Journal of Cleaner Production 320 (2021) 128852

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A systematic review of the life cycle inventory of clothing

Prabod Munasinghe [a,b], Angela Druckman [b,*], D.G.K. Dissanayake [a]

[a] Department of Textile and Apparel Engineering, Faculty of Engineering, University of Moratuwa, Moratuwa, 10400, Sri Lanka
[b] Centre for Environment and Sustainability, University of Surrey, UK

ARTICLE INFO

Handling editor: Kathleen Aviso

Keywords:
Life cycle analysis
Fashion
GHG emissions
Water use
Energy use
Sustainable development goal 12 (responsible consumption and production)

ABSTRACT

The clothing industry is a significant contributor to environmental degradation. Many life cycle assessment (LCA) studies have been conducted to analyse its environmental impacts, however the majority of studies focus on either just one or a few stages of the product life cycle, and/or on a specific type of product. Therefore, easily accessible life cycle inventory (LCI) data that can be used in decision making by practitioners and researchers are lacking. This study addresses this gap. By collating data through a systematic literature review and meta-analysis, it provides LCI data on energy use, water use and greenhouse gas emissions for a range of materials across all stages of the life cycle on a consistent basis. A framework is developed that groups each material at each life cycle stage according to the intensity of its energy and water use, and greenhouse gas emissions. The analysis revealed that the raw material extraction stage generally has the highest environmental impact. In this life cycle stage, flax is the virgin fibre with the lowest environmental impacts, recycled cotton is the recycled fibre which has the lowest environmental impacts and Indian silk is found to have the highest impacts. The review identifies the gaps in the availability of LCI data and provides recommendations for LCA studies to address these gaps, as without comprehensive data, robust decisions cannot be made. The results presented in this paper must be looked at in the wider context of consumption: the best way to reduce impacts is to reduce consumption. However, noting that production cannot be reduced to zero, the results of this study will aid pro-environmental decision making by stakeholders of the fashion industry, such as designers and consumers, as well as being of use to researchers.

1. Introduction

Clothing consumption has risen steeply in recent years (Niinimäki et al., 2020), with total fibre production having increased from 5.9 kg per capita in 1975 to 13 kg per capita in 2018 (Peters et al., 2019). Furthermore, it has been predicted that the volume of apparel manufacturing will increase by 81% between 2018 and 2030 (Lehmann et al., 2019). However, while creating a significant contribution to the global economy, the fashion industry creates serious environmental impacts in terms of climate change, resource depletion, air and water pollution and the use of toxic chemicals (Kerr and Landry, 2017; House of Commons, 2019; Martinez-Pardo et al., 2020). For instance, the clothing life cycle is responsible for significant amounts of energy, chemicals and water, while releasing waste and microfibres to the environment, which create problems in terrestrial and aquatic environments (Payne, 2016; Yasin et al., 2016; H&M Group, 2017; WRAP, 2017). Therefore, reducing the environmental impacts of clothing is increasingly in the spotlight, and it is an important component of working towards United Nations Sustainable Development Goal 12 (Responsible Consumption and Production) (Loetscher et al., 2017; WRAP, 2017; Republique Francaise, 2018; House of Commons, 2019; United Nations, 2021). For example, in the UK, the Sustainable Clothing Action Plan (SCAP) has signatories representing 45% of the UK's retail sales in 2020 who have committed to targets of 15% reduction in carbon footprint, water footprint and waste to landfill by 2020 compared to 2012 levels (Palmer and Gray, 2019).

Decisions on how best to reduce environmental impacts require comprehensive data concerning inputs (such as water, energy, chemicals and raw materials), and outputs (such as releases to air, land, and water) that arise at all stages of the life cycle of clothing. This is known as the Life Cycle Inventory (LCI) data (ISO, 2018). Recent publications include Niinimäki et al. (2020) who reviewed the environmental impact literature in the fashion life cycle, and Peters et al. (2021) who examined the environmental impact of fast fashion. However, a comprehensive collation of LCI data is currently lacking. This is because while some Life Cycle Assessment (LCA) studies pertaining to the fashion industry

* Corresponding author. Centre for Environment and Sustainability, University of Surrey, Guildford, Surrey, GU2 7XH, UK.
E-mail address: a.druckman@surrey.ac.uk (A. Druckman).

https://doi.org/10.1016/j.jclepro.2021.128852
Received 5 February 2021; Received in revised form 15 August 2021; Accepted 26 August 2021
Available online 29 August 2021

present LCI data, most studies focus on just one or a few areas of the product life cycle, and/or on a specific type of product. For instance, Sandin et al. (2019b) and Sandin and Peters (2018) reviewed the literature relating to the fibre manufacturing and the end of life stages respectively. Bevilacqua et al. (2014) conducted an LCA on the raw material extraction and the material manufacturing stages while Zamani et al. (2015) investigated the carbon footprint at the end of the life stage using a case study in Sweden. Esteve-Turrillas and de la Guardia (2017) studied the carbon footprint of cotton recycling while Lee and Tansel (2012) studied the carbon footprint of the domestic washing phase. Examples of studies that report on the whole life cycle are limited to a certain material/product type, for example, a cotton T-shirt (Zhang et al., 2015), a polyester blouse (Muthukumarana et al., 2018) and a wool sweater (Bevilacqua et al., 2011). Furthermore, Sandin et al. (2019a) presented information on the LCAs of six different garments along with comprehensive inventory data relating to those garments. However the materials used in the study are limited.

In addition, for LCI data to be of use in decision making, comparability in terms of functional unit and system boundaries is required. However, these vary across studies. For example, Roos et al. (2018) present LCI data based on 1 kg of cotton material while Steinberger et al. (2009) present it based on a 0.25 kg cotton T-shirt. Furthermore, Roos et al. (2016) present data based on the total output of apparel manufacturing of Sweden.

The current study fills a specific gap in the literature. Through a systematic literature review flowed by a meta-analysis, this study synthesizes published LCI data across all phases of the life cycle of clothing adjusted to a comparable function unit. It includes all types of materials on which published studies were found. These data are analysed to group each material at each stage of the life cycle according to the intensity of its water use, energy use and GHG emissions. These groupings will be of use for practitioners as a basis for decision making to improve the sustainability of the fashion industry. It will also be of use for academics studying the environmental sustainability of the fashion industry. Furthermore, it has the capacity to be used as a basis for a tool for helping consumers to make better decisions. The study also identifies data gaps in order to give an insight into future research requirements.

The structure of this paper is as follows: in Section 2 the background of the study is described, and the methodology is detailed in Section 3. Results and discussion of the systematic review are presented in Section

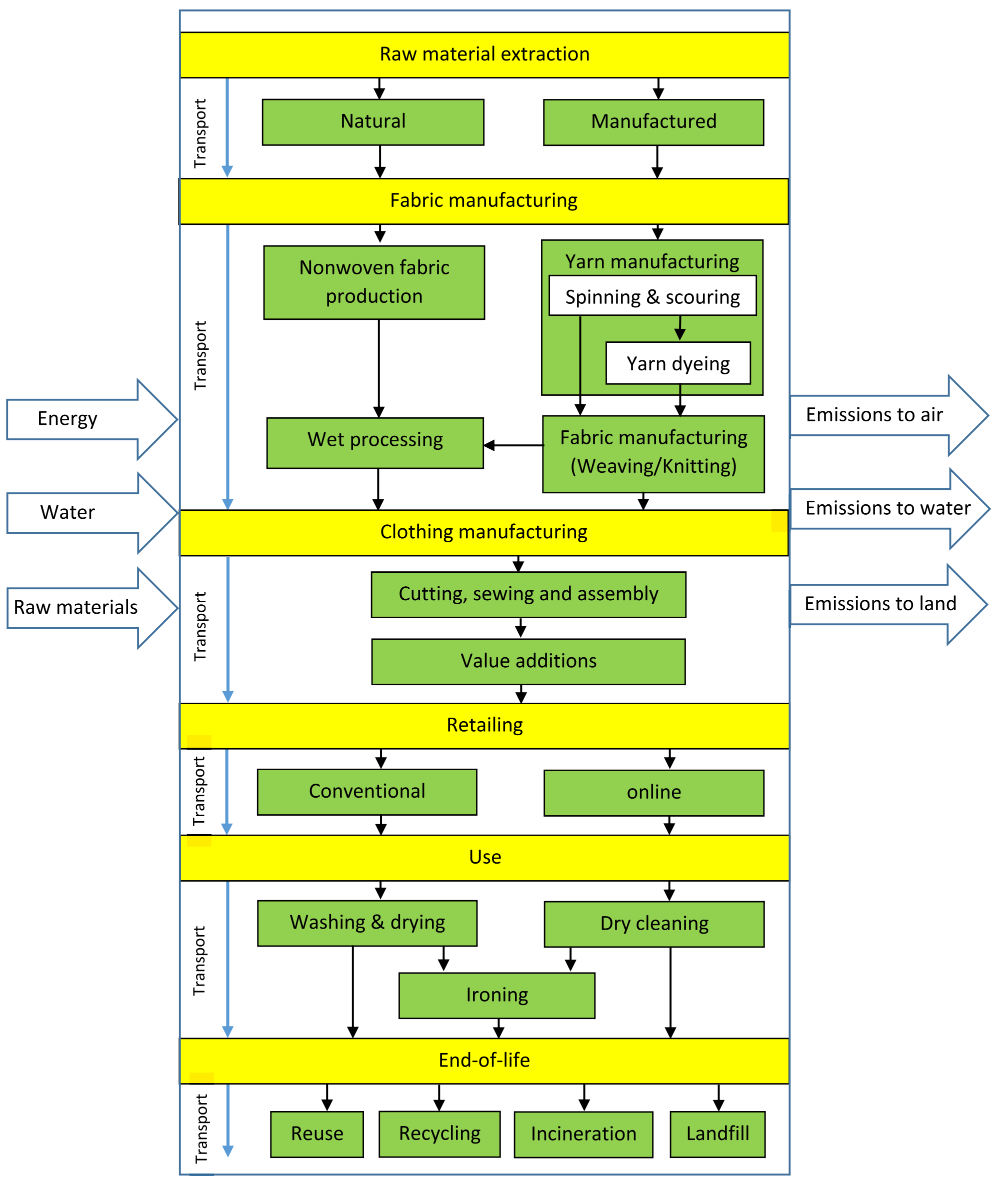


Fig. 1. A generic life cycle diagram for clothing.

4, and Section 5 makes conclusions and recommendations.

2. Life cycle of clothing

The life cycle of a clothing item consists of several key stages which start from raw material extraction and proceed to fabric manufacturing, clothing manufacturing, retailing, use and end of life stages (Eryuruk, 2012; Muthu, 2014; O'Rourke, 2014). Fig. 1 shows an overview of a generalized clothing life cycle based on the literature (Eryuruk, 2012; Muthu, 2014; O'Rourke, 2014). Each stage is described in the subsequent sub-sections.

Raw material extraction - The raw material of an item of fashion clothing can be either single or a combination of several fibre types. As shown in Fig. 2, textile fibres can be categorized as natural fibres (animal and vegetable) and manufactured fibres, which includes synthetic, regenerated cellulosic, inorganic and recycled fibres (Muthu, 2014; Textiles Intelligence Limited, 2017).

The process of raw material extraction varies depending on the type of raw material. For instance, cotton and cellulose fibre production start with agricultural cultivation (Esteve-Turrillas and de la Guardia, 2017), while polyester and acrylic fibres are produced using petro-chemicals (Shen et al., 2010; Yacout et al., 2016; Petrescu et al., 2016). Cotton farming has high water and chemical demand (Chapagain et al., 2005; Muthu et al., 2012; House of Commons, 2019), while polyester fibre manufacturing involves energy and chemicals (Muthu et al., 2012; Claudio, 2007).

Fabric manufacturing- There are three methods of fabric manufacturing: nonwoven, weaving and knitting, as shown in Fig. 1. Nonwoven fabric manufacturing uses fibres or filaments to construct fabrics through technologies such as felting and binding (Das, 2014). There is scarce literature on the environmental impacts of nonwoven fabric manufacturing: therefore it is not considered here, but is noted as an important research gap. Research gaps such as this are illustrated in Appendix Fig. A1, which presents a copy of Fig. 1 in which the life cycle stages for which data are missing are highlighted red.

The woven and knitted fabric manufacturing stage can be divided into two sub-stages: yarn manufacturing and fabric manufacturing. Yarn manufacturing involves spinning, in which fibres are made into yarns (Bevilacqua et al., 2014) which are then used to produce fabrics (Steinberger et al., 2009; Moazzem et al., 2018) through processes such as knitting (Zhang et al., 2015) and weaving (Ioppolo et al., 2017). Fibre spinning involves a sub-stage called scouring which removes impurities from fibres to improve the quality of the yarn (Terinte et al., 2014; Hassan and Shao, 2015). In some cases yarn dyeing occurs before the fabric production takes place. Wet processing is the final stage of fabric manufacturing: it includes pretreatment, dyeing (or printing) and finishing of the fabric (Bevilacqua et al., 2014; Ioppolo et al., 2017). If the yarn has been dyed prior to fabric manufacturing, final fabric dyeing is not necessary.

Spinning, knitting and weaving processes involve a substantial amount of energy (De Saxce et al., 2012) and generate solid wastes (Fletcher, 2014) while wet processing phase (yarn and fabric dyeing) involve high water intake, chemical intake and wastewater output (Fletcher, 2014; Adidas, 2015; Hartsia, 2017; Muthu, 2018). The scouring process, which is only required for natural fibres, requires extra water and chemical demand (Eryuruk, 2012; Muthu, 2018).

Clothing Manufacturing - This stage is where clothing (garments) are manufactured from fabrics: it includes fabric cutting, sewing and assembly, followed by value-adding activities (Fung and Choi, 2018) such as embellishments, ironing and packaging (Eryuruk, 2012). This is a highly labour-intensive process and energy is generally the main input in this life cycle stage. Garments may also be dyed at this stage (Sorger and Udale, 2006) in which case water and chemical use may be substantial (Eryuruk, 2012; Fletcher, 2014; Adidas, 2015; Muthu, 2018). The amount of energy or chemical usage is dependent upon the type and category of the garment which may include, for example, casual wear, outerwear, party wear, swimwear, sportswear, performance wear, work wear and lingerie (Posner, 2015; Babu and Arunraj, 2019).

Retailing- Retailing of fashion clothing occurs in two ways; conventional retailing and online retailing (Wrigley and Lambiri, 2015; Weinswig, 2016; Chiu, Yip and Tang, 2018). The main impact of retailing is through energy used in stores (Steinberger et al., 2009; Eryuruk, 2012), and conventional retailing has been found to have a higher environmental impact than online retailing (Bertram and Chi, 2018).

Use –The use stage is a critical stage in the lifecycle of clothing, in which energy and water are used for clothes washing, drying, ironing and dry cleaning (Druckman and Jackson, 2010; Eder-Hansen et al., 2012; Fletcher, 2014; Yun et al., 2016). The types of appliances used (or the absence of their use) can make a significant difference to the

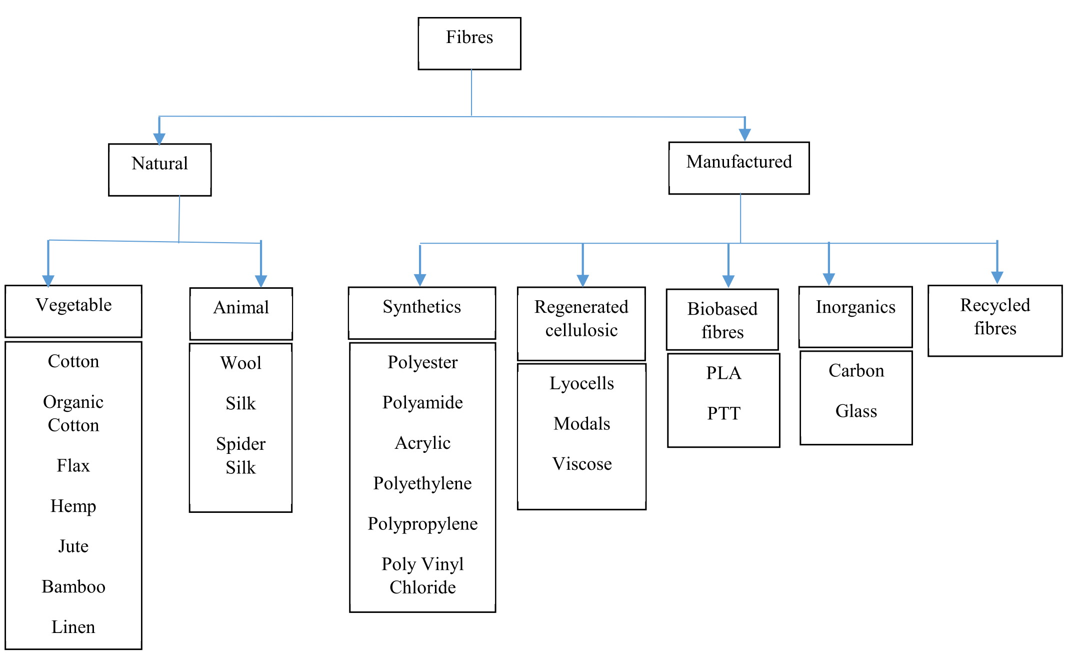


Fig. 2. Types of fibre. Adapted from Muthu (2014) and Textiles Intelligence Limited (2017)

environmental impacts of this phase (Hicks et al., 2015; Kim et al., 2015). The number of washing cycles operated during the user phase is critical since it affects the durability and increases energy use. Generally, the colour of the garment should be retained for at least 20 washes (WRAP, 2015a). However, there are standards, such as the Durawash test method which is widely used by the mass-market fashion brands (Roaches, 2019), which considers 45 domestic washes in its garment durability testing (WRAP, 2015b).

End of life - This stage creates significant environmental impacts due to unsustainable disposal methods of post-consumer textiles and clothing (Hole and Hole, 2019). Re-use (Lecerf et al., 2017), recycling (Peters et al., 2019) and incineration are commonly used waste management strategies in the fashion industry (Jensen, 2017). Reuse is the best waste management strategy (Farrant et al., 2010) followed by recycling (Castellani et al., 2015), as reusing does not involve further processing of materials (DEFRA, 2011). Charity shops commercial and government organizations are involved in collecting, sorting, cleaning and re-selling of used textiles and clothing (Fletcher, 2014). Recycling, on the other hand, processes materials via monomer, oligomer and polymer recycling, fibre recycling or fabric recycling methods (Sandin and Peters, 2018; Sandin et al., 2013). Incineration and gasification are used as energy recovery methods but are least preferred from the resource recovery perspective. Landfill is generally considered to have the worst environmental impact (Fletcher, 2014) as, for instance, landfilling of natural and bio-based fibres can emit GHGs while synthetics can remain in the soil for centuries without decomposing (Muthu, 2014).

Transportation **-** Transportation is involved in and between every stage of the clothing life cycle (Tseng and Hung, 2014). The clothing supply chain is global and air freight, in particular, if it is used, causes significant contributions to GHG emissions (Eryuruk, 2012).

3. Methodology

This study used a systematic literature review to find LCA studies of textiles and clothing, followed by meta-analysis to extract the LCI data from the studies found. In order to make the LCI data more useful for practitioners a system for grouping impacts was developed.

3.1. Systematic literature review

A systematic literature review is a rigorous method of reviewing empirical data, in order to obtain a credible outcome for a specific research question (Gough et al., 2012; Higgins et al., 2019). The review used a set of keywords for the literature search and the keyword plan as given in Table 1. The keywords are categorized into three areas: life cycle analysis, fashion industry and sustainability.

Based on the keywords, the search terms used in the study are presented in Appendix A.

The literature was searched using online databases Scopus, ProQuest and Web of Science. The search was conducted during the month of March 2019 with the search restricted to academic peer-reviewed journal articles published 2009–2019 to obtain the most up-to-date data (Jesson et al., 2011). This study did not include grey literature since its inclusion would have implications for the reliability of the final output of the study (Jesson et al., 2011).

Fig. 1 shows a generic life cycle of clothing. The scope of this study was energy and water inputs, and GHG emissions to air as the output. Other inputs and outputs were excluded from the study. All the selected articles were initially filtered by using the Mendeley desktop application, version 1.19.4 based on the relevancy of the papers, because certain papers which had no relevance to the current study were selected due to the similarities of the keywords. This initial screening was conducted by examining the keywords and abstracts. The second round of filtration focused on eliminating studies which were not based on ISO 14000/40/44 standards, and studies in which the nature of the functional unit was not described with adequate transparency for the purposes of this review. The final round of filtration was conducted by screening through the full papers. Eliminations at this stage were based on the quality and clarity of data, and transparency of the numerical calculations concerning the functional unit.

Table 1
Systematic review-keywords plan.

Keyword category 1	Keyword category 2	Keyword category 3
LCA, Life cycle Assessment, Supply Chain	Fashion, Apparel, Textile, Clothing	Environment, Sustainability

3.2. Meta-analysis

Meta-analysis is a formal quantitative approach that is used to systematically synthesize the results of multiple studies into a single quantitative estimate (Haditch, 2010; Cheung, 2015). It is a widely used method to combine quantitative values of different empirical studies where each study evaluates the same type of hypothesis (Lipsey and Wilson, 2001; Mark Petticrew, 2006; Cheung, 2015).

Articles selected through the systematic literature review were analysed and coded using Nvivo 12 software: a product of QSR International Pty Ltd (QSR International PVT Ltd, 2018). LCI data in those studies were then extracted to Microsoft Excel. First, the LCA data of each paper were extracted separately to Excel sheets while extracting general information such as journal, published year, authors, country of the study, functional unit, goal and scope, material types and research tools used in the study in order to identify the context of each study in a comprehensive manner. Then data were analysed and tabulated according to the stages of the life cycle: raw material extraction, fabric manufacturing, clothing manufacturing, retailing, use and end of life. All extracted data were then converted to provide the environmental impact of each category per 1 kg of material, based on the functional unit of each study (Appendix A, Table A1). An exception to using impact per kg material is in washing during the consumer use phase. For this, the calculations were done for 1 kg of materials for 45 washing cycles, as defined by the Durawash test method (WRAP, 2015b). Information on standard conversion factors used (ConvertLive, 2020; Metric-Calculator.com, 2020; PlanetCalc, 2020; RapidTables, 2020; EPA, 2014) is provided in Appendix A, Table A2.

3.3. Framework for grouping of impacts according to intensity

In order to make the results useful for practitioners and as a basis for decision making, a framework that groups each material at each life cycle stage according to the level of intensity of its energy and water use, and GHG emissions per kg of material was developed.

The procedure to do this was as follows. First, for a specific impact category for a specific life cycle phase, the extracted data were graphed according to intensity (impact per kg of material). Next these data are

Table 2
Summary of selected articles according to the journal.

Journal	No of Papers	Percentage
Journal of Cleaner Production	15	27.3
International Journal of Life Cycle Assessment	8	14.5
Resources, Conservation and Recycling	4	7.8
Fibres and Polymers	3	5.5
Environmental Science and Technology	2	3.6
Journal of Environmental Management	2	3.6
Journal of Industrial Ecology	2	3.6
Procedia CIRP	2	3.6
Sustainability (Switzerland)	2	3.6
Sustainable Production and Consumption	2	3.6
Other journals	13	23.6
Total	55	100

plotted. The impacts per kg material were then divided into groups, with Group 1 being the lowest environmental impact, and Group 7 the highest. The framework boundaries were set according to the break-points in the graphs for the material extraction stage. The material extraction phase was chosen as this phase has the highest data availability amongst all life cycle phases. A more detailed description of this process is presented in Section 4.2.1.

4. Results and discussion

4.1. Research journals and themes

The initial search results gave 1601 journal articles, with the first and second filtration processes giving 432 and 140 articles respectively, as shown in Fig. 3. The final filtration process yielded 57 papers.

The databases in which the final 57 papers were found are shown in Fig. 4. The highest number of papers were published in the Journal of Cleaner Production, followed by the International Journal of Life Cycle Assessment, as shown in Table 2. The most-reported impact categories were GHG emissions and energy use, followed by water use, as shown in Table 3. Raw material extraction was found to be the area of greatest focus, being investigated in 52% of the papers, while the fabric manufacturing stage was also discussed in 50% of the papers, as shown in Table 4.

4.2. Life cycle analysis of clothing

Each of the selected 57 papers was analysed in detail in order to identify LCI data for the various stages of the fashion life cycle. Appendix A, Table A3 summarizes the life cycle stage covered by each publication. It presents an overall picture of all selected articles and the data availability for each stage of the clothing life cycle as well as the availability of GHG emissions, energy and water use data. According to Table A3, the majority of the studies (96.5%) address one or two stages of the life cycle. The most commonly reported inputs are energy and water (83% and 66% of studies respectively) and the most commonly reported output was GHG emissions (83%).

The methodologies used in each paper are presented in Appendix A, Table A4. All papers were searched for information about whether they used consequential or attributional LCA. While Koligkioni et al. (2018) state that they mainly used consequential life cycle analysis and Wiedemann et al. (2018) used both attributional and consequential methodologies, none of the other papers mention which approach was used. Studies were also scrutinized for information about whether reported GHG emissions from energy use were biogenic and nonbiogenic (Arvidsson and Svanstrom, 2015). Apart from Agnhage et al. (2017), Ioppolo et al. (2017), Russell (2009) and Shen et al. (2010), this information was not reported. Furthermore, each study was also investigated to assess whether blue, green or grey water was reported (Kounina et al., 2013): most studies failed to report this information (see Table A3).

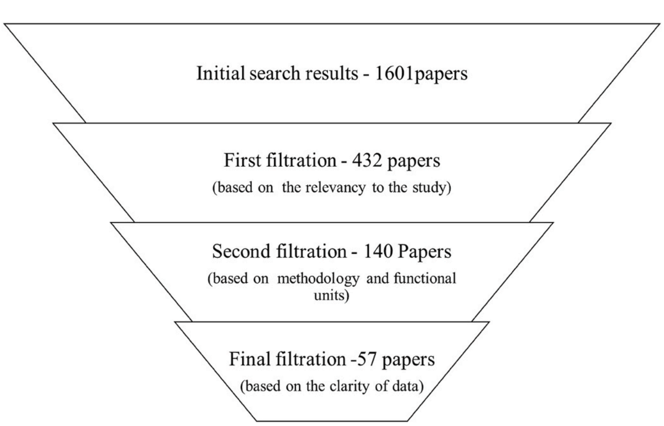


Fig. 3. Filtration process for selection of peer-reviewed journal papers.

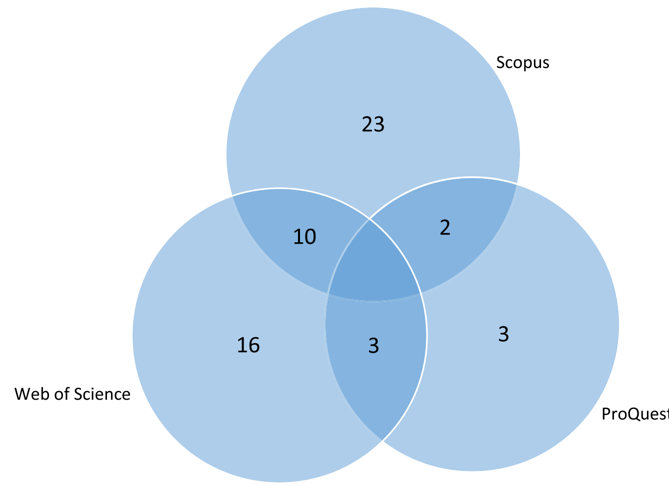


Fig. 4. Selection of peer-reviewed journal papers by database.

Table 3
The percentage of the selected papers reporting each impact category.

Subcategory	% papers reporting impact category
Greenhouse gas emission (GHG)	84
Renewable and non-renewable energy usage	84
Water usage	65
Chemical usage	44
Emissions to water	33
Emissions to land	29

Table 4
Data availability for different lifecycle stages in the selected papers.

Raw material extraction	Fabric manufacturing	Clothing Manufacturing	Retailing	Use	End of life
53%	49%	22%	11%	31%	38%

4.2.1. Raw material extraction

The raw material extraction stage is the most studied area in the selected articles, and the LCI data for different fibre types used in textile production are summarized in Table 5. This evidence shows that Indian silk fibre production causes the highest environmental impact (based on GHG emissions, energy and water use) while Nylon 66-A and flax have the lowest environmental impact among virgin fibres. Recycled cotton also shows good environmental performance across all the fibre types. However, there are practical issues in using recycled cotton (Loetscher et al., 2017) due to the limited technological improvements in the commercial context, quality issues, and limited availability of cotton for recycling (Esteve-Turrillas and de la Guardia, 2017; H&M Group, 2017).

Figs. 5, Figs. 6 and 7 show the environmental impacts of raw material extraction based on GHG emissions, energy use and water use, respectively. Materials are divided into seven Groups according to the break-points in these graphs, as explained in the Methodology section. The range of the values for each Group for each impact category is presented in Table 6: these ranges are used for all life cycle stages.

Fig. 8 collates the information from Figss. 5–7 to show the Groups in which each material lies for each impact category of the raw material extraction phase. The materials are grouped from low impact to high impact along each row. Fig. 8 shows that, with regards to GHG emissions, jute fibre production has the lowest impact (Group 1), with

Table 5
LCI data of raw material extraction stage.

		GHG emissions (kg CO_2eq/kg)	Energy usage (MJ/kg)	Water use (L/kg)	Reference sources
Acrylic Egypt		5	133	144	Yacout et al. (2016)
Acrylic		5.4	175	210	Muthu et al. (2012)
Cotton -general	A	–	12.1	–	Zamani et al. (2015)
	B	–	44.19	–	Bhalla et al. (2018)
	C	–	–	2100	Terinte et al. (2014)
	D	2	54	5732	Shen et al. (2010)
	E	–	–	7000–13500	Baydar et al. (2015)
	F	6	60	22000	Muthu et al. (2012)
	G	2.62	–	–	Dahlbo et al. (2017)
	H	0.755–1.764	–	9310	Esteve-Turrillas and de la Guardia (2017)
Cotton - Afghanistan		–	–	22009	Chico et al. (2013)
Cotton - Africa		0.871	–	3400	Esteve-Turrillas and de la Guardia (2017)
Cotton - Brazil		–	–	520	Chico et al. (2013)
Cotton -china	A	0.72	2.33	3882	Bevilacqua et al. (2014)
	B	2.37	19.8	9130	Esteve-Turrillas and de la Guardia (2017)
	C	3.4	–	7000	Astudillo et al. (2014)
Cotton - Gambia		–	–	34923	Chico et al. (2013)
Cotton India	A	7.28	113.2	–	Steinberger et al. (2009)
	B	0.89	3.18	14742	Bevilacqua et al. (2014)
	C	9.466	–	2610–2617	Esteve-Turrillas and de la Guardia (2017)
Cotton India for handloom		9.46	34.46	750	Bhalla et al. (2018)
Cotton Egypt		0.63	3.08	7000	Bevilacqua et al. (2014)
Cotton - Pakistan		3.15	1.89	5160	Esteve-Turrillas and de la Guardia (2017)
Cotton - Syria		–	–	4904	Chico et al. (2013)
Cotton - Spain		–	–	4842	Chico et al. (2013)
Cotton - Turkey		5.5	–	177	Esteve-Turrillas and de la Guardia (2017)
Cotton – USA (No irrigation)		0.62	1.54	1.48	Bevilacqua et al. (2014)
Flax		3.8	10	214	Muthu et al. (2012)
Hemp		29.5	–	–	George and Bressler (2017)
Jute		−1.5	–	–	Kiffle et al. (2017)
Merion Wool – Australia		19.46–25.04	7.18–22.39	204–394	Wiedemann et al. (2016)
Merion Wool – New Zealand		2.2	38	–	Russell (2009)
Modal		0.03	78	472	Shen et al. (2010)
Modal - Australia		–	78	–	Koligkioni et al. (2018)
Nylon 6		5.5	120.47	185	Muthu et al. (2012)
Nylon 66 general	A	8.0	1.3	200	Astudillo et al. (2014)
	B	6.5	138.65	663	Muthu et al. (2012)
Organic Cotton -general	A	2.5	54	24000	Muthu et al. (2012)
	B	0.978	–	182	Esteve-Turrillas and de la Guardia (2017)
Organic Cotton - Finland		3.9	53.6	24000	Esteve-Turrillas and de la Guardia (2017)
Organic Cotton - India		1.08	–	2793	Esteve-Turrillas and de la Guardia (2017)
Organic Cotton - Turkey		1.95	–	1061	(Esteve-Turrillas and de la Guardia (2017)
Polypropelene - general	A	2.8	89	76	Muthu et al. (2012)
	B	1.7	115	43	Shen et al. (2010)
Polyester - General	A	2.8	125	62	Muthu et al. (2012)
	B	–	87.62	–	Zamani et al. (2015)
	C	2.24	–	–	Kissinger et al. (2013)
	D	4.2–6.9	109	–	Russell (2009)
Polyester - Australia		5.0	–	–	Moazzem et al. (2018)
Polyester - China		3.1	53.64	–	Steinberger et al. (2009)
Polyester – western Europe		4.1	96	130	Shen et al. (2010)
Polyethelene		1.015	–	–	Kissinger et al. (2013)
Poly Vinyl Chloride (PVC)		1.92	–	–	Kissinger et al. (2013)
Recycled cotton - Spain		0.214	1.31	0	Esteve-Turrillas and de la Guardia (2017)
Recycled Polyester		–	5.4	–	Zamani et al. (2015)
Tencel 2012 Austria		0.05	65	263	Shen et al. (2010)
Tencel Lenzing Austria		1.1	101	263	Shen et al. (2010)
Silk		52.5	1467.3	26700	Astudillo et al. (2014)
Silk - India		80.9	1858	54000	Astudillo et al. (2014)
Synthetic Spider Silk		55–572	–	–	Edlund et al. (2018)
Viscose Rayon - general	A	9.0	100	640	Muthu et al. (2012)
	B	3.43	–	–	Dahlbo et al. (2017)
Viscose Asia		3.8	108	319	Shen et al. (2010)
Viscose Austria		−0.25	70	445	Shen et al. (2010)
Wool- general	A	2.2	63	125	Muthu et al. (2012)
	B	1.7	–	–	Agnhage et al. (2017)
	C	24.7	–	–	Moazzem et al. (2018)
Wool- China and India		30.2	38.64	17.8	Wiedemann et al. (2018)
Wool - USA		18.5	–	–	Astudillo et al. (2014)

Table 6
Group ranges.

	GHG Emissions	Energy footprint	Water footprint
	kg CO_2eq/kg	MJ/kg	L/kg
Group 1	≤0	≤0	≤0
Group 2	0–0.25	0–10.0	0–250
Group 3	0.25–4.0	10.0–40.0	250–1500
Group 4	4.0–10.0	40.0–80.0	1500–3500
Group 5	10.0–40	80.0–150	3500–10000
Group 6	40.0–100.0	150–200	10000–35000
Group 7	>100.0	>200	>35000

viscose-Austria being the next best fibre (also in Group 1). Natural and synthetic silk varieties generally have the highest GHG emissions at this life cycle stage (Group 6–7). Wool (Group 3 to 5) cotton (Group 3 to 4), polyester (Group 3 to 4) and viscose rayon (Group 3 to 4) varities show a span of values due to the differences in the methods and technologies used.

Nylon 66-A has the lowest energy use at this life cycle stage, followed by recycled cotton - Spain, cotton - USA (no use of irrigation water), and cotton - Pakistan (Fig. 8). It is evident that virgin synthetic fibre varieties generally show higher energy use than natural fibres and fibres made using manufactured cellulosic fibres, with the exception of silks. Silk varieties have the highest energy use: this is due to high energy consumption in the fibre processing phase (Astudillo et al., 2014). Recycled cotton represents the best environmental performance in this stage. Silk (India) shows the highest water consumption, which is due to the mulberry farming phase (Astudillo et al., 2014).

Fig. 9 shows a heat map of all three environmental impacts under study for the raw material extraction phase. The heat map excludes materials without data for all three environmental impacts (GHG emissions, energy and water use). The heat map shows that recycled cotton (Spain) may be considered the best performing fibre with relatively low environmental impact across all three impact categories. Cotton varieties are spread in the middle to lower end of the heat map because cotton fibre production has high water use and moderate GHG emissions and energy use. Silk fibre production has the highest environmental impact. The heat map also illustrates that a material such as acrylic may perform well in one impact category (water use) but poorly in another (energy use).

The systematic literature review showed that most LCA studies focus on the extraction of cotton, wool, nylon and polyester. There is, however, a variety of other fibre types which should be explored. For instance, it is recommended that LCA studies should be carried out on: recycled fibres (polyester, wool, nylon), biobased fibres (polylactic acid - PLA, polytrimethylene terephthalate -PTT), inorganic fibres (glass, carbon fibre), lyocell (acetate rayon), synthetic fibres (elastane, polyethylene, polyolefin, polyvinylecholride, synthetic silk), animal fibres (silk, spider silk), vegetable fibres (bamboo, flax, jute) and organic fibres (wool, silk, flax, etc.). Moreover, conducting LCA studies on smart textiles (textiles with functionalities to address needs in applications such as biomedical, healthcare and sports (Mondal, 2014)), is also an important area in order to understand the sustainability implications.

4.2.2. Fabric manufacturing

This section covers yarn manufacturing and fabric manufacturing

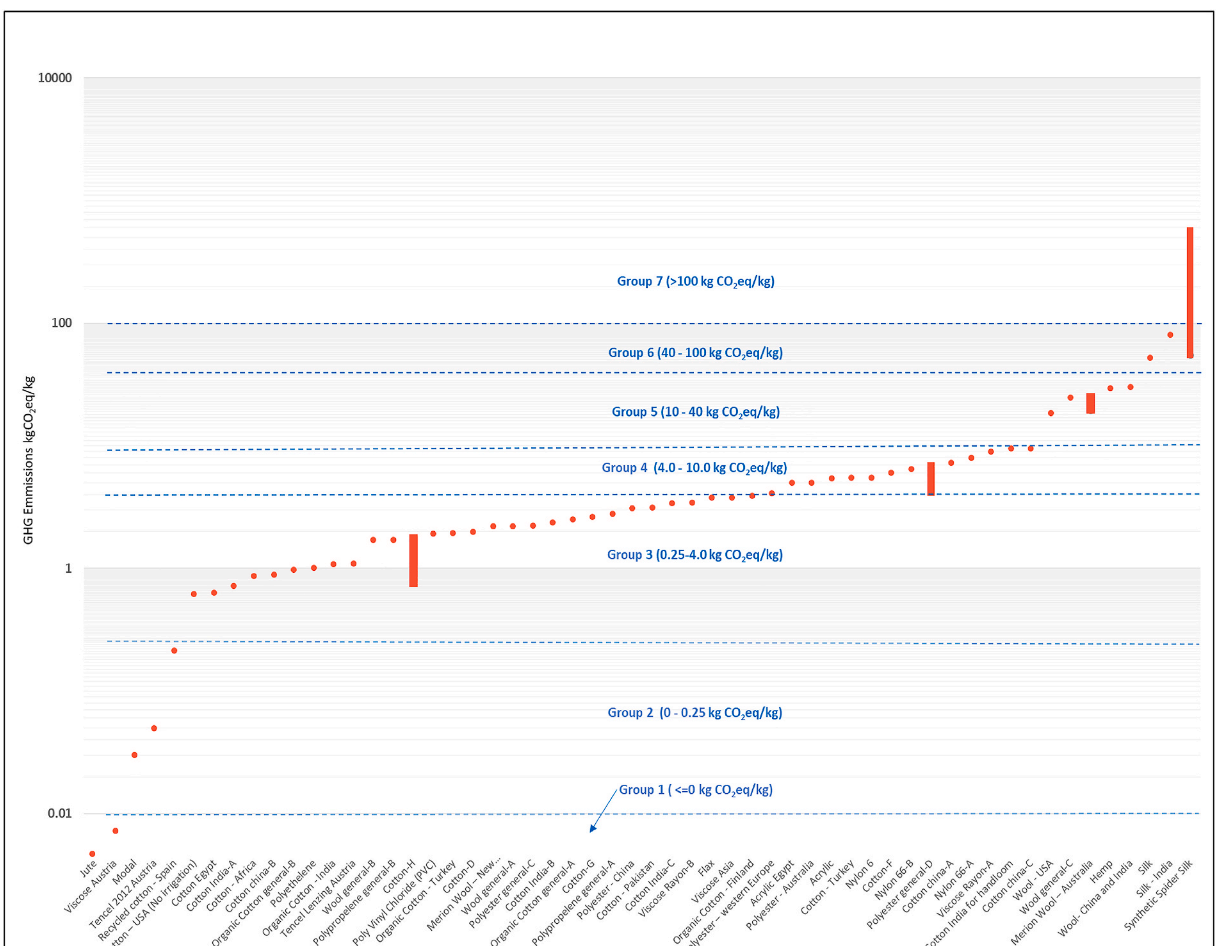


Fig. 5. GHG emissions in the raw material extraction stage.

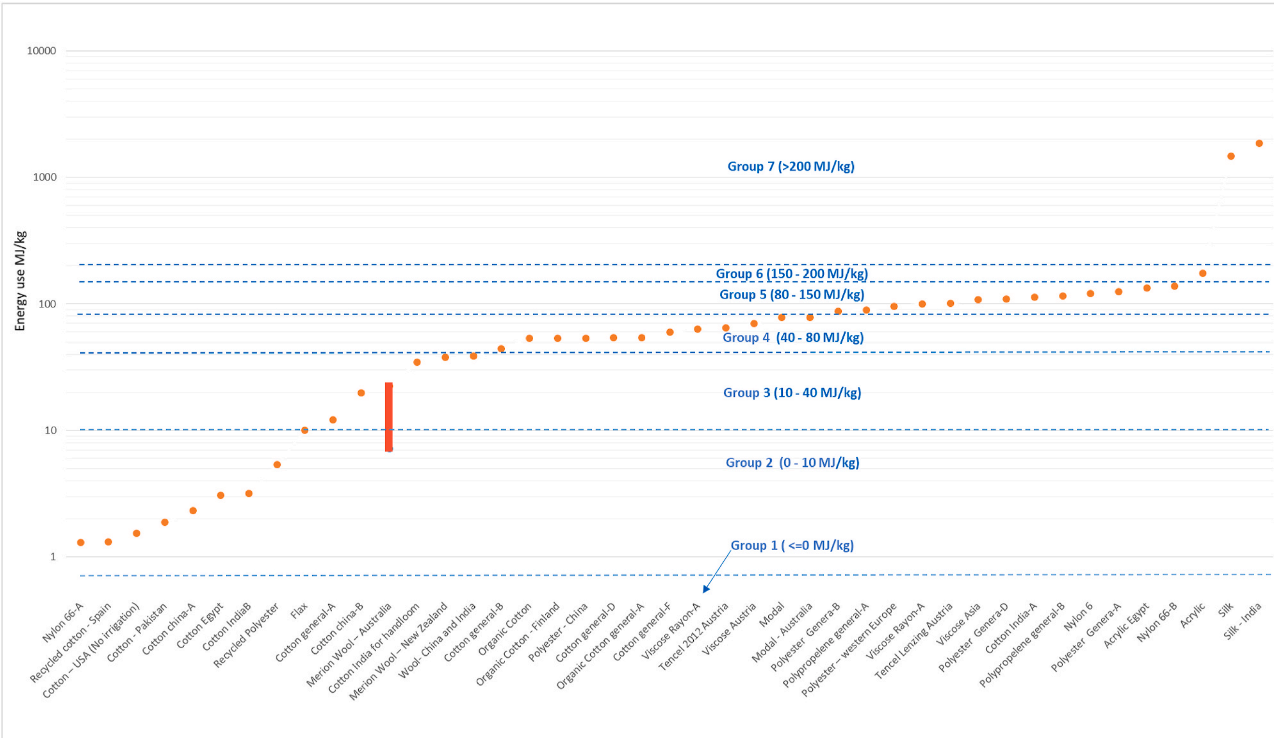


Fig. 6. Energy use in the raw material extraction stage.

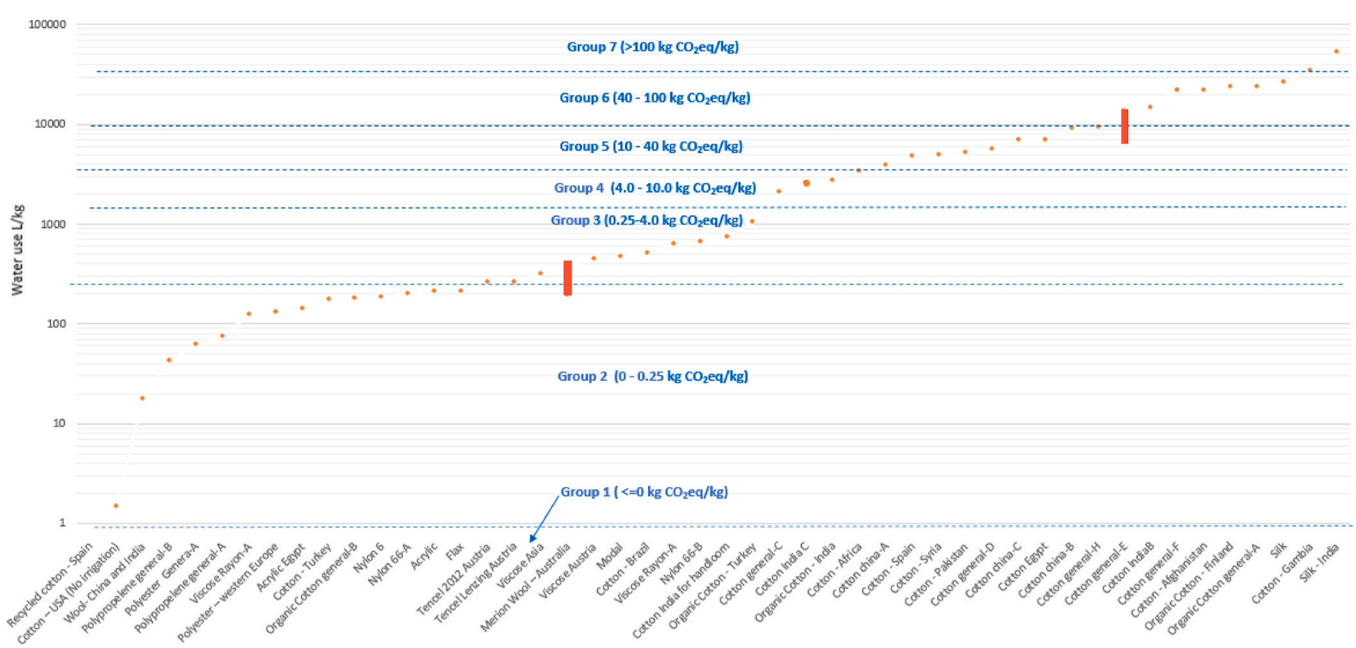


Fig. 7. Water use in the raw material extraction stage.

processes (as shown in Fig. 1). A key process in yarn manufacturing is spinning (Kang et al., 2018), and the literature finds that energy use and GHG emissions are the major impact categories in this process, while water use is seldom discussed because it is generally negligible (see Table 7). For example, Zhang et al. (2015) indicated that the water use of cotton spinning in China is zero. Also, manual spinning as used by traditional handloom weavers in India does not consume energy and thus has zero GHG emissions (Bhalla et al., 2018). Also of note is that, while scouring is an integral sub-stage associated with the spinning of natural fibres for the removal of impurities, no study within the selected

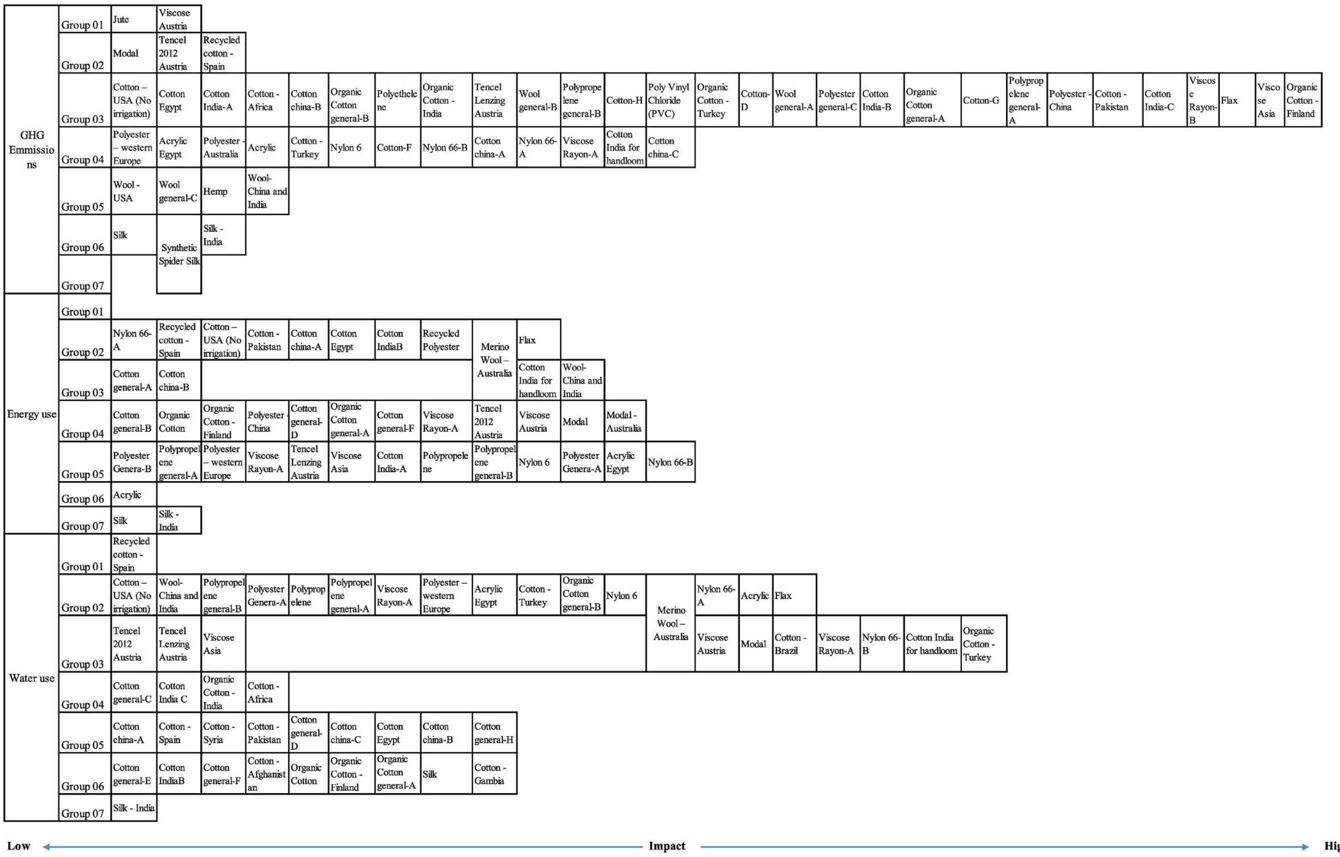


Fig. 8. Fibre groupings according to the different environmental impact categories in the raw material extraction stage.

journal articles investigated it separately.

As mentioned previously, sometimes, yarn dyeing occurs before the fabric production takes place. Table 7 shows that polyester dyeing has the highest energy and water use while a wool acid jet dyeing method (AgResearch Limited) shows the lowest impact in all three categories (Hassan and Shao, 2015). In a comprehensive study of wool dyeing methods, Hassan and Shao (2015) found significant variations according to the machines and dyestuff used. Their study emphasizes the importance of conducting LCA studies that consider different techniques, methods and materials, to shed light on the variations in environmental impacts.

Fig. 10 shows the impacts of the various materials grouped according to the ranges defined in Table 6 for the yarn manufacturing and yarn dyeing phases. As mentioned above, traditional handloom Kadhi cotton weaving in India consumes zero energy (Bhalla et al., 2018) and is shown to have the lowest impacts. This highlights the importance of sustainable values in traditional techniques. It is difficult to assess the environmental impacts of the fabric manufacturing stage (knitting, weaving and nonwoven material production) due to the limited availability of data, and this research gap needs addressing.

Turning now to the fabric manufacturing sub-stage, the impacts of the dyeing and finishing processes on the environment are significant as they use a substantial amount of water and harmful chemicals, and discharge toxic effluent (Roos and Peters, 2015) (see Table 8). The literature provides rich LCA data for cotton dye techniques. According to the studies, conventional wool dyeing consumes the highest energy, and cotton blue dyeing results in high GHG emissions. Furthermore, cotton dyeing has the highest water consumption of the yarn dyeing processes, with Chinese cotton dyeing having the highest water consumption (Table 8). Cotton fibre recycling does not involve a dyeing stage, as the recycling process is designed to sort raw materials according to the colours before spinning. This results in recycled cotton being identified as the most sustainable type of cotton material, scoring better than organic cotton (Table 8).

Fig. 11 presents a heat map of the grouping framework of activities in the fabric manufacturing phase. There is currently limited data relating to the environmental impacts of various machinery and techniques used in the fabric manufacturing process and therefore the impacts are difficult to analyse (Fig A1). In particular, traditional fabric construction methods such as handloom, hand knitting and crochet have not, to date, been investigated much: this should be addressed, as such traditional methodologies are now commonly discussed with regards to their potential sustainability advantages. Furthermore, value-adding techniques such as textile printing, textile embroidery and washing techniques need to be investigated in future LCA studies since the fashion industry currently uses these techniques a great deal, but the LCI data on them is extremely limited.

4.2.3. Clothing manufacturing stage

The literature on the clothing manufacturing phase presents LCI data for specific product types such as a jacket, T-shirt, blouse, and bra, as shown in Table 9.

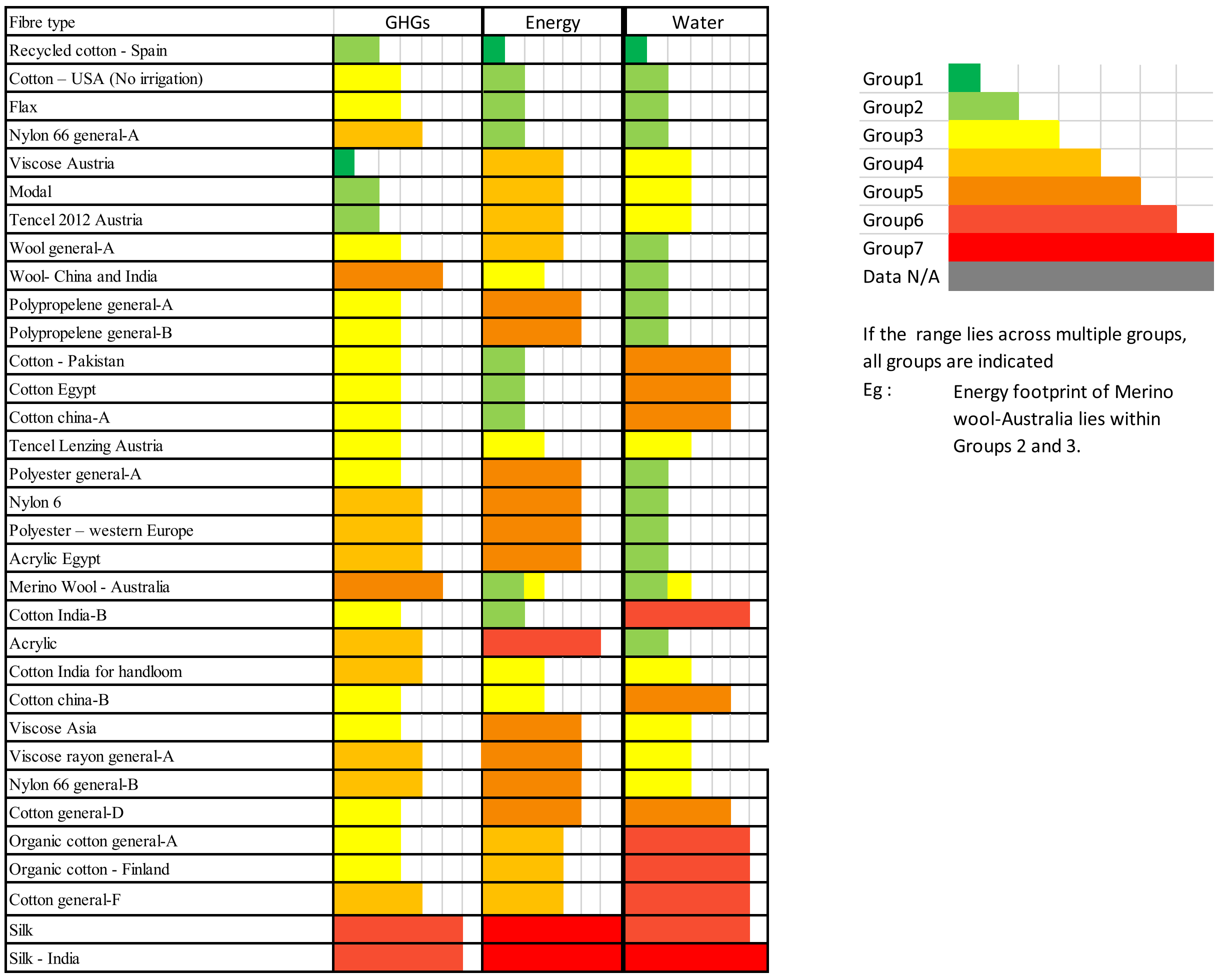


Fig. 9. Heat map of groupings for all three impact categories for the raw material extraction phase.

Table 7
LCI data for the yarn manufacturing stage.

		GHG (kg CO_2eq/kg)	Energy Usage (MJ/kg)	Water Usage (L/kg)	Reference sources
Yarn Spinning	Cotton	3.84–4.05	0–52.28	0	Moazzem et al. (2018); Steinberger et al. (2009); Bhalla et al. (2018); Zhang et al. (2015)
	Kadhi Cotton from traditional spinning	0	0	0	Bhalla et al. (2018)
	Modal	–	19.4	–	Terinte et al. (2014)
	Polyester	2.8–4.56	40.2–58.46	–	Moazzem et al. (2018); Steinberger et al. (2009)
	Wool	4.5	–	–	Moazzem et al. (2018)
Yarn dyeing	Cotton	–	7.2	180	Bevilacqua et al. (2014)
	Modal –spin dyeing	–	21.6	43	Terinte et al. (2014)
	Polyester	–	21.87	200	Ioppolo et al. (2017)
	Wool –Open winch – traditional acid dyeing	2.9	15.3	90	Hassan and Shao (2015)
	Wool – Winch – AgResearch rapid acid dyeing	2.0	10.5	90	Hassan and Shao (2015)
	Wool – Open winch – low LR acid dyeing	1.4	7.2	75	Hassan and Shao (2015)
	Wool – Jet - traditional acid dyeing	1.42	7.5	75	Hassan and Shao (2015)
	Wool – Jet – AgResearch rapid acid dyeing	0.49–0.99	2.6–5.21	30–36	Hassan and Shao (2015)
	Wool –Open winch – traditional reactive dyeing	3.5	18.12	160	Hassan and Shao (2015)
	Wool – Open winch – low LR reactive dyeing	0.69	3.62	140	Hassan and Shao (2015)
	Wool – Jet – traditional reactive dyeing	1.0	5.436	48	Hassan and Shao (2015)
	Wool – Jet – lower LR reactive dyeing	0.52	2.718	42	Hassan and Shao (2015)

Fig. 10. Heat map of groupings for the yarn manufacturing phase.

Table 8
LCI data relating to the fabric manufacturing stage.

		GHG (kg CO_2eq/kg)	Energy Usage (MJ/kg)	Water Usage (L/kg)	Reference sources
Nonwoven material production	1.2 mm Chromium tanned leather Spain	27.31	327.69	1485.52	Laurenti et al. (2017)
	1.2 mm Vegetable-tanned leather Spain	–	622.61	1157.84	Laurenti et al. (2017)
	1.2 mm Chromium tanned leather Austria	131.07	535.23	–	Laurenti et al. (2017)
	1.2 mm Vegetable-tanned leather Argentina	–	294.92	2337.52	Laurenti et al. (2017)
Fabric Knitting	Polyester	0.882–7.08	–	–	Moazzem et al. (2018); Steinberger et al. (2009)
	Wool	1.76	–	–	Moazzem et al. (2018)
	Cotton	0.64–0.97	1.28–10.24	0	Moazzem et al. (2018); Steinberger et al. (2009); Zhang et al. (2015)
	Cotton - Turkey	–	5	–	Baydar et al. (2015)
	Modal- Australia	–	2.5	–	Terinte et al. (2014)
Fabric Weaving	Cotton	–	19.76	–	Bhalla et al. (2018)
	Kadhi Cotton in handloom weaving	–	0	–	Bhalla et al. (2018)
	Not specify	–	13.85	–	Ioppolo et al. (2017)
Fabric dyeing	Polyester	8.8	–	–	Moazzem et al. (2018)
	Wool – conventional dyeing	7–10	108	40	Parisi et al. (2015); Moazzem et al. (2018)
	Wool – (BISCOL project)	3.25	48.9	39.5	Moazzem et al. (2018)
	Cotton	2.52–17.3	6.34–26.98	23–185	Steinberger et al. (2009); Esteve-Turrillas and de la Guardia (2017); Zhang et al. (2015)
	Cotton - bleaching	–	32.5	60	Roos et al. (2018)
	Cotton -Turkey	12.1	25.2	150	Baydar et al. (2015)
	Cotton – stone dyeing	12.7	18.06	46	Esteve-Turrillas and de la Guardia (2017)
	Cotton – Blue dyeing	17.3	21.79	60	Esteve-Turrillas and de la Guardia (2017)
	Cotton – red dyeing	7.0	6.34	23	Esteve-Turrillas and de la Guardia (2017)
	Cotton – synthetic reactive dyes	12.4	–	–	Linhares and De Amorim (2017)
	Cotton pad dyeing	10.64	14.28	110.6	Yuan et al. (2013)
	Modal	–	85.4	119	Terinte et al. (2014)
	Organic Cotton -turkey	9.361	15.28	90	Baydar et al. (2015)
	Recycled Cotton	0	0	0	Esteve-Turrillas and de la Guardia (2017)
Natural dyeing	Polyester with madder dyeing	14.9	43.4	74.7	Agnhage et al. (2017)
	Cotton with vegetable dyes	0.085	1.09	–	Agnhage et al. (2017)
	Cotton with Acacia Dealbata tree bark	0.7	–	–	Agnhage et al. (2017)
Fabric finishing	Polyester	N/A	0.55	–	Ioppolo et al. (2017)
	Nanosilver finish	1.54–1.61	–	–	Walser et al. (2011)
	Fire retardant finish on cotton	–	29.9	180	Yasin et al. (2018)
Fabric printing	Not specified	–	–	16	Parisi et al. (2015)

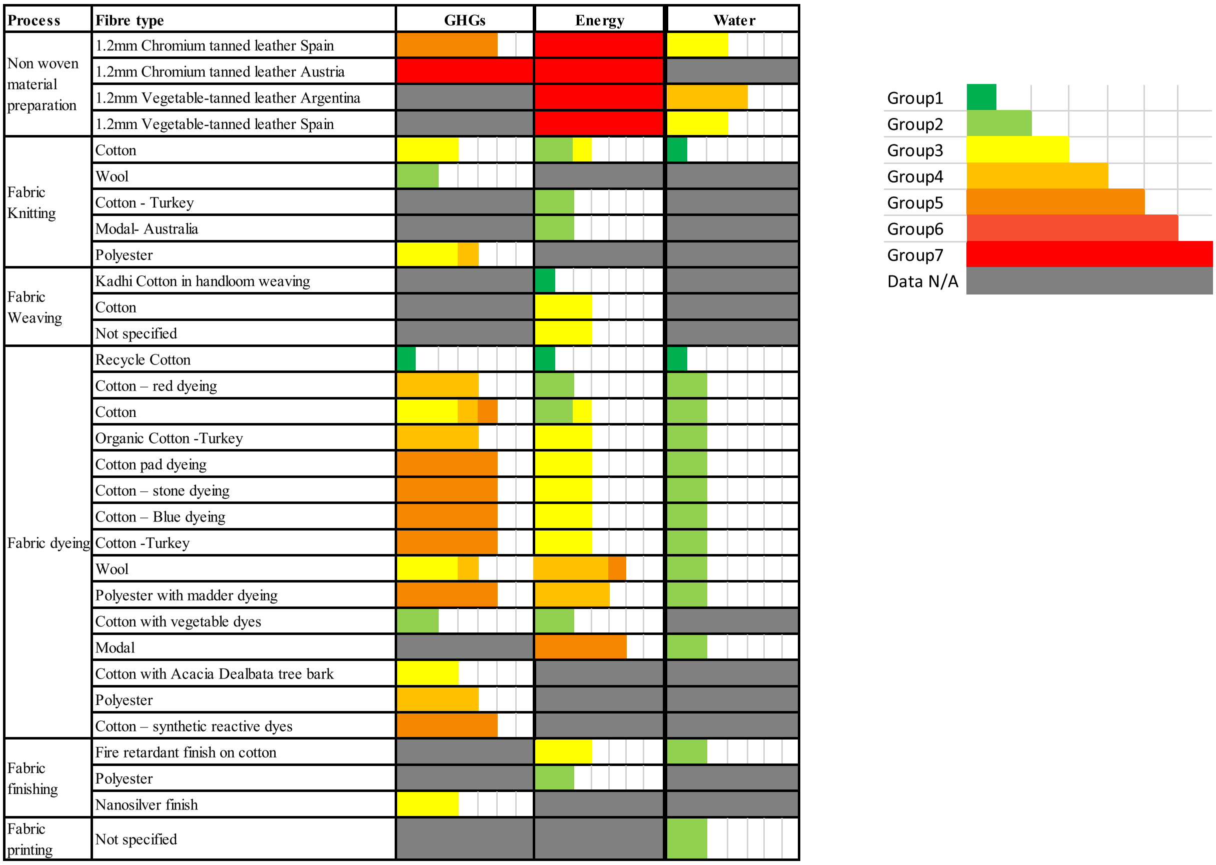


Fig. 11. Heat map of groupings for the fabric manufacturing phase.

Table 9
LCI data relating to the garment manufacturing and retailing stages.

		GHG (kg CO_2eq/kg)	Energy Usage (MJ/kg)	Water Usage (L/kg)	Reference sources
Clothing Manufacturing	Polyester Jacket	0.22	2.92	–	Steinberger et al. (2009)
	Cotton T shirt	0–0.32	8.92–40.58	0	Steinberger et al. (2009; Zhang et al. (2015)
	Cotton blouse	6.37	2.34	6.02	Muthukumarana et al. (2018)
	Bra	0.14	34.3–39.4	–	Munasinghe et al. (2016)
	T-shirt (material not specified)	N/A	2.0	–	Baydar et al. (2015)
Retailing	Cotton T-shirt - Germany	3.64	–	–	Steinberger et al. (2009)
	Polyester Jacket - Germany	3.66	–	–	Steinberger et al. (2009)
	Bra - UK	0.08	0.65	–	Munasinghe et al. (2016)
	Packaging –online retailing	0.226	–	–	Bertram and Chi (2018)
	Packaging – conventional retailing (material type not specified)	0.181	–	–	Bertram and Chi (2018)

The clothing manufacturing stage is one of the vital phases in the clothing life cycle, however, there appears to be a lack of analysis focused on this phase (Fig A1). As in the fabric manufacturing stage, the environmental impact of clothing value additions such as embroidery, printing, laser cutting and bonding techniques have not, according to this study, been investigated. Furthermore, other intermediate activities such as fabric inspection and cutting, sewing, finishing and packaging should be studied. Additionally, there are new technologies such as seamless knitting technologies, molding, ultrasonic welding and bonding which may worth exploring through LCA studies. While it is vital that these knowledge gaps are addressed, the large variety of product types makes the production of comprehensive LCI data for the clothing manufacturing stage highly challenging.

4.2.4. *Retailing stage*

The systematic literature review revealed a lack of LCA studies conducted for the retailing stage of clothing, and that the studies available focused on specific products such as a cotton T-shirt, a polyester jacket and a bra again, as shown in Table 9. One of the key questions with respect to the retail stage concerns the benefits/disbenefits of on-line versus bricks-and-mortar retail. Bertram and Chi (2018) explored differences in GHG emissions due to the distance of the user

Table 10
LCI data of user transportation (adapted from Bertram and Chi (2018)).

Method	Distance between the retailer and the customer location/km	GHG (kg CO_2eq/kg)	Group
Conventional shopping using own transportation	Below 14	0.43	Group 3
	14–25	0.801	Group 3
	25–50	1.445	Group 3
	50–100	2.263	Group 3
	Above 100	2.624	Group 3
Online shopping	Below 14	0.242	Group 2
	14–25	0.242	Group 2
	25–50	0.24	Group 2
	50–100	0.24	Group 2
	Above 100	0.237	Group 2

location, and their study presents literature-based values as shown in Table 10. They found that online shopping has lower GHG emissions (Group 2) due to transportation than conventional shopping (Group 3). In view of the shift to online shopping due to Covid-19, it is vital that more in-depth and comprehensive LCA studies are carried out in this area, to help understand and minimize the effects of this shift.

Fig. 12 shows the heat map of the grouping framework for the clothing manufacturing and retailing stages. Values of clothing manufacturing range between Group 1 to 4 in all the impact categories. However, the heat map reflects the lack of data (Fig A1). This is particularly true of the retail stage, although what data there is suggests that the environmental impacts are relatively low (Steinberger et al., 2009; Zhang et al., 2015).

4.2.5. Use

The use stage is considered one of the key stages that creates adverse environmental impacts of clothing (Neral et al., 2011) through domestic washing and ironing, and dry cleaning. As presented in Table 11, the impact of domestic washing was investigated for different temperatures and materials such as wool, cotton and polyester. As expected, energy consumption and GHG emissions are found to increase with increasing washing temperatures. Dry cleaning has only been investigated in one study (Laitala et al., 2018).

Investigations into the environmental impacts of different washing machine types show that high efficiency washing machines combined with line drying have the lowest GHG emissions and lowest water usage, while regular efficiency washers combined with regular drying have the highest GHG emissions and highest water usage. Pulsator washer machines combined with line drying have the lowest energy consumption while regular efficiency washers combined with regular efficiency drying has the highest energy consumption (Table 11). These shreds of evidence show that different technologies, energy sources and materials can make a difference in the environmental impacts in the use.

The heat map for the use phase is shown in Fig. 13. Domestic ironing and dry-cleaning phases are difficult to analyse due to poor data availability. Fig. 13 emphasizes that the use stage has relatively high environmental impacts, as expected. Apart from the energy usage of high-efficiency washer with line drying, all the other impact values of the methods are in Group 3 or above. Therefore, the use stage needs addressing through consumer guidance on low impact methods of clothes' care, alongside new innovations to reduce environmental impacts. Furthermore, this heat map shows the knowledge gaps in the use stage which need to be addressed in order to make robust decisions. During the use stage of a garment, LCA studies are mainly focused on the garment washing phase, however garment drying, dry cleaning and ironing also needs to be investigated (Fig A1).

4.2.6. End of life stage

LCI data for recycling, reuse, gasification, incineration and landfill are presented in Table 12. The data confirm that reuse is the best strategy in terms of saving energy, followed by recycling. Recycling and reuse methods are shown to have negative GHG emissions values meaning that they are considered to avoid more GHG emissions than they emit (Erbach, 2015). Incineration and gasification can be used as energy recovery options, although, as stated above, these are the least preferred methods in the waste hierarchy (DEFRA, 2011).

A heat map of the grouping framework of the different techniques at the end of life stage is shown in Fig. 14. Sorting can be considered as a common activity in this stage unless the garment is sent directly to the landfill without sorting. The heat map highlights that recycling has lower GHG emissions than gasification and incineration, however, its energy consumption is high. But recycling avoids the use of virgin materials, for example, as discussed in the material extraction stage, with recycled cotton being the best-performing fabric among the presented material lists. Therefore, recycling can be recommended before gasification and incineration. Fig. 14 demonstrates the lack of data on water use, although water use during the end of life phase is assumed to be negligible.

4.3. Summary of impacts across all lifecycle stages

A summary of the grouping framework for the entire clothing lifecycle is presented in Fig. 15. This shows the range of values reported above for each lifecycle stage: for example, GHG emissions for the

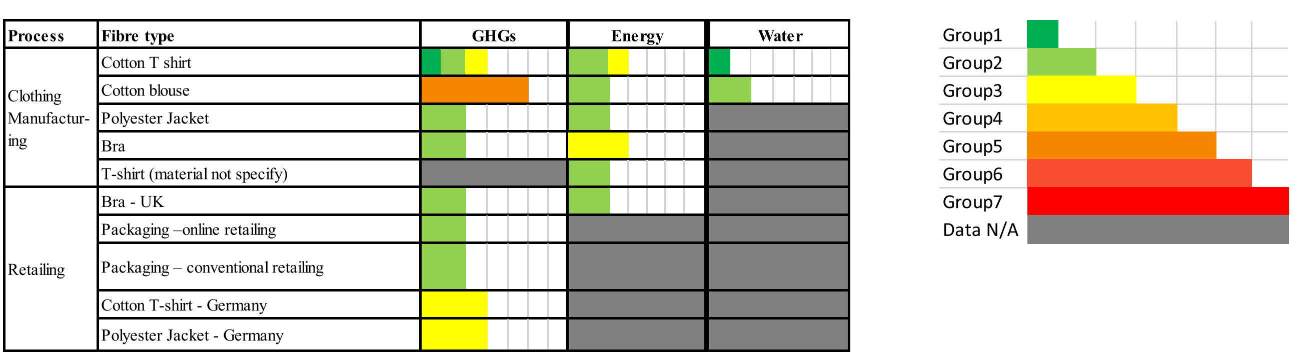


Fig. 12. Heat map of groupings for clothing manufacturing and retailing stages.

Table 11
LCI data for the use phase.

		GHG (kg CO_2eq/kg)	Energy Usage (MJ/kg)	Water Usage (L/kg)	Reference sources
Washing per 45 cycles (including drying)	Wool at 30 °C	3.195	–	–	Bevilacqua et al. (2011)
	Wool at 40 °C	3.555	–	–	Bevilacqua et al. (2011)
	Wool at 25 °C	–	37.26	805.5	Laitala et al. (2018)
	Wool at the cold water	1.035	–	–	Bevilacqua et al. (2011)
	Polyester	34.65	634.95	–	Steinberger et al. (2009)
	Cotton at 40C	28.26	–	–	Steinberger et al. (2009)
	Cotton at 49.7 °C	–	51.84	621	Laitala et al. (2018)
	Cotton at 60 °C	31.68	184.68	2205	Steinberger et al. (2009); Baydar et al. (2015)
	High-efficiency washer with line drying	1.71	8.865	614.25	Hicks et al. (2015)
	High-efficiency washer with high-efficiency dryer	21.825	98.82	614.25	Hicks et al. (2015)
	Regular efficiency washer line drying	11.745	54	1116.63	Hicks et al. (2015)
	Regular efficiency washer with regular efficiency drying	51.57	232.74	1116.63	Hicks et al. (2015)
	Drum washer with a Condenser dryer	–	49.86	–	Kim et al. (2015)
	Drum washer with heat pump dryer	–	23.31	–	Kim et al. (2015)
	Drum washer with line drying	–	1.485	–	Kim et al. (2015)
	Pulsator washer with a Condenser dryer	–	49.41	–	Kim et al. (2015)
	Pulsator washer with heat pump dryer	–	22.86	–	Kim et al. (2015)
	Pulsator washer with line drying	–	1.035	–	Kim et al. (2015)
Dry cleaning per 45 cycles	Decamethylcyclo-pentasiloxane D	–	193.59	–	Laitala et al. (2018)
	Hydrocarbon	–	126.81	–	Laitala et al. (2018)
	LCO_2	–	110.34	–	Laitala et al. (2018)
	PERC, C2Cl4	–	94.905	–	Laitala et al. (2018)
	Wet cleaning	–	33.21	–	Laitala et al. (2018)
Domestic ironing per 45 cycles	Cotton	–	29.16–409.5	–	Kim et al. (2015); Yun et al. (2017)
	65/35 Poly-Cotton with durable press finish	–	454.5	–	Yun et al. (2017)
	65/35 Poly-Cotton	–	508.5	–	Yun et al. (2017)

Fig. 13. Heat map of groupings for the end-use phase of clothing.

Table 12
LCI data for the End of life stage.

		GHG (kg CO_2eq/kg)	Energy Usage (MJ/kg)	Water Usage (L/kg)	Reference sources
Sorting	Lithuania	–	73.7	0.00021–0.00024	Norup et al. (2019)
	Australia	–	6.12	–	
	Manual Sorting	–	0.005	–	Dahlbo et al. (2017)
	Automatic Sorting	–	0.198	–	Dahlbo et al. (2017)
Fibre Recycle	Cotton and Polyester sorting	8.0	–	–	Baydar et al. (2015)
Recycling	Mix textiles	(-7.7) -(-8.0)	73.7	0.00021	Bertram and Chi (2018); Baydar et al. (2015); Norup et al. (2019)
Chemical Recycling	Polyester	–	23.76	–	Dahlbo et al. (2017)
	Cellulose	–	26.88	–	Dahlbo et al. (2017)
Reuse	Any textile	(-3.6) -(-8)	(-164) -(-324)	−6000	Bertram and Chi (2018) Baydar et al. (2015) Eryuruk (2012) Zamani et al. (2015)
	Cotton and Polyester in the UK	(-33)	–	–	Baydar et al. (2015)
	Polyester	–	(-324)	–	Baydar et al. (2015)
	Cotton	–	(-234)	–	Baydar et al. (2015)
Gasification		1.028	(-4.1)	–	Arafat et al. (2015)
Incineration	For energy generation	0.36–2.054	(-5) -(-20)	–	Yuan et al. (2013) Arafat et al. (2015) Arafat et al. (2015)
Landfill	Cotton	0.073–12.5	0.0001	–	Yuan et al. (2013), Yasin et al. (2018),Yacout and Hassouna (2016)

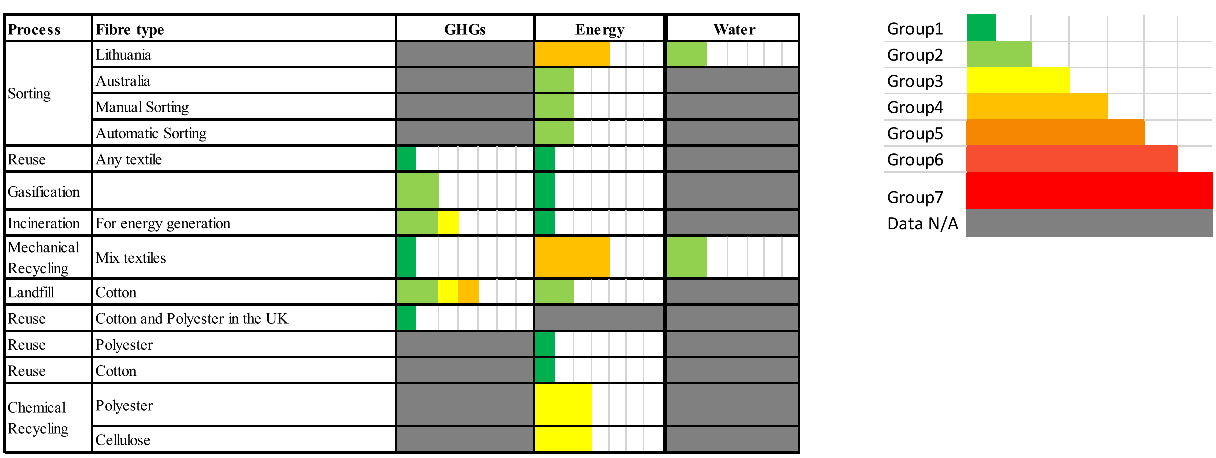


Fig. 14. Heat map of groupings for the post-end-use phase.

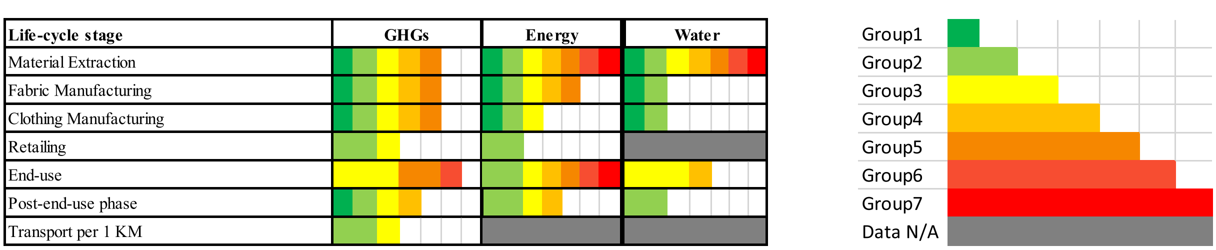


Fig. 15. Summary heatmap for all lifecycle stages.

material extraction stage span from Group 1 to 6. Fig. 15 highlights that the two most damaging stages can be the raw material extraction and use stages. When comparing those two stages, the range of GHG emissions for the material extraction stage has options from Group1 to Group 7 while the use stage has options only from Group 2 upwards. This suggests that the material extraction stage has more available options to reduce GHG emissions by selecting better materials while the use stage needs more innovations to improve the current context. The retail stage can be considered the least impactful, although data on water use is not available for this as it is generally assumed to be negligible. However, as noted above, the environmental impacts of the shift from conventional to on-line retail are still important to investigate.

4.4. Limitations of the study

The study revealed that the papers reviewed used different methods and datasets when conducting the LCA studies, although some important information about methodologies, such as whether attributional or consequential LCA was used, was largely missing. Various different databases were used in the studies, such as Ecoinvent and GaBi Educational, while other studies used secondary data sources such as industrial reports. This may be a cause of inconsistencies in the data reported here. Furthermore, the impact assessment methodologies also varied amongst the selected papers, with methods including, for example, CML 2001, IPCC 2007 and ReCiPe Mid/Endpoint. This may result in uncertainties when comparing data. Additionally, most of the selected articles do not mention whether reported carbon dioxide emissions from energy use were biogenic and nonbiogenic, or whether the water footprint is that of blue, green or grey water, or a combination. This is important because, for example, in the material extraction stage for plant-based fibres, green water (i.e. water from precipitation) is involved and so it should, ideally be reported. 63% of the papers that reported water footprint data in this study focus on plant-based fibres, however 70% of these studies do not report the type of water footprint (i.e. blue or green). Such lack of information should be born in mind when interpreting the results presented in this paper.

5. Discussion and conclusion

This study presents a systematic literature review and meta-analysis that collates data on the environmental impacts which occur throughout the life cycle of clothing. The data collated will be of use to researchers who require LCI data on GHG emissions and energy and water use. However, to be of further use to a wider set of stakeholders, the data have been used to group the various materials and processes at each stage of the life cycle according to their environmental impact intensity.

The study shows that the raw material extraction phase was the life cycle phase most studied during the years 2009–2019, and this was found to be the life cycle stage with the highest environmental impact. Recycled cotton is identified as having the lowest environmental impact in this phase, while flax is identified as the virgin fibre with the lowest environmental impacts in this phase. Apart from the material extraction stage, fabric dyeing has the highest environmental impact among the sub-phases of the clothing manufacturing life cycle phase, while the use phase has significant environmental impacts due to domestic washing. Furthermore, reuse is shown to be the lowest impact method in the end of life phase. Initial studies show that online retailing can contribute to reducing the environmental impact of retailing, due to lower energy use and associated GHG emissions associated with transportation.

This review has highlighted that if fashion industry stakeholders are to base decisions on comprehensive data, more studies are required. There are parts of the life cycle - fabric manufacturing, clothing manufacturing and retailing - for which there is sparse information as illustrated in Appendix A, Fig. A.1. In particular, it is vital that LCA studies on nonwoven fabric production are carried out, because the demand for nonwoven materials is increasing and it is becoming an important category of the textile apparel manufacturing sector. The review has also demonstrated the lack of data on innovative materials such as smart textiles: this should be addressed as there is a rising trend in their use, especially in the military, health, sports and fitness sectors, and hence it is vital that their environmental impacts are understood. Furthermore, there is also a lack of data on options that may be considered more sustainable, such as traditional methods of production like handloom weaving as carried out in India and Sri Lanka. Without LCI data that allow comparison to mainstream techniques, it is unknown whether these are truly more sustainable options.

It is also important to note that a lack of transparency regarding the functional unit and methodologies used in some studies led to their exclusion from this analysis. Within the studies that were included in this report, very few reported whether attributional or consequential LCA was used, and there was often a lack of detail with respect to, for example, the type of energy (biogenic or nonbiogenic) and water (blue, green or grey). Furthermore, robust calculations were difficult for the consumer use stage because different brands use different standards in the washing process. Hence it is concluded that not only are more studies needed in specific areas, but that care must be taken to ensure their robustness and transparency. Also, industry standards on methods for assessing the impact of clothes washing should be established in order to increase the comparability of studies.

It is imperative that the results presented in this paper are looked at in the wider context of consumption: the best way to reduce impacts from the production stage is to reduce consumption. However, noting that production cannot be reduced to zero, the results of this study will be of use to stakeholders in the fashion industry such as manufacturers and designers, and also to consumers, in addition to being of use to researchers. Thus by combining use of the findings in this paper with steps to reduce the overall volume of consumption, progress may be made towards meeting the United Nations Sustainable Development Goal 12 - Responsible Consumption and Production (United Nations, 2021).

Declaration of competing interest

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

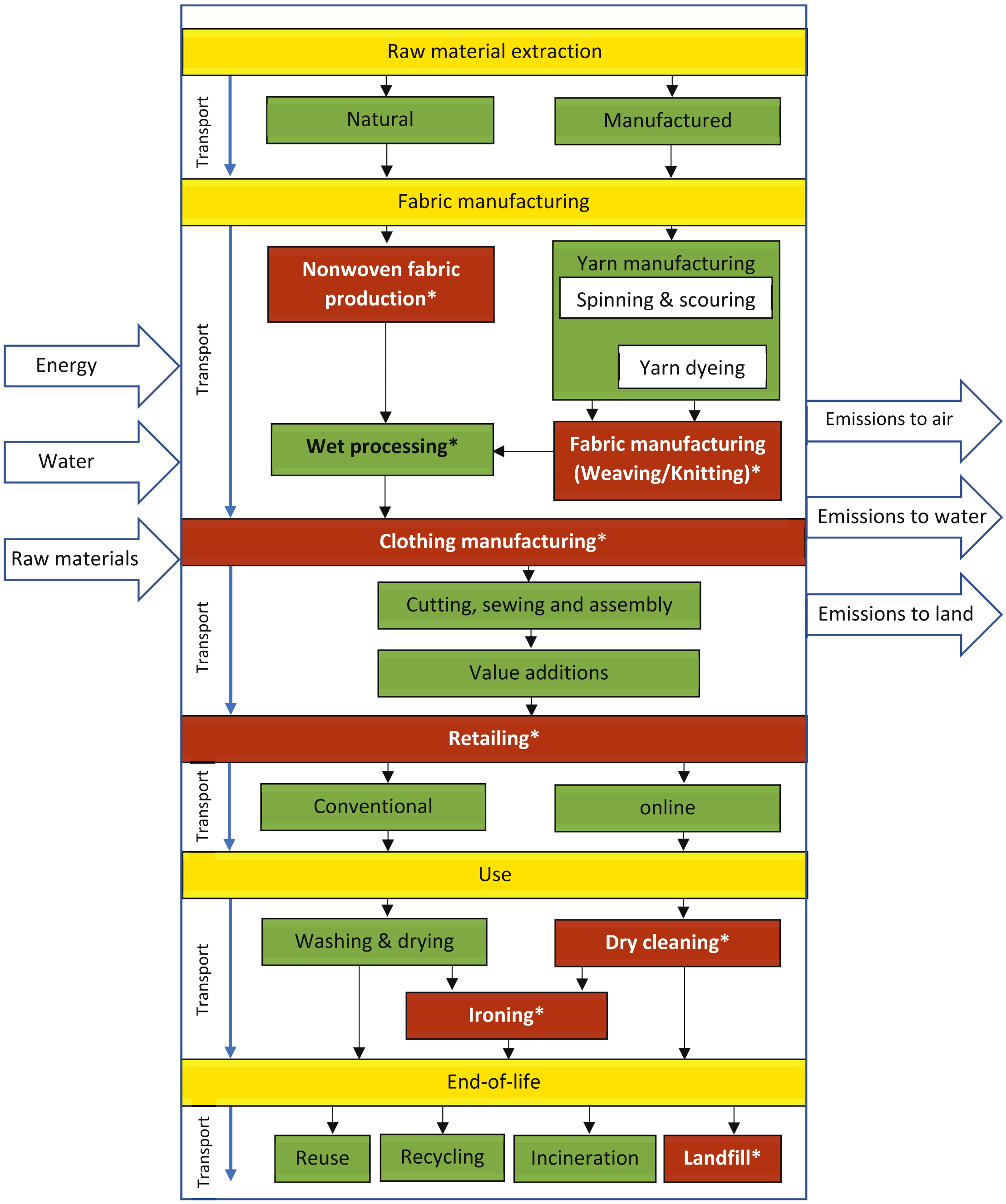
Acknowledgements

We are grateful for support from the University Grants Commission, Sri Lanka, grant number DRIC/PG2017(II)/MRT/01 and support from the UK Economic and Social Research Council's support for the Centre for the Understanding of Sustainable Prosperity, grant number ES/M010163/1.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128852.

Appendix A



*** Life cycle stages/sub-stages where there are large research gaps – highlighted red**

Fig. A.1. Research gaps in the clothing product life cycle

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Update

Journal of Cleaner Production
Volume 422, Issue , 10 October 2023, Page

DOI: https://doi.org/10.1016/j.jclepro.2023.138615

Journal of Cleaner Production 422 (2023) 138615

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Corrigendum to "A systematic review of the life cycle inventory of clothing" [J. Clean. Prod. 320 (2021) 128852]

Prabod Munasinghe [a,b], Angela Druckman [b,*], D.G.K. Dissanayake [a]

[a] *Department of Textile and Apparel Engineering, Faculty of Engineering, University of Moratuwa, Moratuwa, 10400, Sri Lanka*
[b] *Centre for Environment and Sustainability, University of Surrey, UK*

The authors regret that an error was made when writing-up the results of which materials are reported in the peer-reviewed literature to have the lowest environmental impact during the raw material extraction stage. Unfortunately Cotton- USA (no irrigation) was missed out, and Nylon 66-A was listed instead. On the basis of this mistake, the 7th sentence in the Abstract is revised to "*In this life cycle stage, Cotton- USA (no irrigation) and flax are the virgin fibres with the lowest environmental impacts, recycled cotton is the recycled fibre which has the lowest environmental impacts and Indian silk is found to have the highest impacts.*". The 2nd and 3rd sentences of section 4.2.1 'Raw material extraction' in the 'Results and discussion' section are revised to "*This evidence shows that Indian silk fibre production causes the highest environmental impact (based on GHG emissions, energy and water use) while Cotton- USA (no irrigation) and flax have the lowest environmental impact among virgin fibres. Recycled cotton also shows good environmental performance.*". The 2nd sentence of the 2nd paragraph in section 5.0 'Discussion and conclusion' is revised to "*Recycled cotton is identified as having the lowest environmental impact in this phase, while Cotton- USA (no irrigation) and flax are identified as the virgin fibres with the lowest environmental impacts in this phase.*"

Also, an incomplete version of the appendix was published. A complete version is available below.

The authors would like to apologise for any inconvenience caused.

Appendix A

Search terms used in the study.

Based on the keywords, the search terms used in the study were "(((TITLE-ABS-KEY (lca) OR TITLE-ABS-KEY ('life AND cycle') OR TITLE-ABS-KEY ('supply AND chain') AND TITLE-ABS-KEY (anal*))) AND ((TITLE-ABS-KEY (environm*) OR TITLE-ABS-KEY (sust*))) AND ((TITLE-ABS-KEY (textile*) OR TITLE-ABS-KEY (fabric*)))) OR (((TITLE-ABS-KEY (lca) OR TITLE-ABS-KEY ('life AND cycle') OR TITLE-ABS-KEY ('supply AND chain') AND TITLE-ABS-KEY (anal*))) AND ((TITLE-ABS-KEY (environm*) OR TITLE-ABS-KEY (sust*))) AND ((TITLE-ABS-KEY (apparel*) OR TITLE-ABS-KEY (cloth*) OR TITLE-ABS-KEY (fashion))))".

Table A1
Functional unit of each study

	The functional unit of study
Agnhage, Perwuelz and Behary (2017)	1kg of woven polyester fabric (110GSM)
Arafat, Jijakli and Ahsan (2015)	1kg of textile waste
Astudillo, Thalwitz and Vollrath (2014)	1kg of raw silk
Baydar, Ciliz and Mammadov (2015)	1000 items of knitted and dyed cotton T-shirt with a total weight of 200kg and 50 washing cycles at 60 °C temperature
Bertram and Chi (2018)	100g corrugated cardboard box and up to 33 g of insulation material for one package
Bevilacqua et al. (2014)	1kg of dyed cotton yarn.
Bevilacqua et al. (2011)	100% Merino wool sweater of 264.85g in weight
Bhalla, Kumar and Rangaswamy (2018)	1kg of hand-woven cotton-Khadi fabric
Chico, Aldaya and Garrido (2013)	1000kg of cotton materials
Dahlbo et al. (2017)	1kg of textile waste
De Saxce, Pesnel and Perwuelz (2012)	115GSM cotton and cotton blended bed sheets

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DOI of original article: https://doi.org/10.1016/j.jclepro.2021.128852.
* Corresponding author. Centre for Environment and Sustainability, University of Surrey, Guildford, Surrey, GU2 7XH, UK.
E-mail address: a.druckman@surrey.ac.uk (A. Druckman).

https://doi.org/10.1016/j.jclepro.2023.138615

Available online 7 September 2023

Table A1 (*continued*)

	The functional unit of study
Edlund et al. (2018)	1kg of synthetic spider silk
Esteve-Turrillas and de la Guardia (2017)	1kg of coloured cotton yarn
Eryuruk (2012)	1000kg of materials per 1km
George and Bressler (2017)	1kg of hemp fibre
Hassan and Shao (2015)	1kg of wool
Hicks et al. (2015)	Shirt of 130g in weight and 100 washing cycles
Ioppolo et al. (2017)	1kg of PET materials
Kang et al. (2018)	2000kg of polyester-cotton products
Kiffle et al. (2017)	1kg of materials
Kim et al. (2015)	250g of clothing, washed and dried for 25 cycles
Kissinger et al. (2013)	1kg of materials
Koligkioni et al. (2018)	1000kg of used textiles
Laitala, Klepp and Henry (2018)	1kg of textiles
Laurenti et al. (2017)	$1m^2$ of leather of 1.2- to 1.4-mm thickness
Lee and Tansel (2012)	1l of wastewater from washing appliance and one washing cycle
Linhares and De Amorim (2017)	1kg of 125GSM plain weaved woven cotton fabric
Moazzem et al. (2018)	1kg of clothing over the lifetime
Munasinghe et al. (2016)	Padded, Preform Plunge Bra with Lace Cradle design with 46.4g in weight
Muthu et al. (2012)	1kg of fibre
Muthukumarana et al. (2018)	100% cotton blouse 146g in weight, Standard Allowed Minutes 29.82
Neral, Sostar-Turk and Fijan (2011)	1kg of laundered textile
Norup et al. (2019)	1000kg of imported mixed waste, sold textiles and reuse textiles
Parisi et al. (2015)	1kg of woolen fabric (300GSM)
Petrescu, Fermeglia and Cormos (2016)	1000kg of acrylic acid produced.
Roos et al. (2018)	1kg of materials
Roos and Peters (2015)	1kg of fabrics
Russell (2009)	1kg of wool
Shen, Worrell and Patel (2010)	1000kg of staple fiber
Steinberger et al. (2009)	250g Cotton t shirt and 500g Polyester Jacket
Terinte et al. (2014)	1kg of modal knitted fabric
Tseng and Hung (2014)	1000kg of goods
Walser et al. (2011)	130g T-shirt
Wiedemann et al. (2018)	500g of 100% superfine Merino wool
Wiedemann et al. (2016)	1kg greasy wool
Yacout, Abd El-Kawi and Hassouna (2016)	1kg of acrylic fibre
Yacout and Hassouna (2016)	1000kg production of acrylic fibre.
Yasin et al. (2018)	A curtain 1kg in weight
Yuan et al. (2013)	10,000m of cotton fabric, which weighs 2,000kg
Yun et al. (2017)	2000kg of polyester–cotton products
Yun et al. (2016)	3kg of goods, 50 washing cycles
Zamani et al. (2015)	1000kg of household textile waste
Zhang et al. (2015)	100% cotton knitted dyed short-sleeved T-shirt 153g in weight

Table A2
Conversion factors used to standardise functional units.

1 kg CO_2 = 1 $kgCO_2eq$	EPA (2014)
1 kg CH_4 = 25 $kgCO_2eq$	EPA (2014)
1 kg N_2O = 298 $kgCO_2eq$	EPA (2014)
1 ounce = 28.35g	RapidTables (2020)
1kWh = 3.6MJ	ConvertLive (2020)
1mol CO_2 weighs 44g	PlanetCalc (2020)
1 L of water weighs 1kg	Metric-Calculator.com (2020)

Table A3
Selected journal articles and their LCI contents

	Stages in the Life Cycle							Environmental impacts		
	Raw material extraction	Fabric Manufacturing	clothing Manufacturing	Retailing	Use	End of life	Transport	GHG Emissions	Energy Use	Water use
Agnhage, Perwuelz and Behary (2017)		✓						✓	✓	✓
Arafat, Jijakli and Ahsan (2015)						✓		✓	✓	
Astudillo, Thalwitz and Vollrath (2014)	✓							✓	✓	✓
Baydar, Ciliz and Mammadov (2015)	✓	✓	✓		✓	✓	✓	✓	✓	✓

(*continued on next page*)

Table A3 (*continued*)

	Stages in the Life Cycle							Environmental impacts		
	Raw material extraction	Fabric Manufacturing	clothing Manufacturing	Retailing	Use	End of life	Transport	GHG Emissions	Energy Use	Water use
Bertram and Chi (2018)				✓		✓		✓		
Bevilacqua et al. (2014)	✓	✓						✓	✓	✓
Bevilacqua et al. (2011)	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Bhalla, Kumar and Rangaswamy (2018)	✓	✓	✓		✓		✓	✓	✓	✓
Castellani, Sala and Mirabella (2015)						✓		✓	✓	✓
Chico, Aldaya and Garrido (2013)	✓	✓	✓							✓
Dahlbo et al. (2017)	✓	✓				✓	✓	✓	✓	
De Saxce, Pesnel and Perwuelz (2012)	✓	✓	✓		✓			✓	✓	✓
Edlund et al. (2018)	✓							✓		
Esteve-Turrillas and de la Guardia (2017)	✓	✓					✓	✓	✓	✓
Eryuruk (2012)							✓	✓		✓
Farrant, Olsen and Wangel (2010)						✓		✓		
George and Bressler (2017)	✓							✓	✓	✓
Hassan and Shao (2015)		✓						✓	✓	✓
Hicks et al. (2015)	✓	✓			✓	✓	✓	✓	✓	✓
Hole and Hole (2019)						✓		✓	✓	✓
Ioppolo et al. (2017)		✓			✓	✓			✓	✓
Kang et al. (2018)	✓	✓				✓		✓	✓	✓
Kiffle et al. (2017)	✓	✓					✓	✓		
Kim et al. (2015)					✓				✓	
Kissinger et al. (2013)	✓	✓						✓		
Koligkioni et al. (2018)						✓		✓	✓	
Laitala, Klepp and Henry (2018)					✓	✓			✓	✓
Laurenti et al. (2017)		✓						✓	✓	✓
Lee and Tansel (2012)					✓			✓	✓	✓
Linhares and De Amorim (2017)	✓	✓						✓		✓
Moazzem et al. (2018)	✓	✓	✓		✓	✓		✓	✓	
Munasinghe et al. (2016)	✓	✓	✓	✓	✓		✓	✓	✓	
Muthu et al. (2012)	✓							✓	✓	✓
Muthukumarana et al. (2018)		✓	✓				✓	✓	✓	✓
Neral, Sostar-Turk and Fijan (2011)					✓			✓	✓	✓
Norup et al. (2019)						✓	✓		✓	✓
Parisi et al. (2015)		✓					✓	✓	✓	✓
Petrescu, Fermeglia and Cormos (2016)	✓	✓						✓	✓	✓
Roos et al. (2018)	✓	✓							✓	✓
Roos and Peters (2015)			✓							
Russell (2009)	✓	✓	✓		✓	✓		✓	✓	✓
Shen, Worrell and Patel (2010)	✓							✓	✓	✓
Steinberger et al. (2009)	✓	✓	✓	✓	✓			✓	✓	
Terinte et al. (2014)	✓	✓						✓	✓	✓
Tseng and Hung (2014)							✓	✓		
Walser et al. (2011)	✓	✓	✓		✓	✓	✓	✓		
Wiedemann et al. (2018)	✓							✓	✓	✓
Wiedemann et al. (2016)	✓							✓	✓	✓
Yacout, Abd El-Kawi and Hassouna (2016)	✓							✓	✓	✓
Yacout and Hassouna (2016)	✓							✓	✓	
Yasin et al. (2018)		✓				✓		✓	✓	✓
Yuan et al. (2013)		✓				✓	✓	✓	✓	✓
Yun et al. (2017)					✓				✓	
Yun et al. (2016)					✓				✓	✓
Zamani et al. (2015)						✓		✓	✓	
Zhang et al. (2015)	✓	✓	✓	✓	✓	✓		✓	✓	✓

Table A4
Methodologies and databases used in each paper

	GHG calculation method (if specified)	GHG unit	Inventory collection method for energy and water: Energy	Water	Software used in the study	Analysis Method
Agnhage, Perwuelz and Behary (2017)		kg CO_2 eq.	ELCD, EcoInvent and CODDE (energy type* is not specified)	ELCD, EcoInvent and CODDE (Not specified the type of the water)	EIME software	Direct data from EIME software
Arafat, Jijakli and Ahsan (2015)		mol CO_2	Eco-Invent database (energy type* is not specified)	Not studied	SimaPro V.7.3.2	CML 2001
Astudillo, Thalwitz and Vollrath (2014)	IPCC 2007 - GWP_{100}	kg CO_2eq/kg	Ecoinvent database and literature (CED presented as NREU + REU)	Ecoinvent database and literature (Bluewater footprint)	Simapro v 8.0.2	IPCC 2007 - GWP_{100} v1.02, Cumulative energy demand v 1.08 (CED)
Baydar, Ciliz and Mammadov (2015)	GWP (IPCC)	kg CO_2 eq.	Databases from GaBi software (energy type* is not specified)	Databases from GaBi software (not specified the type of the water)	GaBi 5 LCA modelling software	EDIP 2003, GWP(IPCC)
Bertram and Chi (2018)	Literature survey	CO_2/kg	Not studied	Not studied		Literature review
Bevilacqua et al. (2014)	IPCC 2007 - GWP_{100}	kg CO_2 eq.	Questionnaires and secondary sources, Ecoinvent v2 database (energy type* is not specified)	Questionnaires and secondary sources, Ecoinvent v2 database (Egypt, China, India –Blue water/USA- Green water)	Not mentioned	IPCC 2007 - GWP_{100} and Ecoindicator99
Bevilacqua et al. (2011)	IPCC 2007 - GWP_{100}	kg CO_2	Ecoinvent database (energy type* is not specified)	–	Simapro' software	IPCC 2007 - GWP_{100}, PAS 2050 2008,
Bhalla, Kumar and Rangaswamy (2018)		kg CO_2 eq.	Field study and GaBi educational databases (energy type* is not specified)	Field study and GaBi educational databases (not specified the type of the water), Ecoinvent 3.0	Not mentioned	CML 2001
Chico, Aldaya and Garrido (2013)	Not studied	Not studied	Not studied	Data gathered using AITEX and Lenzing Group (total water = blue water + green water)	Not mentioned	
Dahlbo et al. (2017)		kg CO_2 eq.	literature (energy type* is not specified)	–	SimaPro	ReCiPe Mid/Endpoint method
De Saxce, Pesnel and Perwuelz (2012)		kg CO_2 eq.	PE International database (energy type* is not specified)	Literature (not specified the type of the water)	GaBi 4 LCA software	CML 2001
Edlund et al. (2018)	IPCC 2007 - GWP_{100},	kg CO_2 eq/kg	Not studied	Not studied	Inventory was taken from National Renewable Energy Lab (NREL) and Argonne National Lab (ANL) including the U.S. LCI database and GREET 2015	IPCC 2007 - GWP_{100},
Esteve-Turrillas and de la Guardia (2017)	IPCC (GWP)	kg CO_2 eq.	Literature which is based on ISO 14040 and ISO 14044 (energy type* is not specified)	Literature which is based on ISO 14040 and ISO 14044 (not specified the type of the water)	GaBi software, CROPWAT platform, SimaPro	IPCC method
Eryuruk (2012)	Literature survey	kg CO_2	Not studied	Literature survey (not specified the type of the water)	Not mentioned	
George and Bressler (2017)	IPCC 2013 - GWP_{100}, Literature which used Greenhouse Gas Protoco	kg CO_2 eq.	EcoInvent database and literature (energy type* is not specified)	EcoInvent database and literature (not specified the type of the water)	SimaPro 8.0.3.14	Ecopoints, ReCiPe, Eco-indicator
Hassan and Shao (2015)	USEPA 'Greenhouse Gas Equivalencies Calculator'	kg CO_2 eq/kg	Source is not mentioned (energy type* is not specified)	The source is not mention (not specified the type of the water)	USEPA 'Greenhouse Gas Equivalencies Calculator	
Hicks et al. (2015)	Midpoint impact categories	kg CO_2 eq/kg	Ecoinvent, USLCI, ELCD inventories and reports (energy type* is not specified)	Ecoinvent, USLCI, ELCD inventories and reports (not specified the type of the water)	SimaPro 8.0.1 software,	TRACI (2.1) assessment method
Ioppolo et al. (2017)	–	–	GaBi and Plastics Europe database (energy type* is not specified)	GaBi database, industry experts and literature (not specified the type of the water)	GaBi software	Emissions defined within the EU Ecolabel scheme for textiles (JRC), Data Quality Rating (DQR) guidelines
Kang et al. (2018)		kg CO_2	Literature, GaBi 5.0 database (energy type* is not specified)	Literature, GaBi 5.0 database (not specified the type of the water)	LCA software (not specified)	CML 2001, SETAC, GWP_{100}
Kiffle et al. (2017)	TenCate carbon footprint software	kg CO_2/kg	Not studied	Not studied	TenCate carbon footprint software	

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Table A4 (*continued*)

	GHG calculation method (if specified)	GHG unit	Inventory collection method for energy and water: Energy	Inventory collection method for energy and water: Water	Software used in the study	Analysis Method
Kim et al. (2015)	Not studied	Not studied	washing and drying processes were taken from the literature survey, Inventory of ironing collected in lab conditions (energy type* is not specified)	Not studied	Not mentioned	
Kissinger et al. (2013)	Academic literature, and commercial and industrial reports	kg CO_2 eq/ tonne	Not studied	Not studied	Not mentioned	Literature survey
Koligkioni et al. (2018)	ILCD 2011 midpoint + method	kg CO_2 eq/ tonne	Ecoinvent 3.1 database (energy type* is not specified)	–	STAN 2.5 software, Ecoinvent 3.1, SimaPro 8.3.0.0	Mass flow analysis (MFA), ILCD 2011 midpoint + method cLCA approach used
Laitala, Klepp and Henry (2018)	Not studied	Not studied	Literature (energy type* is not specified)	Literature (not specified the type of the water)	Not mentioned	Literature survey
Laurenti et al. (2017)	Calculated through GaBi software and Thinkstep database	kg CO_2 eq./m2	Survey (energy type* is not specified)	Survey (not specified the type of the water)	GaBi software, Thinkstep database	Survey, LWG auditing protocol
Lee and Tansel (2012)	Calculated through EIO-LCA tool	mt CO_2 eq	Literature (energy type* is not specified)	Literature (not specified the type of the water)	Economic Input-Output Life Cycle Assessment (EIO-LCA) tool	
Linhares and De Amorim (2017)	ReCiPe 1:08 (H)- the time frame of 100 years	kg CO_2 eq	Not studied	GaBi Education database 2014 (not specified the type of the water)	GaBi software	ReCiPe 1:08 (H)- time frame of 100 years
Moazzem et al. (2018)	CML baseline 2001- GWP	kg CO_2 eq/kg	Ecoinvent v3 databases (energy type* is not specified)	–	Open LCA software,	CML baseline method 2001
Munasinghe et al. (2016)	Not mentioned	kg CO_2 eq.	literature survey (energy type* is not specified)	literature survey (not specified the type of the water)	Not mentioned	PAS2050
Muthu et al. (2012)		kg CO_2	literature survey (energy type* is not specified)	literature survey (not specified the type of the water)	SIMAPRO 7.2	Eco-indicator'99
Muthukumarana et al. (2018)	ReCiPe (Ver 1.11) Midpoint and endpoint methods	kg CO_2 eq.	Reports and Ecoinvent 3 database (energy type* is not specified)	Ecoinvent 3 database (not specified the type of the water)	SimaPro software,	ReCiPe (Ver 1.11) Midpoint and endpoint methods
Neral, Sostar-Turk and Fijan (2011)	CML2001-GWP	g CO_2 eq.	Own recordings (energy type* is not specified)	Own recordings (not specified the type of the water)	Not mentioned	CML2001, CERA-Cumulative Energy Require- ments Analysis, Eco-indicator 99, Ecological footprint, EDP-Ecosystem Damage Potential, EDIP2003, IMPACT 2002+, IPCC 2001, TRA- CI, SLCI
Norup et al. (2019)	Not studied	Not studied	Inventory were taken from On-site visits, visual inspections, On-site interviews and onfiled documents (energy type* is not specified)	Inventory were taken from On-site visits, visual inspections, On-site interviews and onfiled documents (not specified the type of the water)	STAN (ver-sion 2.6.801)	Material flow analysis
Parisi et al. (2015)	CML 2 baseline 2001 V2.05- GWP_{100}	kg CO_2 eq.	field data and interviews, scientific reports and literature. (Only NREU considered)	field data and interviews, scientific reports and literature. (not specified the type of the water)	Ecoinvent database V3.01, SimaPro 7.3.3	CML 2 baseline 2001 V2.05, GWP_{100},
Petrescu, Fermeglia and Cormos (2016)	CML2001	kg CO_2 eq/ tonne	GaBi Manual (energy type* is not specified)	GaBi Manual	Aspen Plus and PROII	CML2001,
Roos et al. (2018)	–	–	Case studies, the literature and databases (energy type* is not specified)	case studies, and the literature and databases	Not mentioned	USEtox model
Roos and Peters (2015)	Not studied	Not studied	Not studied	Not studied	Not mentioned	USEtoxmodel
Russell (2009)	PAS 2050	kg CO_2 eq.	EcoInvent 2.0 database (2008) and literature (energy type* is not specified)	EcoInvent 2.0 database (2008) and literature	SimaPro software	EU eco-label
Shen, Worrell and Patel (2010)	IPCC 2007 - GWP_{100}	t CO_2 eq/ tonne	Ecoinvent database (version 1.3, 2.0) and literature CED=NREU + REU	Ecoinvent database (version 1.3, 2.0) and literature	Not mentioned	CML baseline method, IPCC 2007 - GWP_{100},

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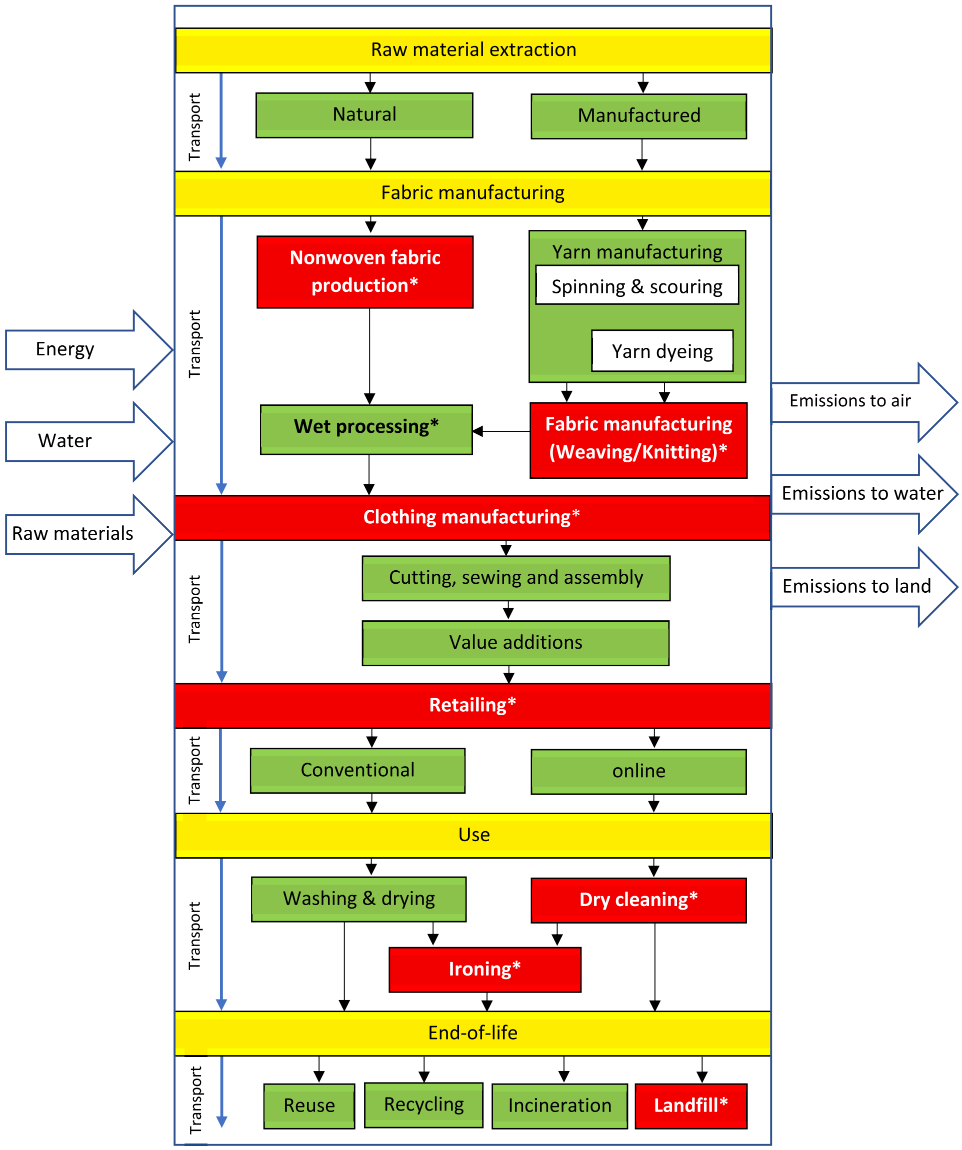
Table A4 (*continued*)

	GHG calculation method (if specified)	GHG unit	Inventory collection method for energy and water: Energy	Water	Software used in the study	Analysis Method
Steinberger et al. (2009)	–	kg CO_2	EcoInvent database and literature, Primary energy = NREU + REU	EcoInvent database and literature	Not mentioned	
Terinte et al. (2014)	IPCC 2007 - GWP_{100}	kg CO_2 eq/kg	Literature CED, NREU + REU	Literature	SimaPro 7.3, Ecoinvent 2.2 database	CML 2001(baseline), IPCC 2007 - GWP_{100}
Tseng and Hung (2014)	From literature	kg CO_2/ tonne per mile	Not studied	Not studied	GHGenius	
Walser et al. (2011)	IPCC 2007 - GWP_{100}	kg CO_2 eq/kg	Not studied	Not studied	Not mentioned	IPCC 2007 - GWP_{100}
Wiedemann et al. (2018)	IPCC 2007 - GWP_{100}	kg CO_2 eq.	Ecoinvent v3.0, AusLCI inventories (energy type is not specified)	Ecoinvent v3.0, AusLCI inventories	SimaPro	IPCC 2007 - GWP_{100}, ReCiPe midpoint (H) indicator set v 1.13 CLCIA and ACLIA methods used
Wiedemann et al. (2016)	IPCC 2007 - GWP_{100}	kg CO_2 eq/kg	Ecoinvent (2.2) database, Australian life cycle inventory database (energy type* is not specified)	Ecoinvent (2.2) database, Australian life cycle inventory database	SimaPro 8.0	IPCC 2007 - GWP_{100},
Yacout, Abd El-Kawi and Hassouna (2016)	Eco-indicator 99 - GWP	kg CO_2 eq/kg	Case study and Ecoinvent v2.2	Case study and Ecoinvent v2.2	SimaPro 7.1,	Eco-indicator 99 methodology,
Yacout and Hassouna (2016)	Eco-indicator 99 - GWP	kg CO_2 eq/kg	Case study and Ecoinvent v2.2 (energy type* is not specified)	–	SimaPro7, Eco-Invent v2 database	Eco-indicator 99
Yasin et al. (2018)		kg CO_2 eq.	ELCD, Eco-Invent and CODDE databases and literature (energy type is not specified)	ELCD, Eco-Invent and CODDE databases and literature	EIME software,	
Yuan et al. (2013)	CML2001 -GWP	kg CO_2 eq.	GaBi version 4.3 database (energy type* is not specified)	GaBi version 4.3 database	GaBi 4.3 software	CML2001,
Yun et al. (2017)	Not studied	Not studied	An experimental study (energy type is not specified)	Not studied	Not mentioned	
Yun et al. (2016)	Not studied	Not studied	An experimental study (energy type* is not specified)	An experimental study	Not mentioned	Experimental study
Zamani et al. (2015)	CML 2007	t CO_2 eq/ tonne	From the literature (energy type is not specified)	Literature	GaBi database	SwedishWaste management Environmental Assessment model, CML method 2007
Zhang et al. (2015)	CML 2001-GWP	kg CO_2	Ecoinvent database, PE professional database, reports and literature (energy type* is not specified)	Ecoinvent database, PE professional database, reports and literature	GaBi 6.0 software	CML 2001,

* Energy types: Renewable energy / Non-renewable energy.



*** Life cycle stages/sub-stages where there are large research gaps – highlighted red**

Fig. A1. Research gaps in the clothing product life cycle