice of garment style has a pivotal influence on the wear lifetime of the garment and the washing requirements [38–42]. Additionally, the choice of functional unit (or more precisely, reference flow), based on fabric mass, may not relate to the true function of a garment (i.e., the number of years of serviceable garment life) because this does not consider the implications for garment durability. Minimising garment mass at the expense of durability could result in lower apparent environmental impacts for 'throw away' fast fashion garments without considering that (i) additional garments are required to deliver a similar functional requirement (i.e., a certain number of years of serviceable garment life) as longer lived garments, and (ii) that additional end-of-life impacts may result from shorter lived garments compared to longer lived garments. This highlights the potential for burden shifting and potentially confounded recommendations, when comparing the results of the Higg MSI.

Similarly, an unintended consequence could occur if differences in washing requirements between fabrics made from different fibre types are not considered. For example, wool garments, such as sweaters, are worn more times prior to washing, and are washed and dried with lower impact techniques than other fabrics [36]. Considering washing and drying are the primary processes that contribute to the environmental impacts from clothing in the use phase [43,44], the exclusion of the use phase may result in burden shifting if fabrics types with lower impacts in the raw material and manufacturing stages have higher washing frequencies in the use phase.

For example, to investigate the potential risk when comparing different fabric types based on the Higg MSI score, an analysis was performed of three dissimilar fabrics made from either natural fibres (wool, cotton) or a synthetic fibre (polyester), by expanding the MSI score to include the impacts of garment use and garment care. Table 2 shows the impact of the most influential factor in use phase assessment: length of garment use, based on the study of Laitala et al. [36] and Table 3 includes the impacts from GHG, water stress and energy (reported in Higg MSI units) associated with garment care. It was assumed that dry-cleaning rate for sweaters was zero. Garments that are dry-cleaned may have higher environmental impacts as this process requires more energy per kilogram of laundry compared to regular laundering [36]. Noting this, conclusions may differ for garments that are dry-cleaned more frequently, such as suits. The example shows that the apparent differential between wool, cotton and polyester reduced from between 16 (wool and polyester) and 54 (cotton and polyester) per kilogram of fabric to between (-) 4.4 (wool and polyester) and 14.3 (cotton and polyester) when garment lifetime and care requirements were taken into account. This 51–84% reduction in the difference between the fabric types, indicated the choice of system boundary and particularly the exclusion of the use phase overestimated the difference between fabrics based on natural fibres and fabrics based on synthetic fibres. Importantly, in at least one example the differences in use phase practices could lead to a different ordering in the rating, opening the possibility of Higg MSI ratings providing incorrect guidance.

Considering these findings, application of results from the Higg MSI, e.g., [14] to promote the use of 'lower impact' fabric types is not supported, because impacts from the use phase and end-of-life have not been considered, elevating the risk of burden shifting and 'false positive' recommendations in some instances. Consequently, it is recommended that comparative assertions are only made where system boundaries are equivalent, and a complete assessment of the use phase and end-of-life is included. We concluded that further development is required to enable comparison of synthetic and natural fibres to overcome the current limitation. Additionally, revision of the functional unit to reflect garment function (i.e., the number of years of serviceable life for the garment) is required to overcome limitations with comparisons made on the basis of fabric mass. Assessment of the years of serviceable life of a garment can be determined from scientifically robust consumer surveys, applying an evidence-based approach, consistent with LCA principles and guidelines. This is preferable to using indicators such as fabric durability, which is usually based on the material properties of a garment rather than user behaviour and consumption patterns [47] and may have a low correlation with actual consumer decisions regarding whether garments are kept in use or disposed [46].

Table 2. Effect of product lifetime on Higg MSI impacts for an outerwear jumper.

Fabric Type	Higg MSI Score per 1 kg of Fabric [a]	Lifetime (Years) [b]		Higg MSI Score (Amortised over the Years of Garment Wear Life to Approximate Impacts Relative to Active Garment Life)	
		Minimum	Maximum	Minimum lifetime	Maximum lifetime
Polyester	51.6	3.7	7.1	13.9	7.3
Cotton	105.6	3.7	7.1	28.5	14.9
Wool	89.6	3.7	10.8	24.2	8.3

[a] Higg MSI values accessed on the 21/11/2018, including finishing impacts of 7.6. [b] Laitala et al. [36].

Table 3. Effect of product lifetime, washing and drying frequency on Higg MSI impacts for an outerwear jumper.

Fabric Type	Washing and Drying Impacts Reported in Higg MSI Units (per 1 kg of Fabric Washed/Dried) [a]	Washes per yr Based on Garment Owned and Wears per Year (Years) [b]	Higg MSI Score per 1 kg of Fabric Washed/Dried per Year	Corrected Higg MSI Score (Reported per Year of Garment Wear Life) [c]			
				Minimum Lifetime	Percent Reduction Compared to Initial Fabric Score [d]	Maximum Lifetime	Percent Reduction Compared to Initial Fabric Score [d]
Polyester	**1.33**	**8.40**	11.18	25.12	51%	18.44	64%
Cotton	1.30	8.40	10.92	39.46	63%	25.79	76%
Wool	1.30	4.4	5.8	30.0	67%	14.1	84%

[a] Higg MSI score adjusted for temperature based on Laitala et al. [36]. The additional impacts for washing and drying polyester were: 0.22 kg CO_2-e global warming, 2.67 MJ fossil energy, water stress of 2.83 L H_2O-e and 0.001 kg PO_4-eq eutrophication. The additional impacts for washing and drying wool and cotton were: 0.22 kg CO_2-e global warming, 2.62 MJ fossil energy, water stress of 2.81 L H_2O-e and 0.001 kg PO_4-eq eutrophication.[b] Washes per year was calculated by: wear per wash (from [45])/ (365-day x 80% year/ jumpers owned (from [46]). Washes per year for polyester were assumed to be the same as cotton. [c] Corrected Higg MSI score (Table 2) + Higg MSI score per 1 kg of fabric washed/dried per year. [d] Corrected Higg MSI score compared to Higg MSI score per 1 kg of fabric in Table 2.

3.3. *Choice of LCA Method and Implications for Handling of Multi-Functionality*

Depending on the goal and scope, an LCA study may be conducted using either attributional (aLCA) or consequential (cLCA) methods. The choice of appropriate methods has been covered in the ILCD [48] but has not been explicitly addressed in the ISO Standards 14040 or 14044, though choices relating to methods for handling multi-functionality (allocation) have been specified and this is a key difference between the methods. The SAC [19] Higg MSI method, and others such as PEF [24] have not given prescriptive guidance regarding use of aLCA or cLCA methods and do not give proscriptive guidance with respect to methods for handling multi-functionality. This leaves a degree of ambiguity in the Higg MSI and potential inconsistencies in the underlying datasets and results. Having noted this, the review of primary data sources revealed a series of studies that had aims and methods consistent with attributional LCAs i.e., [49–52] and one study that had aims and methods consistent with consequential LCA [53].

Historically, most LCA research has used the aLCA approach to identify hotspots and track environmental impacts through a product's supply chain through to during use and disposal [12]. This 'accounting' assessment characterises the average production of a static system irrespective of market trends and external influences. In contrast, cLCA is focused on determining the environmental impacts of a decision (i.e., to use more or less of a product) and is recommended where decision support is the primary aim [30,54], because this modelling approach specifically aims to take into account the impact of the change in supply or demand, while aLCA does not. While this is a topic of debate in LCA science, arguably aLCA could be considered unsuitable where there is an inherent drive to influence supply and demand [55,56]. The ILCD Handbook explicitly recommends attributional modelling for micro-level decisions and consequential modelling for macro-level decisions [30]. It is assumed that micro-level decisions have limited and no structural consequences outside the decision-context, while macro-level are assumed to have structural consequences outside the decision-context. While it could be suitable for the Higg MSI to use aLCA modelling for micro-level decisions, macro-level recommendations have also been made using the Higg MSI. For example, the Higg MSI was used to underpin recommendations to reduce cotton use by 30% [14]. Considering the Higg MSI promotes comparison and choice of 'better' fabrics and aims to support future labelling systems, the suitability of aLCA methods to underpin the system warrants further investigation.

For example, the relevance of this difference can be explored by considering the handling of co-products, which are common in natural fibre production systems. Figure 3 shows the co-products of the example fabrics, cotton and wool. For the cotton fabric production system, cotton fibre (lint) is the main product and cottonseed is a valuable co-product, which is in the order of 53% of the total mass of the harvested cotton [57]. Cottonseed is a source of oil (15–22% of seed mass) and protein (17% by mass) [58,59]. Cottonseed is typically fed to livestock or processed to produce vegetable oil and cotton seed meal (which is high in protein) and these products are globally traded. When considered using consequential modelling, these important co-products displace marginal vegetable oil and protein meal, which are typically known to generate high environmental impacts i.e., palm oil [60] and soybean meal, [61]. In wool production systems, sheep meat is an important co-product, which displaces meat from alternative sheep systems that don't produce high quality wool, or other red meat production systems such as beef. Wiedemann et al. [62] found that application of system expansion in wool systems resulted in 31% and 47% lower impacts than when an allocation approach was used, because of the influence of changes in the co-product system. These results indicate that cLCA modelling may result in different results than aLCA modelling, with significant implications for understanding the environmental impacts of fabric made from natural fibre types.

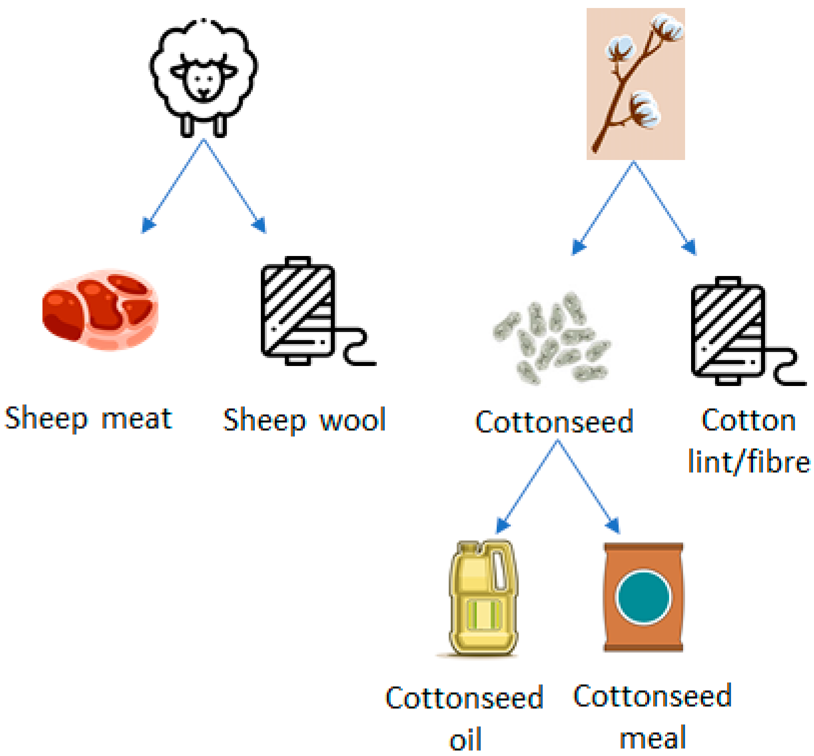


Figure 3. Diagram of primary products and co-products for natural fibres: wool and cotton.

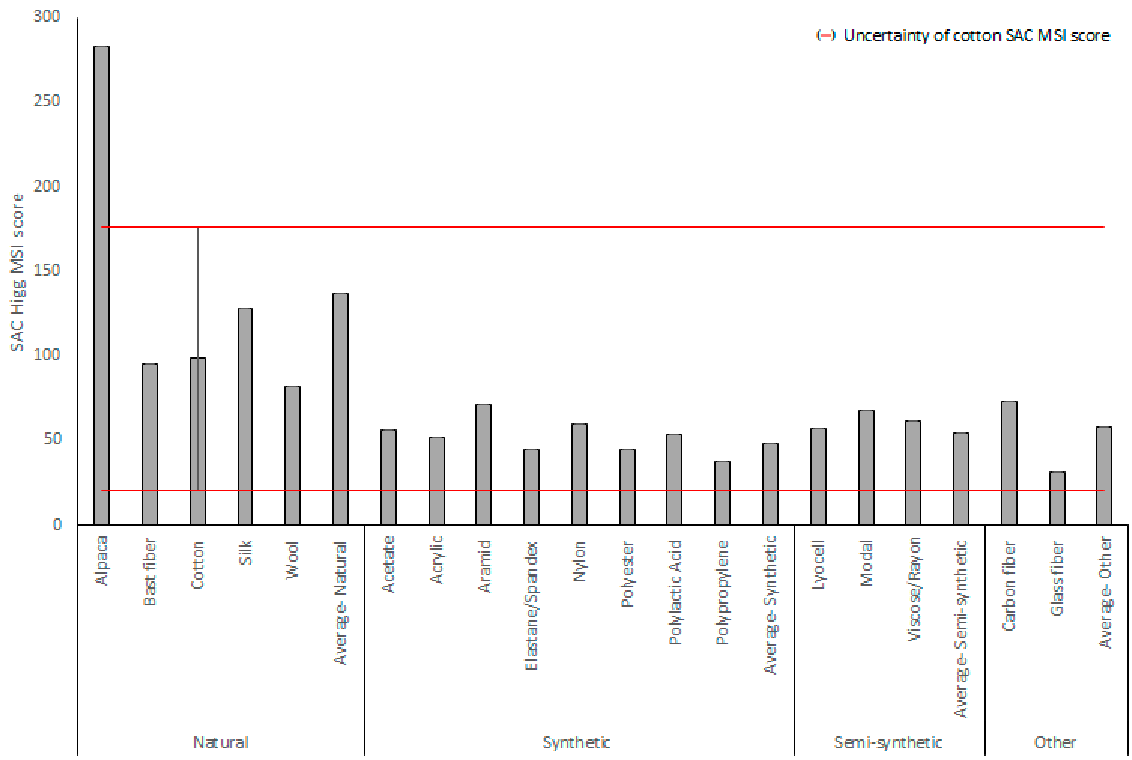
Considering the goals of the Higg MSI, it is contended here that cLCA methods would be more suitable than aLCA methods in the Higg MSI and that future iterations of the system would be enhanced by adopting cLCA datasets and methods to improve the quality of the decision support aspect of the system. Where aLCA results are used to propose changes in environmental performance that may result in macro-level changes, sensitivity analyses should be performed using cLCA methods to test the outcomes prior to implementation to avoid the risk of unintended outcomes that would challenge a core function of the Higg MSI.

3.4. Data quality, Transparency and Handling of Uncertainty

To comply with ISO requirements, the Higg MSI must apply high standards with respect to data quality assurance because of the public disclosure and the comparative nature of the results. The Higg MSI database was found to rely heavily on three source documents: van der Velden et al. [51] for yarn formation and preparation, Cotton Incorporated [52] for colourisation and the Koç and Kaplan [63] study for textile formation (which reported results from one factory in Turkey). These data were applied for multiple fibre types, resulting in a high proportion of the resulting Higg MSI score relying on similar or uniform textile manufacturing processes (i.e., for yarn formation, textile formation, preparation, colouration and additional colouring and finishing). For example, generalised data were used to assess the yarn formation, textile formation, preparation and colouration stages for lyocell fabric, contributing to over 56% of the total Higg MSI score for this fabric. Similarly, generalised data was used to assess yarn formation, textile formation, preparation and colouration stage for wool fabric, with these stages contributing 25% of the wool fabric Higg MSI score. The heavy reliance on generalised data from a limited number of studies may not be representative of global textile manufacturing trends and has the effect of reducing the representativeness of the results for different fabrics, and inherently reducing variability between fabric types because of the standardisation of underlying datasets. This is especially relevant where data from the Koç and Kaplan [63] study was used, as it only investigated only one textile manufacturing plant in Turkey, but was used in the Higg MSI for 16 out of 18 fabrics in the textile formation stage, and 5 out of 18 fabrics in the yarn formation stage. The impact of such heavy reliance on Koç and Kaplan [63], van der Velden et al. [51] and Cotton Incorporated [52] in the yarn formation to colouration stages has not been assessed or reported. It was also found that there was a lack of regional specificity in the datasets used in the Higg MSI across multiple fabric types, despite the regional specificity of impacts such as eutrophication and water scarcity. The datasets and modelling methods applied to generate results in the Higg MSI were also not transparent in all instances. Some source documents, for example, cover only one or two impact categories while four were reported in the Higg MSI, making verification difficult without additional information. Additionally, multiple source references used in the Higg MSI utilise small and unrepresentative datasets. For example, the Higg MSI raw material stage of bast fabric (flax and hemp) are based on the Turunen and van der Werf [50] study, which was developed using a small, non-verified farm inventory dataset from a subset of European countries, and does not include major hemp producers such as China or Canada [64]. Similarly, inventory data for silk are based on the Vollrath, et al. [53] study, which was developed using a small, unrepresentative low technology silk production farm inventory from the Karnataka State in India, and does not include China which produces over 82% of the worlds silk via a high technology production system [65].

Despite the high reliance on generalised datasets, and small or unrepresentative datasets, the Higg MSI contains no uncertainty analysis, which is considered best practice in published LCA and is needed to make comparative assertions with scientific confidence [66,67]. It is therefore unclear whether apparent differences between fabric types are statistically valid. Considering operational methods exist to model uncertainty, this can be readily undertaken.

For example, to investigate the potential significance of uncertainty on Higg MSI scores, uncertainty data from the major cotton dataset developed by Cotton Inc [52] was used to produce an idealised error margin for cotton MSI values, for illustrative purposes (see Figure 4). The idealised uncertainty represented one standard deviation from the mean for global cotton [52]. Interestingly, this resulted in the Higg MSI value for cotton overlapping with the mean value for all other fabrics, with the exception of alpaca.



[a] A 79% uncertainty was calculated from the average coefficient of variation of global warming, primary energy demand, eutrophication and water consumption for impact measures in the average agricultural phase of cotton production in U.S.A, China and India from the Cotton Incorporated [52] report. The diverse production regions are expected to influence the uncertainty in the data. (–) Potential range the cotton SAC MSI score.

Figure 4. Higg MSI rating of fabrics compared with cotton (79% [a]) uncertainty ranges.

Considering the current extensive use of generalised data and small datasets in the Higg MSI, provision of uncertainty analysis results is required to understand if the apparent differences between fabrics are statistically significant. Moreover, an analysis of the impact of generalised data with comparison with specific industry data would provide key insight into the implications of using these data extensively in the tool. In addition, it is recommended that the transparency of data sources and methods used is improved by providing more detailed documentation with respect to the modelling of each process contained in the Higg MSI.

3.5. Exclusion of Important Impact Categories, LCIA Methods and Coverage of Non-LCA Assessed Issues

As stated by the ISO 14040, comparative product assessment using LCA should employ a sufficiently comprehensive set of category indictors and be used as part of a more comprehensive decision process or used to understand the broad impacts or general trade-offs. The Higg MSI currently reports impacts from a subset of LCA impact categories, namely global warming, eutrophication, water scarcity and abiotic resource depletion (fossil fuels). In addition to this, a qualitative assessment of impacts from chemicals is included. The method notes that a broader suite of impact categories has been evaluated for inclusion, including ecotoxicity, human toxicity, land occupation and abiotic resource depletion (minerals), and these have generally not been adopted where the methods were considered immature. While the limitation of categories to well documented LCIA methods may increase the robustness of Higg MSI, overall the limited suite of impact categories currently used fails to capture a number of important environmental burdens from apparel. The T-shirt PEFCR [26] identifies acidification, climate change, resource use, respiratory inorganics, water scarcity, freshwater eutrophication and marine eutrophication as the most relevant impact categories for T-shirts; as assesses a total of 13 impact categorises in the benchmarking assessment. Thus, while the limited suite of impact categories is reasonable, the outcome of comparing fabrics on a small subset of indicators is arguably insufficient to meet the comprehensiveness requirement of the Standard.

With respect to the applied methods, it was noted that use of the generalised eutrophication indicator (CML) is not supported by the ILCD or PEF guidelines, as it assumes 100% of nutrient emissions will cause eutrophication and the fate of nutrients, environmental transport, attenuation or use of nutrients in an agricultural system is not included in the model and thus, the CML model is a "worst case scenario" [24,48,68].

Additionally, LCIA should not provide the sole basis of comparative assertion intended for public disclosures of overall environmental superiority or equivalence [20]. It is also noted that additional non-LCA impact categories that have not been considered in the Higg MSI to date are also relevant for textiles. For example, microplastics are a particular area of concern for textiles and are not included. Microplastics are small (<5 mm) pieces of debris resulting from the weathering of consumer and industrial products, including textiles [69,70]. Recent research has shown microplastic pollution has global distribution, including marine, lakes, rivers, and terrestrial environment [71–77]. Chemical toxicity from microplastics can occur due to the leaching of component monomers, endogenous additives or adsorbed environmental pollutants [78–80]. There is also the potential for microplastics to impact human health, however there is limited research on dose-dependent human toxicity, accumulative effects or exposure concentrations [81]. Washing textiles made from synthetic materials has been identified as a source of environmental microfibre pollution [70,71,77,82–86]. Furthermore, Pirc et al. [87] found that the release of microfibres during tumble drying was approximately 3.5 times higher than during washing, suggesting that microplastics in the atmosphere may also originate from clothes drying. While current LCIA methods to quantify flows of microfibres from apparel to the environment are lacking, this evidence suggests that microplastics are an important environmental (non-LCA) impact aspect for inclusion in textile LCAs and the Higg MSI, to meet the comprehensiveness requirements of ISO 14044 that *"An LCIA shall not provide the sole basis of comparative assertion intended to be disclosed to the public of overall environmental superiority or equivalence, as additional information will be necessary to overcome some of the inherent limitations in the LCIA."*, and to avoid the risk of burden shifting between assessed and non-assessed impact categories.

Considering these review findings, a broader range of indicators are required for assessing the sustainability of textiles; and at a minimum the inclusion of microplastic impacts is a priority considering the relevance for textiles. It is noted that non-LCA methods, as have been applied for chemical impacts, may be warranted for a wider range of categories that are difficult to assess with LCA, to reduce the risk of skewed results from an incomplete analysis, and to reduce the risk of burden shifting between impact categories.

3.6. Weighting and Normalisation

The Higg MSI method involves a normalisation and weighting process to aggregate impacts from greenhouse gas emissions, fossil energy, water stress and eutrophication into a single score. The normalisation is based on the weighted average of impacts for a representative set of the most-often-used materials for the relevant industries. While both normalisation and weighting are optional elements of LCIA, the ISO 14044 requires that normalisation and weighting methods are consistent with the goal and scope of the LCA and are fully transparent, and notes that *"there is no scientific basis for reducing LCA results to a single overall score or number"* (ISO 14044, Section 4.1) and *"weighting steps are based on value-choices and are not scientifically based."* (ISO 14044, Section 4.4.3.4). Weighting has significant impacts on the Higg MSI score and the use of immature weighting values could result in unintended environmental outcomes and burden shifting when different fabrics are compared. To improve transparency, it is recommended that non-aggregated, non-normalised, non-weighted scores are provided in the Higg MSI tool and comparison should be conducted category indicator by category indicator in accordance with the ISO 14044. Additionally, as global supply chains produce environmental impacts in multiple regions, normalisation factors used in environmental assessments must reflect the regions of these impacts.

4. Discussion

The SAC's Higg MSI has laudable aims, and the SAC and its members have invested heavily in developing the methods and data required to improve sustainability of the textile industry. It is essential that this important work continues, and that robust, accurate and reliable methods are used to generate results that can be trusted by all parts of the textiles supply chain, including consumers.

This paper has highlighted a series of issues with the Higg MSI that relate to inconsistencies with the international guidelines and best practice for LCA, specifically with reference to fabrics made from natural fibre types. When considered collectively, we conclude that the Higg MSI is not suitable for public disclosure or comparative assertions, and has limited capability in its present form to enable the textile industry or interested stakeholders to compare different fabric types, or reliably choose between fabric types with confidence that this will result in lower impacts to the environment. We found that revising the system to improve alignment with LCA standards and guidelines would rectify most, if not all the issues raised. By improving compliance with LCA Standards, the Higg MSI has the potential to become a robust system for benchmarking impacts, and potentially for informing users to make better choices between fabric types.

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