Waste Management 151 (2022) 10–27

Contents lists available at ScienceDirect

Waste Management

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

Life cycle assessment to tackle the take-make-waste paradigm in the textiles production

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ARTICLE INFO

Keywords:
Textile industry
Textile fibers
Life cycle assessment
Circular economy
Environmental sustainability
Literature review

ABSTRACT

Under the environmental perspective, textiles represent the fourth highest pressure commodity worldwide. In Europe, it is estimated that over 95 Mt of textile waste are generated along the entire supply chain, with still high percentages of textiles addressed to landfill or incineration. The present research, through a systematic literature review on textiles production and consumption, investigates their environmental concerns assessed through the application of the life cycle assessment. Considering the importance of identifying the products' life cycle hotspots on which actions are needed to reduce the overall impact, the manuscript focuses on the environmental performance related to the cradle-to-grave phases of textile products differentiated by type, composition, and intended use. It results that the production and use phases are those responsible for the greatest share of negative impacts, while the end-of-life generally has a small contribution. Distribution and consumption phases are less investigated, and considering the emerging consumption patterns (e.g., sharing and renting platforms), it seems essential to collect data. Circular practices can bring benefits under the environmental perspective, but in-depth studies are still required to estimate the shift of impacts from one phase of the life cycle to another. Overall, there is a paucity of studies comparing the use of different fibers, ownership models, manufacturing and disposal processes for the same functional unit, or data that would be necessary for low-impact design. The topic is still under-researched among academics and practitioners of the textile industry.

1. Introduction

Textiles encompass fibers, yarns and fabrics manufacturing, as well as clothes and other made up articles production, and represent the fourth highest pressure category after food, housing, and transport worldwide (European Environmental Agency, 2019). On a global scale, the clothing industry consumes over 80 billion m^3 of water, generating at the same time more than 1,715 Mt of CO_2eq emissions and roughly 95 Mt of textile waste (European Parliament, 2020). Under a business-as-usual scenario, these figures are expected to increase by 50 % in Europe, where it is estimated that approximately 26 kg of textiles per person are consumed each year (i.e., 19 Mt at European level) (European Environmental Agency, 2019). The carbon footprint of each consumer has been estimated at approximately 650 kg of CO_2eq in 2017 (European Parliament, 2020; Eurostat, 2021). As concerns textiles waste pathways in Europe, on average 37 % of textiles waste are separate collected (Watson et al., 2020), whereas 35 % are destined to incineration with energy recovery and 28 % addressed to landfilling (Eurostat, 2022). Germany records the highest rate of separate collection (75 %), followed by the Netherlands (45 %) and Denmark (43 %) (Watson et al., 2020). However, of the entire amount of sorted textile waste, solely 25 % are recycled, whereas more than 60 % are addressed to incineration and 5 % to landfill (Watson et al., 2018, 2020; Schmidt et al., 2016). The residual quota is not accounted in official statistics, since it is abandoned on field, streets or hidden places (Faraca et al., 2019). Several efforts are required to achieve the sustainable transition in the textile industry, either under social, economic, or environmental perspective, and to reduce its environmental burdens in terms of resource consumption and waste production. In the light of the most recent circular paradigms, three levels of efficiency should be pursued: from the efficient use of raw materials to the increase in products lifespan and the smart design of products (Luo et al., 2021). Circular clothing systems are expected to design clothes for longevity, enhance sorting and collection at municipal level, increase re-use and repair, and enact strategies on either the side of consumers or on the side of public procurers (WRAP, 2017). As a consequence, international authorities have implemented sustainable and circular policies, developing transversal targets and green goals. The United Nations have promoted the 17 Sustainable Development Goals, aiming at raising awareness towards sustainable production and consumption patterns for

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https://doi.org/10.1016/j.wasman.2022.07.032
Received 22 April 2022; Received in revised form 11 July 2022; Accepted 24 July 2022
Available online 31 July 2022

Nomenclature

Abbreviations

ADP	Abiotic Depletion
AgNPs	Silver Nanoparticles
ALO	Agricultural Land Occupation
AP	Acidification Potential
AT	Air Toxicity
BATs	Best Available technologies
CC	Climate Change
CE	Circular Economy
CED	Cumulative Energy Demand
CHP	Combined Heat and Power
COD	Chemical oxygen demand
D	Distribution
ECP	Ecotoxicity Potential
EI	Environmental impact
EOL	End of Life
EP	Eutrophication Potential
FD	Fossil Depletion
FEW	Freshwater Ecotoxicity
FFD	Fossil Fuel Depletion
FR	Flame retardant
FU	Functional Unit
FWAE	Freshwater Aquatic Ecotoxicity
FWE	Freshwater Eutrophication
GHG	Greenhouse gas emissions
GWP	Global Warming Potential
HPB	HDPE plastic bags
HDPE	High-density polyethylene
HT	Human Toxicity
HTP	Human Toxicity Potential
LC	Life Cycle
LCA	Life Cycle Assessment
LO	Land Occupation
M	Manufacturing
MAETP	Marine Aquatic Ecotoxicity Potential
MENA	Middle East and North Africa
MFA	Material Flow Analysis
nAg	Nanosilver
nr-CED	Non-renewable Cumulative Energy Demand
ODP	Ozone Layer Depletion Potential
PED	Primary Energy Demand
PET	Polyethylene terephthalate
PLA	Polylactic Acid
POCP	Photochemical ozone creation potential
PNB	Polypropylene non-woven bags
PTT	Polytrimethylene Terephthalate
RM	Raw Materials
RQs	Research questions
TE	Terrestrial Ecotoxicity
U	Use
U.S.	United States
WD	Water Depletion
WOS	Web of Science
WU	Water Use

a zero-waste fashion (United Nations, 2019), whereas the European Union has announced the European strategy for textiles (European Parliament, 2021; European Commission, 2022). Specifically, the strategy aims at applying a new sustainable product framework, introducing circular materials and circular production processes, as well as a new guidance for separate waste collection by 2025. Further, it aims at boosting sorting, re-use, and recycling of textiles, and appears as a key-factor to reduce resource consumption and waste generation along the entire supply chain, (Kasavan et al. 2021; Li et al., 2021).

As regards common methodologies to estimate the environmental impact (EI) associated with textile production, consumption and disposal, several academics and practitioners have applied the life cycle assessment (LCA) to evaluate cotton shirts (Kazan et al., 2020), woolen apparel (Wiedemann et al., 2020), jeans and other garments (Morita et al., 2020) or total clothing purchased and used in an entire country (Sandin et al., 2019) whereas others have adopted the material flow analysis (MFA) approach (Nørup et al., 2019) to evaluate entire textile sorting centers. Researchers have assessed the environmental footprints of clothing, either estimating the carbon and the water, or evaluating the chemical one (Laurenti et al., 2016; Mair et al., 2019; Serweta et al., 2019). Moreover, several authors have investigated water consumption, exploring green wastewater treatment techniques (Tasneem et al., 2021) or sustainable approaches to reduce the impacts of chemicals (Roos and Jönsson, 2021). Furthermore, researchers have highlighted the need to create sustainable fibers (Patti et al., 2021). However, great efforts are still needed to map the entire textile industry, considering that non-renewable resources and cheap labor are used to produce textiles, and the main disposal pathways are landfilling or incineration (Nørup et al., 2019).

The purpose of the present research is to investigate the environmental concerns associated with fibers, yarns, fabrics, clothes and made up textiles other than clothes assessed in literature through the LCA, which represents a standardized technique for assessing the EIs associated with products over their life cycle (ISO 2006, 2021). The LCA is considered a suitable tool to explore the contribution of the life cycle stages to the overall environmental load and prioritize improvements on products or processes, as well as to compare different products' behaviors for practitioners' use (Muralikrishna and Manickam, 2017). It turns out to be an effective tool also because it can support circular economy (CE) practices (Dybikowska and Kazmierczak-Piwko, 2019), whose principles refer to the products' durability and the extension of their lifetime. Indeed, especially for clothes, the life cycle lasts a few weeks, due to the advent of fast fashion (overconsumption of clothes), causing important impacts related to the excessive production and disposal of tons of textiles wastes, which are difficult to treat because of the wide assortment of fibers and related manufacturing processes (Soyer and Dittrich, 2021; Gazzola et al., 2020; Marques et al., 2020).

The textile sector encompasses several life-cycle activities, from fibers production to final products generation and disposal (Luo et al., 2021). Likewise other commodities, textiles industry products follow the production-consumption-disposal lifecycle and are still anchored to the take-make-waste paradigm, so-called linear economy (Dahlbo et al., 2017; Islam and Huda, 2019).

Based on the latest statistics (Textile Exchange, 2020), polyester represents the most produced fiber in 2019, accounting for less than 60 Mt (approx. 52 % of the global fiber production), followed by cotton with more than 25 Mt (approx. 23 %). Less consumed fibers are wool from sheep (1 Mt), silk (0.16 Mt) and wool from other animals (0.05 Mt). Other plant-based fibers account for roughly 6.5 Mt, whereas other synthetics and polyamide account for 6.4 Mt and 5.6 Mt, respectively.

Natural fibers are distinguished among plant-based and animal-based ones. Plant-based natural fibers are generally extracted from the plant material soon after a retting or decortication process, essential to remove undesired cell wall components (Li et al., 2021). Then, natural fibers manufacturing encompasses several stages, from plant growth to harvesting and processing. Among others, cotton represents the most consumed natural fiber in the textile and clothing industry. At the global level, it is estimated that over 2.5 % of water (Esteve-Turrillas and de la

Guardia, 2017), whereas over 4.7 % of all pesticides measured by total pesticides sales and over 10 % of insecticides, are involved in cotton cultivation (Transformers Foundation, 2021). As regards animal-based natural fibers, the most popular worldwide are silk and wool. It is estimated that livestock are the world's largest land users, requiring grazing land and crop land for feedstock (Henry, 2012). Further, wool and silk production are responsible for significant amounts of energy consumption (i.e., electricity), as well as for water and chemicals use in washing and drying and waste generation (Kviseth and Tobiasson, 2011). In the field of manmade fibers, it is possible to distinguish between organic and inorganic fibers. Organic fibers are made from natural materials (e.g., wood, regenerated fibers), whereas inorganic ones are made from synthetic polymers. Although such fibers can appear as less expensive and less resource intensive, several concerns are related to health risks, chemical use, petroleum consumption and waste management (Muthu, 2020). Overall, there are no sustainable or unsustainable fiber types: fibers' environmental sustainability vary not only based on their nature, but also according to the final product they constitute, or depending on the manufacturing processes to which they are subjected and the type of use to which they are intended (Sandin et al., 2019).

In the light of these considerations and based on the Harmonized System Nomenclature (HS Code), Section XI on "Textiles and Textile articles" (World Customs Organization, 2017), three research questions (RQs) have been developed, as recorded in Table 1.

Overall, the present paper aims at adding an extra step in the field of textile production, consumption and disposal research on a global scale, highlighting novel issues still under-researched in the light of the European strategy for textiles. Although some researches have been conducted in the field, such as Munasinghe et al. (2021), which have reviewed only the environmental impacts of clothes, or Sandin and Peters (2018), which have addressed research in the field of textile reuse and recycling, several information are still needed to tackle the take-make-waste paradigm and reduce resource consumption and greenhouse gas emissions (GHGs) along the entire textile life cycle stages, including fibers, yarns, fabrics, clothes and made up articles other than clothes.

Table 1
RQs and correspondence to the Harmonized System Nomenclature (HS Code).

RQ1. Which are the environmental concerns related to the life cycle stages of fibers, yarns and fabrics?		
HS CODE	50	Silk
	51	Wool, fine or coarse animal hair; horsehair yarn and woven fabric
	52	Cotton
	53	Vegetable textile fibres; paper yarn and woven fabrics of paper yarn
	54	Man-made filaments; strip and the like of man-made textile materials
	55	Man-made staple fibres
	58	Fabrics; special woven fabrics, tufted textile fabrics, lace, tapestries, trimmings, embroidery
	60	Fabrics; knitted or crocheted
RQ2. Which are the environmental concerns related to the life cycle stages of clothing?		
HS CODE	61	Apparel and clothing accessories; knitted or crocheted
	62	Apparel and clothing accessories; not knitted or crocheted
RQ3. Which are the environmental concerns related to the life cycle stages of textile made up articles, other than clothing?		
HS CODE	57	Carpets and other textile floor coverings
	63	Textiles, made up articles; sets; worn clothing and worn textile articles; rags

Source: Personal elaboration by the authors on World Customs Organization (2017). Note: Although worn clothing is included in code 63, for continuity of analysis the studies on used clothes have been incorporated into RQ2.

2. Research methodology

2.1. Research strategy and review criteria

The present research can be defined as a systematic literature review (Snyder, 2019). Among other existing approaches to conduct literature investigations (i.e., semi-systematic or integrative), the systematic review synthesizes and compares either quantitative or qualitative studies, contributing on both the side of practitioners and policymakers. In line with previous studies (Özbük and Coskun, 2020; Rana et al., 2021), the present review is conducted according to a systematic, transparent, and reproducible approach (Davis et al., 2014; Vrontis and Christofi, 2019; Amicarelli et al., 2021), aiming at answering to specific research questions. Starting from three RQs, the authors have followed the PRISMA guidelines (Page et al., 2021), as follows: (a) identification; (b) screening; (c) eligibility; (d) inclusion, qualitative analysis and interpretation of the results.

2.2. Review criteria and research strings

The research has been conducted on Scopus and Web of Science (WOS) databases, identified as collectors of standardized, reputable, and high-quality research. As regards inclusion and exclusion criteria, the authors have selected peer-reviewed articles published in the last ten years (2011–2021), considering only those published in English and dealing with the issues of environmental sustainability and ecological concerns of fibers, yarns, fabrics, clothes and other textile made-up articles production, consumption and disposal. The research timeline helps in investigating production techniques and trends, as well as waste management behaviors, before and after the introduction of the Sustainable Development Goals in 2015 and the new Circular Economy Action Plan in 2020. Although different methodologies to assess EIs have been applied by researchers on a global scale (e.g., MFA, water footprint, carbon footprint, ecological footprint, product environmental footprint), the authors have selected only those contributions applying the LCA in its present standardized procedure (ISO 14040:2006/AMD 1:2020 and ISO 14044:2006/AMD 2:2020). The LCA method represents a suitable tool to investigate all products' life cycle stages and being one of the most replicable and comparable tools on a global scale, it helps practitioners, public organizations, or researchers to determine directions or priorities in planning, products' design, or processes. (Muralikrishna and Manickam, 2017).

In the light of the double purpose of covering as many relevant aspects as possible and creating a suitable database of studies, the authors have applied the subsequent research string: "cotton OR linen OR flax OR hemp OR jute OR bamboo OR coir OR wool OR silk OR acrylic fiber OR elastane OR nylon OR polyamide OR polyester OR polypropylene OR polyurethane OR viscose OR lyocell OR modal OR cupro AND textile AND life cycle assessment", for an amount of 22 different combinations.

The systematic review has been carried out as a structured TITLE-ABS-KEY query (Poponi et al., 2022). During the first step, the so-called *identification* step, 234 articles have emerged. The research strings have been preliminarily explored within article titles, abstracts, and keywords, as to create a first database of metadata including authors' names, articles' titles, year of publication, journal, and digital object identifier (DOI). During the *identification* stage, several articles have been deleted because duplicates (n = 130) or not accessible to the authors (n = 1) and 103 records have been selected for in-depth *screening*. At this stage, 53 articles have been excluded because not in line with the aims and scope of the research. Articles not applying the LCA, as well as articles dealing with technical textile for industrial use, have been considered not in line with the research. Besides, during the *eligibility* stage, four additional articles have been included in the review based on existing knowledge, to experts' recommendation and serendipity. Overall, 54 articles have been included in the systematic review. Fig. 1 illustrates the PRISMA model.

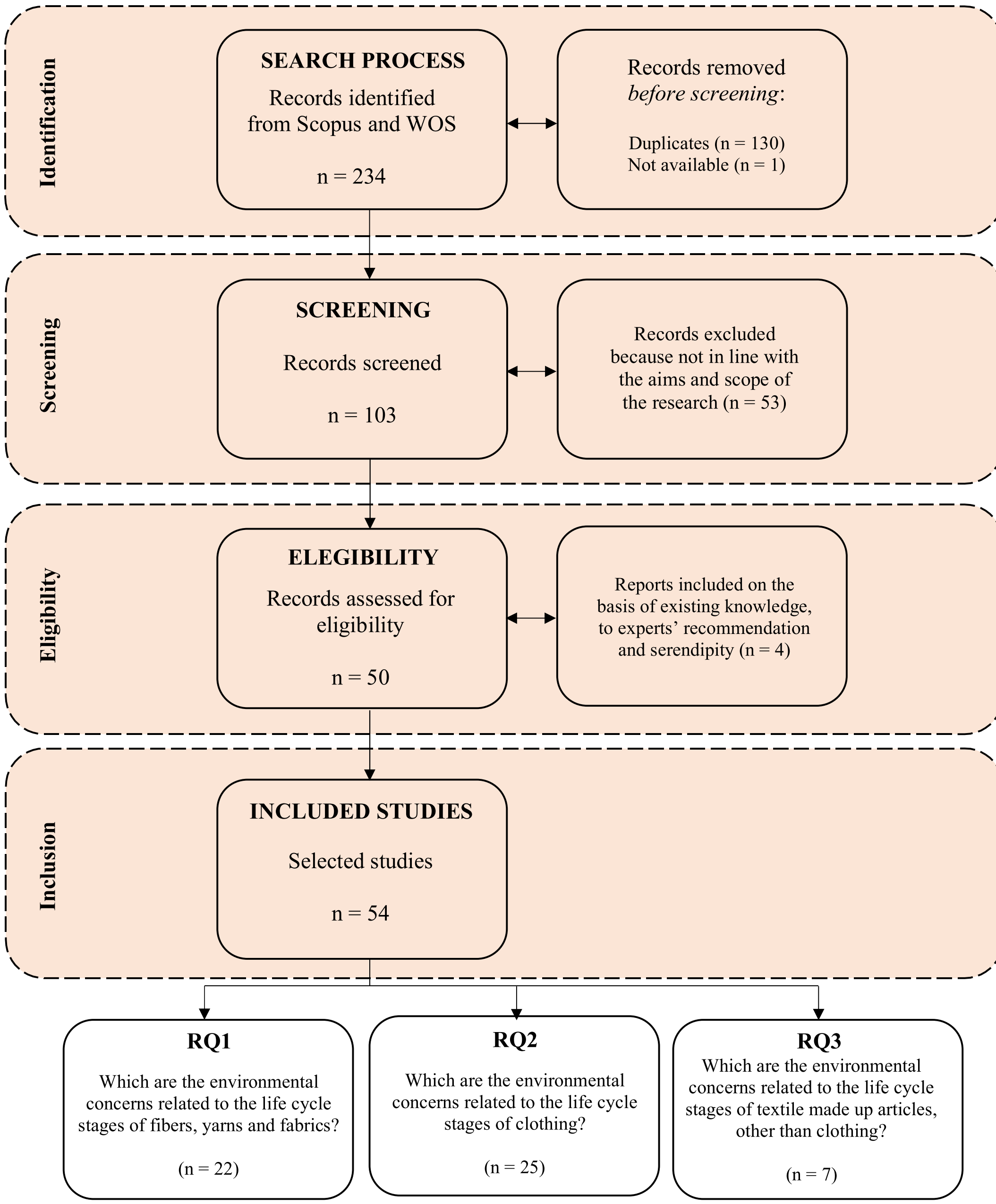

Fig. 1. PRISMA model. Source: Personal elaboration by the authors on Page et al. (2021).

2.3. Life cycle Assessment, impact categories and research scopes

Although the LCA is a standardized methodology, its application leaves great space for the definition of boundaries, scopes, and functional units (FUs). Therefore, the results of each study need to be contextualized according to the chosen impact categories and the phases of the life cycle examined, otherwise it is not possible to make an overall assessment that allows drawing useful remarks for processes' improvement. For that reason, the authors analyzed the results of the selected papers paying particular attention to the impact categories and boundaries examined. Considering that the EI categories estimated through the LCA depend on the methodologies adopted (e.g., CML 2001, EDIP 2003, TRACI, ReCiPe, Eco-indicator 99, EPS 2000) (Park et al., 2020) and in line with Poponi et al. (2022) and Kirchherr et al. (2017), the authors have classified such categories according to their scope, as follows: (a) air scope (e.g., global warming potential – GWP, ozone layer depletion potential – ODP), which monitor the activities causing air pollution and affecting climate change (CC); (b) water scope (e.g., water depletion – WD, eutrophication potential – EP), which evaluate impacts on freshwater systems, either from single products or entire processes; (c) soil scope (e.g., land occupation – LO, acidification potential – AP), which estimate the EIs on land degradation; (d) energy scope (e.g., cumulative energy demand – CED, fossil fuel depletion – FFD), which assess the use of energy, the energy performance and the resource consumption rates; (e) human scope (e.g., human toxicity potential – HTP), which consider the harm of chemicals and pollutants released into the environment causing risks to human health; (f) others, which includes impacts that do not find a place in the main scopes, such as minerals depletion, solid waste, etc.). As regards the boundaries, the different phases that characterize the "cradle-to-grave" approach have been considered, pointing out the following stages: (i) raw materials production; (ii) manufacturing; (iii) distribution; (iv) use; and (iv) end of life. A generic scheme of the textile industry supply chain, according to a LCA approach, is recorded in Fig. 2.

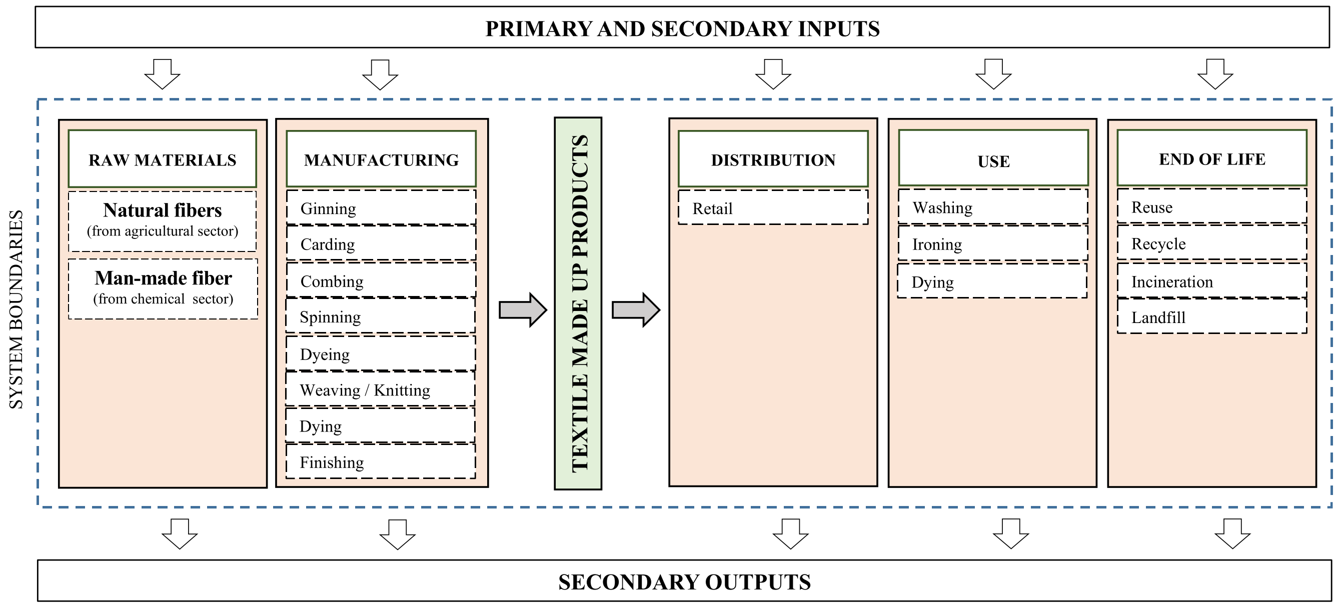

Fig. 2. LCA approach in the textile industry supply chain. Source: Personal elaboration by the authors.

2.4. Qualitative analysis

Data retrieved from each selected contribution have been synthesized according to a qualitative approach. As outlined by Lotteau et al. (2015), the selected contributions have first been catalogued according their goal and scope (e.g., research item, fiber typology, FU), as well as to the impacts and damages categories taken into account. Besides, according to a thematic analysis, the contributions have been synthesized in the light of three stages (Thomas and Harden, 2008), as follows: (i) synthesis of the text "line-by-line", according to the research questions and translating complex concepts into simple ones; (ii) development of the "descriptive themes", in which the authors have looked for similarities and differences between the scientific articles and have started grouping articles into the different boundaries, scopes and research focus; and (iii) investigation of the "analytical themes", which has conducted to the critical interpretation of results. Although the thematic analysis appears controversial and depends on the judgement and insights of the authors (Thomas and Harden, 2008), thematic reviews have been successfully conducted in scientific research and represent suitable methods to synthesize qualitative data (McAuliffe et al., 2016; Lueddeckens et al., 2020).

3. Results

As illustrated by Fig. 3, among 234 contributions identified in Scopus and WOS, only 54 have been selected for in-depth review (see Supplementary Material for the list of the selected articles). Fig. 3 illustrates the research timeline.

An average growing trend has been depicted from the research timeline analysis. The highest peak of articles has been published in 2021, for an amount of 14 contributions investigating the EIs of textiles production, consumption and disposal through the LCA, whereas the lowest amount has been recorded in 2011 and 2012, with one scientific paper per year. Overall, it is possible to notice a significant increase in publications from 2015 to 2021, demonstrating the growing interest in exploring the EIs of textiles and clothes soon after the introduction of the SDGs in 2015 and the new Circular Economy Action Plan in 2020. As regards the publishing journals, 23 different journals have been identified from the *meta*-data analysis. Among them, 12 articles have been published on the *Journal of Cleaner Production*, followed by *The International Journal of Life Cycle Assessment* (ten articles each) and *Resources, Conservation and Recycling* journal (five articles). As regards the research focus of each contribution, Fig. 4 provides results related to the investigated life cycle stages (Fig. 2), identifying at the same time the research scope (i.e., air, water, energy, soil, human, other). The frequency (no. of times) provided in the ordinate axis indicates that, although 54 studies have been selected, many of them have explored different fibers, different supply chain stages and different scopes. Details are provided in the "Discussion" (*Section 4*), according to fibers, items, FU, life cycle stage, scopes and research focus.

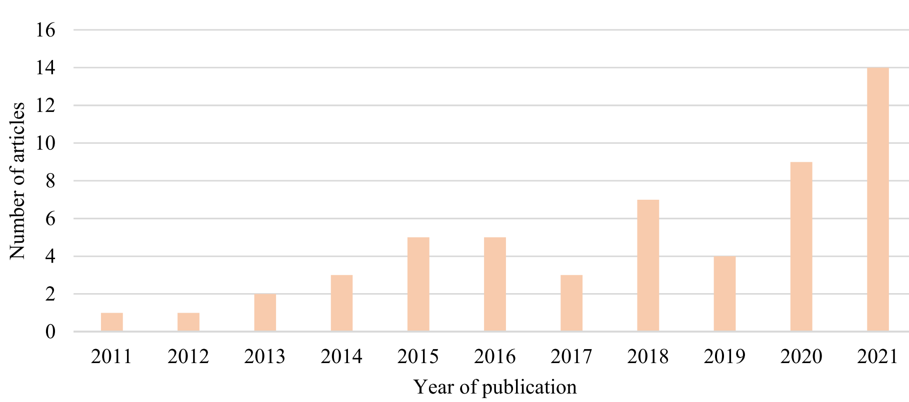

Fig. 3. Research timeline. Source: Personal elaboration by the authors.

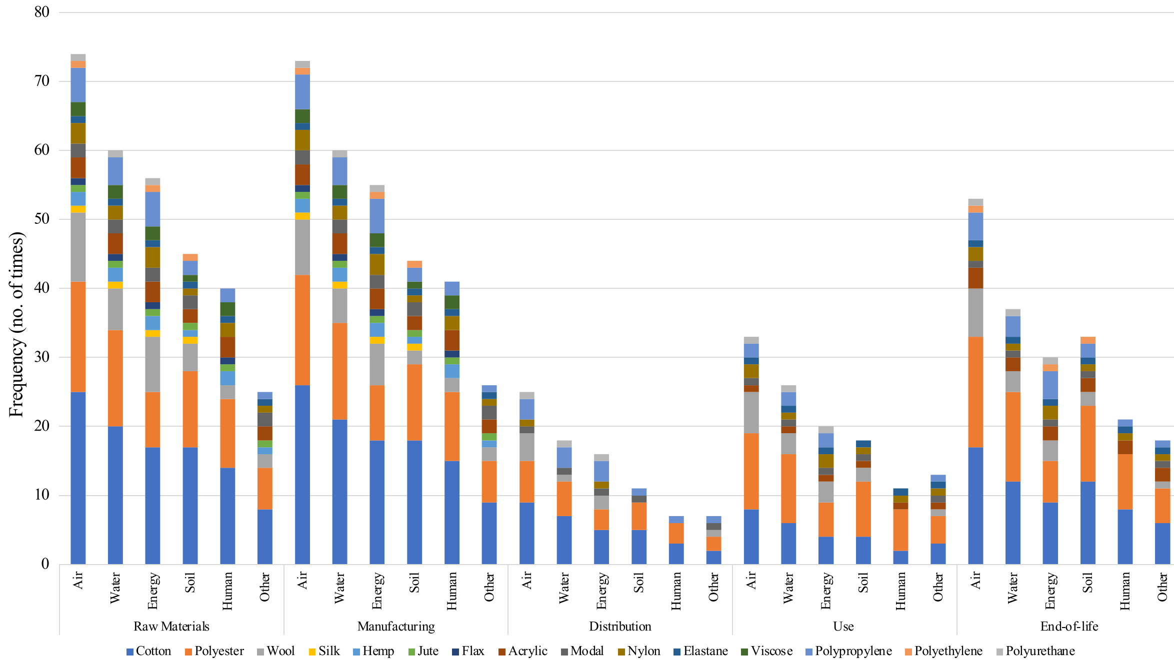

Fig. 4. Scientific literature assessing the environmental scopes of textiles research per supply chain stage. Source: Personal elaboration by the authors.

The selected studies aim to assess the EIs of standard products, or the ones attributable to processes, methods, and behaviors applicable to different stages of the product life cycle. In terms of specific research items, clothing items are the ones most taken into consideration: eight contributions investigated *t*-shirts, whereas three articles are intended at exploring sweaters, three other shirts, and two jeans' trousers; less studies looked at jackets (two articles) capes, underwear, protective, and hospital garments (one article each). Further, significant contributions have been exploring the production and disposal of fabrics (ten articles), while other articles considered only fibres and yarns (11 articles). Fewer articles referred to household textiles like carpets, curtains, and outer covers (five articles), medical devices like face masks (one article), and grocery bags (one article). Discarded apparel, used clothes, and fabric waste have also been considered in four studies. Cotton-based textiles are the most investigated, with 31 studies, of which 14 refer to fibres, yarns, and fabrics, 13 to clothing, and four to other textile made up articles. Polyester is the second most studied fiber (21 articles) and in this case most of the publications refer to clothing (ten articles), followed by fibres, yarns, and fabrics (eight articles) and other textile products (three articles). Animal fibers are the least taken into consideration, with ten studies on wool and one on silk. The FUs mostly refer to units of mass measurement (kg), secondarily to units of surface measurement (m^2), and if provided for by the study, the number of uses or washes are also taken into consideration.

As regard the life cycle stages, the studies considering only cradle-to-gate phases were the majority ($n = 21$), while those that conducted a full LCA were far fewer ($n = 13$). Throughout the papers, the most investigated impact categories were those related to the "air" scope (assessed in all studies), followed by "water" scope (44 studies), "energy" scope (37 studies), "soil" scope (35 studies), and "human" scope (26 studies). Beyond the scopes and in order to draw considerations in line with the aim of this review, an attempt was made to identify the papers taking into account the differences between: (i) biogenic and non-biogenic GHG emissions; (ii) irrigation (or blue) and non-irrigation water; and (iii) renewable and non-renewable primary energy demand (PED) or CED. Besides, the research identifies also the allocation method, distinguishing among biophysical, mass, economic, 50/50, cut-off and system expansion allocation, as well as the LCA modelling approach, namely consequential and attributional (Table 2). In general, most studies did not report this information.

4. Discussion

4.1. Environmental concerns related to the life cycle stages of fibres, yarns, and fabrics (RQ1)

Table 3 summarizes the 22 selected articles related to the RQ1, highlighting explored fibers and items, FUs, investigated life cycle stages, scopes of the research and research focus.

Overall, the studies assessing the EIs attributable to fibres, yarns, and fabrics focused mainly on the cradle-to-gate stages of the life cycle (20 studies). However, five articles also considered the end-of-life, one the use phase, while no publication the distribution phase. Besides, the "air" scope is the most investigated (22 articles), whereas the "human" scope is less assessed (15 studies), as shown in Fig. 5. Cotton is the most investigated fibre (14 papers), followed by polyster (8 papers).

Main outcomes show that natural fibres production and manufacturing have lower EI compared to the artificial and synthetic ones. Considering the energy needs, the water requirements, and the CO_2eq emissions in the production phases, flax has the lowest EI and acrylic fibre the worst (Muthu et al., 2012). In fact, as stated by Yacout et al. (2016), acrylic fibre manufacturing is a process with high energy consumption, therefore the category most affected in this phase is that of FFD, with over 80 % of the impact. In addition, the process also uses inorganic chemicals, which make the impact on human health the second highest with over 15 % of the impact.

The manufacturing of synthetic fibres does not seem to improve environmental externalities either considering bio-based substitutes of fossil-based polyester from crops, corn, and sugarcane. Apart from the climate impact results, which depend on whether biogenic carbon is accounted for (recording a decrease up to 70 %), the extent of the other impacts (AP, EP, ecotoxicity, land and water use) rises with the increase in bio-content, with fully bio-based substitutes having the worst impact (Ivanovic et al., 2021). In addition, they do not allow a substantial decrease in the use of fossil resources, which reach 85 % of the fossil consumption of conventional polyester, since the process chain relies in any case on fossil fuels (Ivanovic et al., 2021).

Generally, natural fibres are derived from a renewable resource and

Table 2
Details related to air (GHGs), water and energy scope, allocation method and LCA modelling approach.

References	GHGs		Water		Energy		Allocation						LCA	
	B	NB	I	NI	R	NR	BF	M	E	SE	50/50	CO	A	C
Costa et al. (2021)														
Fidan et al. (2021)					x	x								
Ivanovic et al. (2021)	x	x												
Powar et al. (2021)														
Zhao et al. (2021)													x	
Avadí et al. (2020)									x					
Liu et al. (2020)			x											
Subramanian et al. (2020)					x	x						x		
Aileni et al. (2019)														
La Rosa & Grammatikos (2019)			x			x								
Peters et al. (2019)												x		
Zhang et al. (2018)														
Agnhage et al. (2017)		x	x											
Wiedemann et al. (2016)							x							
Yacout & Hassouna (2016)														
Yacout et al. (2016)														
Wiedemann et al. (2015)							x		x	x			x	x
Astudillo et al. (2014)			x		x	x			x	x				
Terinte et al. (2014)			x		x	x								
Van der Velden et al. (2014)														
Yuan et al. (2013)														
Muthu et al. (2012)														
Braun et al. (2021)											x			
Levänen et al. (2021)														
Martin & Herlaar (2021)														
Moazzem et al. (2021a)			x					x						
Moazzem et al. (2021b)	x													
Schmutz et al. (2021)						x								
Temizel-Sekeryan & Hicks (2021)														
Wiedemann et al. (2021)													x	
Kazan et al. (2020)														
Morita et al. (2020)	x				x	x							x	
Rosson & Byrne (2020)														
Semba et al. (2020)														
Wiedemann et al. (2020)		x					x	x					x	
Lenzo et al. (2018)														
Moazzem et al. (2018)								x						
Vozzola et al. (2018)			x											
Esteve-Turillas et al. (2017)														
Hicks & Theis (2017)														
Agnhage et al. (2016)														
Hicks et al. (2016)														
Baydar et al. (2015)														
Manda et al. (2015)														
Zhang et al. (2015)									x					
Muthu et al. (2013)														
Bevilacqua et al. (2011)														
Ahamed et al. (2021)	x	x												
Schmutz et al. (2020)		x				x								
Yasin & Sun (2019)														
L'Abbate et al. (2018)	x	x												
Sim & Prabhu (2018)													x	
Yasin et al. (2018)														
Zamani et al. (2015)		x			x	x								

Notes: B = Biogenic; NB = Non-biogenic; I = Irrigation; NI = Non-irrigation; R = Renewable; NR = Non-renewable; BP = Biophysical; M = Mass; E = Economic; SE = System expansion; CO = Cut-off; A = Attributional; C = Consequential.

are biodegradable, plus consume less energy for manufacturing than synthetic ones. However, they present considerable environmental concerns, as silk. According to Astudillo et al. (2014), cocoon production is responsible for most of the EI of sericulture, with drying and irrigation as the main sources of non-renewable CED, while pesticides and disinfectants account for almost all of the ecotoxicity impact (97 %), plus fertilizer and farmyard manure are responsible for most GWP of silk (80.9 kg CO_2eq/kg). In addition, the irrigation in mulberry production determines an important use of surface and groundwater freshwater, while 50 % of Freshwater Eutrophication (FWE) is due to field emissions.

The categories most affected by cotton production and manufacturing are CC, Fossil Depletion (FD), WD, and Human Toxicity (HT) (Liu et al., 2020). Conventional cotton consumes huge amount of water, but also of fertilizers and pesticides, which can be avoided by organic cotton, reaching also lower level of CO_2eq emissions. While organic cotton cultivation can be beneficial in some respects, at the same time it has a lower yield (t/ha). Indeed, since the main hotspots of cotton cultivation are related to pesticide and fertilizers use, conventional cotton production generally has a greater impact than organic per ha of cultivation but considering the t of product organic cotton lint features higher impacts (Avadí et al., 2020). Therefore, using recycled cotton for spinning seems to be a better option, although the energy-intensive spinning process remains the most impactful in all impact categories. Liu et al. (2020) show that it is possible to decrease 60 % of the emitted CO_2eq, reduce the consumption of oil equivalent by 11 % and water by

Table 3
RQ1 publications' main features.

References	Fibers	Items	FU	LC stages	Scopes	Research focus
Costa et al. (2021)	Cotton	Fabric	500 g	RM, M	Air, Water, Human	Comparing the EI of synthetic reactive dyeing and natural dyeing processes of textile fabrics.
Fidan et al. (2021)	Cotton	Denim fabric	638.2 g/1.5 m^2	RM, M	Air, Water, Energy, Soil	Evaluating the EI, product quality, and cost-savings for denim fabric production using recycled cotton fiber and CHP plant.
Ivanovic et al. (2021)	Polyester	Fibre	1 kg	RM, M	Air, Water, Energy, Soil, Human, Other	Comparing the EI of polyester with its bio-based substitutes, namely bio-polyester, PTT fiber, and PLA fiber.
Powar et al. (2021)	Cotton	Fabric	40 g fabric decolorization	M	Air, Water, Energy, Soil, Human, Other	Assessing EI of ozone based decolorization of the reactive dyed cotton textiles.
Zhao et al. (2021)	Cotton, Polyester	Denim fabric	1,000 kg	RM, M	Air	Assessing the virtual flows embodied in the global denim-product trade and the environmental emission factor of denim products.
Avadí et al. (2020)	Cotton	Fibre	1 t and 1 ha of seed cotton/equivalent of baled cotton fibre and cottonseed	RM, M	Air, Water, Energy, Soil, Human, Other	Assessing the EI of Malian conventional and organic cotton bales, per agricultural production system type.
Liu et al. (2020)	Cotton	Yarn	1000 kg	RM, M	Air, Water, Energy, Soil, Human, Other	Comparing the EI of yarns spun from virgin and recycled cotton.
Subramanian et al. (2020)	Cotton, Polyester	Fabric waste	1 kg recovered PET fibre	EOL	Air, Water, Energy, Soil, Human, Other	Evaluating the EI of a textile bio-recycling approach for cotton-polyester blend fabric waste.
Aileni et al. (2019)	Cotton	Fabric	100 kg	RM, M	Air, Water, Energy, Soil, Human, Other	Evaluating the EI of two different technologies to obtain the hydrophobic effect on cotton fabric.
La Rosa and Grammatikos (2019)	Cotton, Hemp, Jute	Fibre, Yarn	1 kg of fibre, 1 kg of textile	RM, M	Air, Water, Energy, Soil, Human, Other	Comparing the EI of traditional and organic cotton cultivation and textiles production with other natural fibres.
Peters et al. (2019)	Cotton, Viscose, Polyester	Fibre	850 t of mixed textile waste management/280 t of cellulosic fiber and 350 t of polyester production	RM, M	Air, Water, Energy, Soil, Human	Examining the EI of alkaline hydrolysis as a textile recycling process of cellulosic fiber in comparison to a single-use benchmark.
Zhang et al. (2018)	Cotton, Polyester	Fabric	2 t	RM, M, EOL	Air, Water, Soil, Human, Other	Identifying new technologies to minimize EI in the polyester–cotton production process in China.
Agnhage et al. (2017)	Polyester	Fabric	1 kg	RM, M	Air, Water, Soil, Other	Evaluating the EI of polyester fabric dyeing with madder dye to optimize the process.
Wiedemann et al. (2016)	Wool	Greasy fibre	1 kg	RM	Air, Water, Energy, Soil	Assessing the EI of three wool types, produced in three different regions of Australia.
Yacout and Hassouna (2016)	Acrylic	Fibre	1000 kg	EOL	Air, Water, Energy, Soil, Human, Other	Modelling the EI of landfill and incineration for hazardous solid waste treatment of acrylic fibers.
Yacout et al. (2016)	Acrylic	Fibre	1 kg	RM, M	Air, Water, Energy, Soil, Human, Other	Analysing the EI of acrylic fiber manufacturing and determining the most impactful base material in MENA region.
Wiedemann et al. (2015)	Wool	Greasy fibre	1 kg	RM	Air, Energy, Soil	Investigating seven approaches for assessing the EI in the co-production of wool and live weight sheep meat.
Astudillo et al. (2014)	Silk	Raw fibre	1 kg	RM, M	Air, Water, Energy, Soil	Assessing the EI of high-quality silk production under tropical conditions in southern India.
Terinte et al. (2014)	Modal	Knitted fabric	1 kg	RM, M	Air, Water, Energy, Soil, Other	Comparing the EI of fabrics made of spun-dyed modal with conventionally dyed modal fabrics.
van der Velden et al. (2014)	Cotton, Polyester, Nylon, Acrylic, Elastane	Greige textile	1 kg	RM, M, U, EOL	Air, Water, Energy, Soil, Human, Other	Investigating which base material and life cycle stage have the worst environmental impact.
Yuan et al. (2013)	Cotton	Fabric	Dyeing of 2,000 kg/10,000 m	RM, M, EOL	Air, Water, Energy, Soil, Human	Evaluating the EI for cotton fabric-dyeing and determining the key processes for mitigating strategies.
Muthu et al. (2012)	Cotton, Flax, Hemp, Wool, Nylon, Polyester, Polypropylene, Acrylic, Viscose	Fibre	1 kg	RM, M	Air, Water, Energy, Human	Quantifying the EI of various textile fibres and positioning them in terms of ecological sustainability.

Notes: LC = Life Cycle; RM = Raw Materials; M = Manufacturing; D = Distribution; U = Use; EOL = End-Of-Life; CHP = Combined Heat and Power; PET = Polyethylene Terephthalate; PLA = Polylactic Acid; PTT = Polytrimethylene Terephthalate; MENA = Middle East and North Africa. Source: Personal elaboration by the authors.

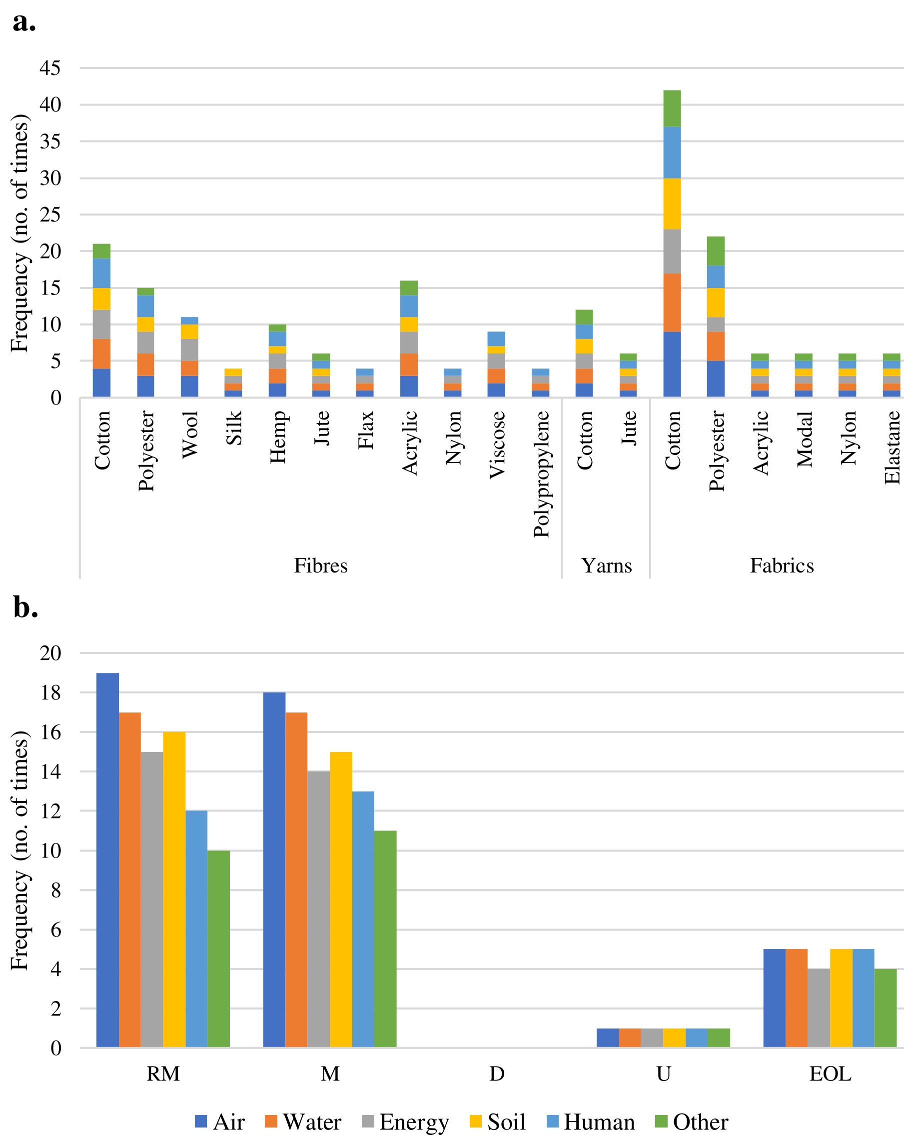

Fig. 5. Frequency in investigating the type of item (a) and the LC stages (b) related to the scope (RQ1). Source: Personal elaboration by the authors.

almost 80 % considering recovered cotton option. Since cotton cultivation is a water-intensive process and uses large amounts of herbicides and pesticides, recycling allows to contain specific effects mainly on Freshwater Ecotoxicity (FEW) category and water scarcity but increasing, for example, the impact in terms of AP. Peters et al. (2019) concluded that conventional production and waste management (incineration) of cotton and viscose do not differ much from the recycling of cellulosic fibre from mixed textile waste through an alkaline hydrolysis process. However, they also highlight that it is necessary to consider the selected end-of-life management process, since if such waste is landfilled, there would be no energy recovery credits and methane would be generated, increasing the climate impacts too.

Other natural fibres such as hemp and jute are very interesting, since they have a much lower impact. Compared to cotton, La Rosa and Grammatikos (2019) show a decrease between 90 % and almost 100 % in the case of ODP, Terrestrial Ecotoxicity (TE), Abiotic Depletion (ADP), and Freshwater Aquatic Ecotoxicity (FWAE), while between 70 and 80 % for Human Toxicity (HT), Marine Aquatic Ecotoxicity Potential (MAETP), EP, ADP on fossil fuels, GWP, and AP. Finally, the most difficult impact to assess is that of wool production, since it varies significantly depending on the allocation method chosen due to co-production of sheep meat, also leading to negative GHGs in the system expansion (Wiedemann et al., 2015). For example, Wiedemann et al. (2016) estimated that arable LO and energy demand were highest for mixed grazing and cropping, as feed grown in arable land was used for sheep production, but also the intensity of production and the climate of the regions were identified as determining factors.

Moving on to also consider the weaving process, according to Zhao et al. (2021), for denim fabric 85 % of CO_2eq emissions are generated in the manufacturing phase, while Fidan et al. (2021) estimated over 50 % contribution to GWP from cotton cultivation. Maybe this difference is due to the dataset used: in the first case the data refers to the world average, while in the second to a specific item. Cotton production appears to contribute 60 %–70 % to AP, CED, and EP, and for almost the totality of WU, referring to denim fabric (Fidan et al., 2021). But, if instead we consider a cotton-polyester textile, cotton cultivation seems to contribute largely only to ODP (over 40 %), while printing and dyeing are responsible for almost the totality of MAETP, GWP, and ADP impacts (Zhang et al., 2018). Not surprisingly many studies have focused on the dyeing process, which stands out for being heavy polluting. Yuan et al. (2013) identified "scouring and oxygen bleaching" in the pre-treatment, "dyeing", and "stentering and setting" in the finishing as the key phases of the whole dyeing process, mainly due to the large amount of electricity consumed and the extensive associated air emissions, which contributed the most to GWP, AP, and Photochemical ozone creation potential (POCP); in addition, EP is affected from chemical oxygen demand (COD), caused by the consumption of additives and dyes, which led to a significant impact related to the wastewater treatment process. According to Costa et al. (2021), natural cotton fabric dyeing using vegetables (white onion) can reduce the impacts on human health and ecosystems; while, concerning natural polyester fabric dyeing, we observe that the dye extraction and the dyeing phases can be responsible for more than 85 % of the overall impact considering the cradle-to-gate dyeing process (Agnhage et al., 2017). The amount of energy and solvents for the extraction of the dye, and that of water for dyeing are considerable and therefore the impact of the process is still significant even for natural dyeing. In the case of modal fibre manufactured in Austria, dyeing the yarns before weaving has been shown to decrease the impact between 40 and 60 % compared to conventionally dyed fabric, halving the amount of water and energy required and consequently also reducing emissions into the atmosphere (Terinte et al., 2014).

The dyeing phase is not always the most impactful among the manufacturing processes. Van der Velden et al. (2014) have observed that dyeing and finishing generally contribute to no more than one third of the impacts in a cradle-to-gate assessment. The most important variable in the estimation of the impacts seems to be the thickness of the yarn, which determines the impacts related to weaving and spinning, due to the energy input/per kilogram. As a result, for cotton fabric made by yarns with linear density less than 150 decitex (dtex), the most polluting processes are weaving and spinning, while weaving is the most impactful process for any yarn less than 70 dtex (van der Velden et al., 2014). In line with these results, cotton is identified as the most impactful base material, while acryl and PET are those that have fewer overall negative externalities (van der Velden et al., 2014), thus coming to different results compared to those obtained from studies that only consider the impacts of fiber production.

Fabrics are generally destined for processes to produce clothes and other textile products, that's why no studies estimated the impacts of the consumption phase, except for van der Velden et al. (2014), who present literature data on the use phase of garments to be included in their study. On the contrary, there are some data regarding the end-of-life stage. It emerges that incineration of cotton fabrics produces higher credits for heat recovery than synthetic ones, since biogenic CO_2eq emissions are not counted (van der Velden et al., 2014). At the same time, it has a higher overall impact than sanitary landfill, since incineration still contributes to almost all the HTP impact category (Yuan et al., 2013). Similar considerations were made by Yacout and Hassouna (2016) for the end-of-life management of acrylic fibre through incineration, which is preferable compared to landfilling, since energy recovery can mitigate the overall impacts. Indeed, both solutions prove to have a strong impact on ecotoxicity and carcinogenic potentials due to release of metals from pigment wastes, with landfill exceeding 45 % as an impact on Human health and 50 % as regards Ecosystems, while incineration stands at less than 30 % and reaches almost 70 %, respectively (Yacout and Hassouna, 2016).

Even for fabrics some studies focused on sustainability, providing solutions. Fidan et al. (2021) observed that the use of recycled cotton fiber has a huge potential to reduce EIs, since it is possible to avoid the production of virgin cotton, which has strong impacts especially regarding the Water scope, with a reduction of up to 98 % if considering the Water Use (WU) category. Also, Zhang et al. (2018) proposed several Best Available Technologies (BATs) to improve the production system, showing environmental benefits from low/unsalted dyeing techniques and the recovery and reuse of alkali, which allowed 95 % water recovery.

Other studies assessed the EIs of emerging technologies for more sustainable processes such as those for hydrophobic effect and color stripping on cotton fabrics. Radio frequency plasma technology for hydrophobic textiles, which does not generate organics vapors, heat, and wastewater, seems to be more than 90 % impactful than classical technology (Aileni et al., 2019). The ozone assisted color stripping method is strongly impactful in the categories of WD and HTP due to water use and energy consumption (Powar et al., 2021). New recycling techniques are also developing, since it is necessary to mitigate the EIs associated with the material and energy intensities of conventional textile recycling methods. Subramanian et al. (2020) assessed the negative externalities of biological recycling enabled by microorganisms for blended polyester-cotton fabric waste to recover PET fibers which, however, consumes energy and chemicals. They highlighted that the impact categories relating to Human health and Ecosystems were affected in the proportion of around 60 % by the pre-treatment; to those categories related to energy resource depletion the pre-treatment contributed around 40 % while 30 % were attributable to melt-spinning. These examples stress how also emerging solutions must be optimized to make textiles production and disposal processes environmentally sustainable.

4.2. Environmental concerns related to the life cycle stages of clothing (RQ2)

Table 4 summarizes the 25 selected articles related to the RQ2, highlighting explored fibers and items, FUs, investigated life cycle stages, scopes of the research and research focus.

Papers considering the clothes' EIs represent the largest number (n = 25). The phases of the life cycle corresponding to the definition of cradle-to-gate were the most investigated (22 papers).

The impacts concerning the "air" scope are investigated in all the studies, while those regarding the "human" scope are less frequently considered (nine studies), as illustrated in Fig. 6.

The phases of raw materials production (or supplying), together with manufacturing, are those that provide the most complete information regarding the EIs, in particular about cotton garments. On the other side, the use and the distribution phases have not been as much investigated as the previous ones, therefore not providing as much information as needed to make comprehensive evaluations. This is an important criticality to stress since, in the life cycle of clothes, the consumption phase represents a large portion of the EIs, together with the distribution phase, which plays an important role in the face of the increasing phenomenon of online shopping, especially with the advent of the COVID-19 pandemic (Ghodsi et al., 2021). Furthermore, considering the emergence of different ownership models based on exchange or rent (Park and Armstrong, 2019; Shrivastava et al., 2021) it would be important to start considering the distribution phase in a more systematic way than is currently done, since it can play a key role in quantifying the impacts and therefore in the choice of more eco-friendly solutions. A recent publication by Levänen et al. (2021), highlights how a share model can generate higher EIs related to the GWP than the classic garment purchasing model, due to the increased mobility of the consumers. In this case, the "share" scenario of a pair of jeans records emissions exceeding 40 $kgCO_2$eq for 200 uses, while the "base" scenario remains below 35 $kgCO_2$eq, recording a lower impact. If considering only the manufacturing process, around 7 $kgCO_2$eq were estimated by Morita et al. (2020) to produce a women's standard pair of jeans size 34 in Brazil.

Taking into account only the GHGs emissions, the cotton cultivation is in third place among the most impactful processes to produce a pair of jeans (Morita et al., 2020). If considering those studies analyzing multiple impact categories (Zhang et al., 2015; Kazan et al., 2020; Moazzem et al., 2021a; Schmutz et al., 2021), it is possible to note an increase in the overall impact potential of the cotton cultivation process. It contributes to the almost all of Agricultural land occupation (ALO), while the contribution to the Ecotoxicity potential (ECP), WU, and WD vary between 70 % and to over 80 % (Zhang et al., 2015; Moazzem et al., 2021a), making raw cotton production the most impactful process along the entire life cycle of a cotton *t*-shirt, mainly due to the use of fertilizer, pesticides, and a large amount of water (Zhang et al., 2015; Schmutz

Table 4
RQ2 publications' main features.

References	Fibers	Items	FU	LC stages	Scopes	Research focus
Braun et al. (2021)	Polyester	Jacket	1 jacket/4 years	RM, M, D, U, EOL	Air, Water, Soil, Human	Comparing circular and linear EI of a workwear polyester jacket.
Levänen et al. (2021)	Cotton	Jeans	200 uses	RM, M, D, U, EOL	Air	Comparing the GWP of five ownership and EOL scenarios for producing and using a pair of jeans.
Martin and Herlaar (2021)	Wool	Sweater	600 g	RM, M, D	Air, Water, Energy, Other	Evaluating the EI and social impacts associated with the valorisation of wool waste in Sweden sheep farm for sweater production.
Moazzem et al. (2021a)	Cotton, Polyester	*T*-shirt, Jacket	1 kg cotton *t*-shirt, 1 kg polyester jacket	RM, M, D, U, EOL	Air, Water, Soil	Evaluating the EI of cotton *t*-shirts and polyester jackets imported to Australia.
Moazzem et al. (2021b)	Cotton, Polyester	Discarded apparel	1 t	EOL	Air, Water, Soil	Comparing apparel recycling and landfill EI in Australia.
Schmutz et al. (2021)	Cotton	*T*-shirt	154 g/44 washing cycles	RM, M, D, U	Air, Water, Energy	Evaluating the EI of a typical cotton *t*-shirt and the relevance of consumer behavior.
Temizel-Sekeryan and Hicks (2021)	Polyester	*T*-shirt	145 g/100 laundering cycles	RM, M, D, U, EOL	Air, Water, Energy, Soil, Human	Evaluating the EI of four silver/nanosilver enabled polyester *t*-shirts.
Wiedemann et al. (2021)	Wool	Sweater	0.3 kg/one wear	RM, M, U, EOL	Air, Water, Energy	Investigating the EI reduction through increased garment use and care best-practices application.
Kazan et al. (2020)	Cotton	Shirt	1,000 pcs (250 kg)	RM, M, D, EOL	Air, Water, Energy, Soil, Human	Evaluating the EI of four alternative production scenarios for cotton woven shirts.
Morita et al. (2020)	Cotton	Jeans	Standard/size 34	RM, M	Air, Energy	Evaluating the usefulness of actions for improving environmental and energy performances in the supply chain of trouser jeans in Brazil.
Rosson and Byrne (2020)	Cotton	Waste garments	10 g fiber	EOL	Air, Water, Energy, Soil, Human, Other	Evaluating the EI of two pre-treatment of cotton waste garments for chemical recycling.
Semba et al. (2020)	Cotton, Wool, Polyester, Acrylic	Used clothes	6.03×10^8 kg	EOL	Air	Calculating the EI reductions by five discharged clothing reusing and recycling methods in Japan.
Wiedemann et al. (2020)	Wool	Sweater	300 g fiber	RM, M, U, EOL	Air, Water, Energy, Soil	Evaluating woolen sweater EI per wear event.
Lenzo et al. (2018)	Wool	Cape	1 piece (60 % wool)	RM, M	Air, Water, Energy, Soil, Human, Other	Evaluating the environmental and social performances of a wool/cashmere cape handmade in Sicily.
Moazzem et al. (2018)	Cotton, Wool, Polyester	Sweater, Shirt	1 kg selected apparel	RM, M, D, U, EOL	Air	Evaluating the CC contribution of three cotton, polyester and wool apparels consumed in Australia.
Vozzola et al. (2018)	Polyester, Polypropylene	Coverall	1,000 uses	RM, M, D, U, EOL	Air, Water, Energy, Other	Evaluating the EI of reusable and disposable cleanroom coveralls
Esteve-Turillas et al. (2017)	Cotton	*T*-shirt	1 kg coloured yarn, 0.3 kg *T*-shirt	RM, M	Air, Water, Energy, Soil, Human	Comparing the EI of recovered cotton and virgin one from traditional and organic crop.
Hicks and Theis (2017)	Polyester	*T*-shirt	145 g/100 launderings	RM, M, U, EOL	Air, Water, Soil, Human	Evaluating the potential environmental benefit of reduced laundering comparing three silver-enabled polyester fabrics to a conventional fabric to produce a *t*-shirt.
Agnhage et al. (2016)	Polyester	Shirt	1 kg fabric, 1 shirt/2.5 years	RM, M, U, EOL	Air, Water	Evaluating the EI of bio-based dye of polyester fabric to produce a shirt.
Hicks et al. (2016)	Polyester	Hospital grown	4600 μg/nAg, one wear and laundering/75 wearings	RM, M, U, EOL	Air, Water, Energy, Soil, Human	Comparing the EI of nanoscale silver (nAg)-enabled reusable hospital gowns and that of disposable ones.
Baydar et al. (2015)	Cotton	*T*-shirt	1,000 pcs (200 kg)	RM, M	Air, Water, Soil	Comparing organic cotton *t*-shirt EI with the conventional one
Krishna Manda et al. (2015)	Modal	*T*-shirt	245 g/100 days wearing	RM, M, D, U, EOL	Air, Water, Energy, Soil, Other	Comparing the EI of a non-commercial antibacterial *T*-shirt with silver nanoparticles made in Europe from modal fibres with commercial antibacterial e non antibacterial *t*-shirts.
Zhang et al. (2015)	Cotton	*T*-shirt	1 piece	RM, M, D, U, EOL	Air, Water, Energy, Soil, Human, Other	Identifying the environmental hotspots of a cotton *t*-shirt in China and seeking for improvement opportunities.
Muthu et al. (2013)	Polyethylene, Polypropylene, Cotton	Diaper, Pant	145.5 g commercial diaper, 198.9 g new diaper, 78.2 g commercial pant, 98.3 g new pant + 26.83 g insert	RM, M, EOL	Air, Energy, Soil	Assessing the EI of four types of adult incontinence products in their commercial and eco alternatives.
Bevilacqua et al. (2011)	Wool	Sweater	264.85 g	RM, M, D, U, EOL	Air	Determining the EI of different players involved in a textile supply chain.

Notes: nAg = Nano silver. Source: Personal elaboration by the authors.

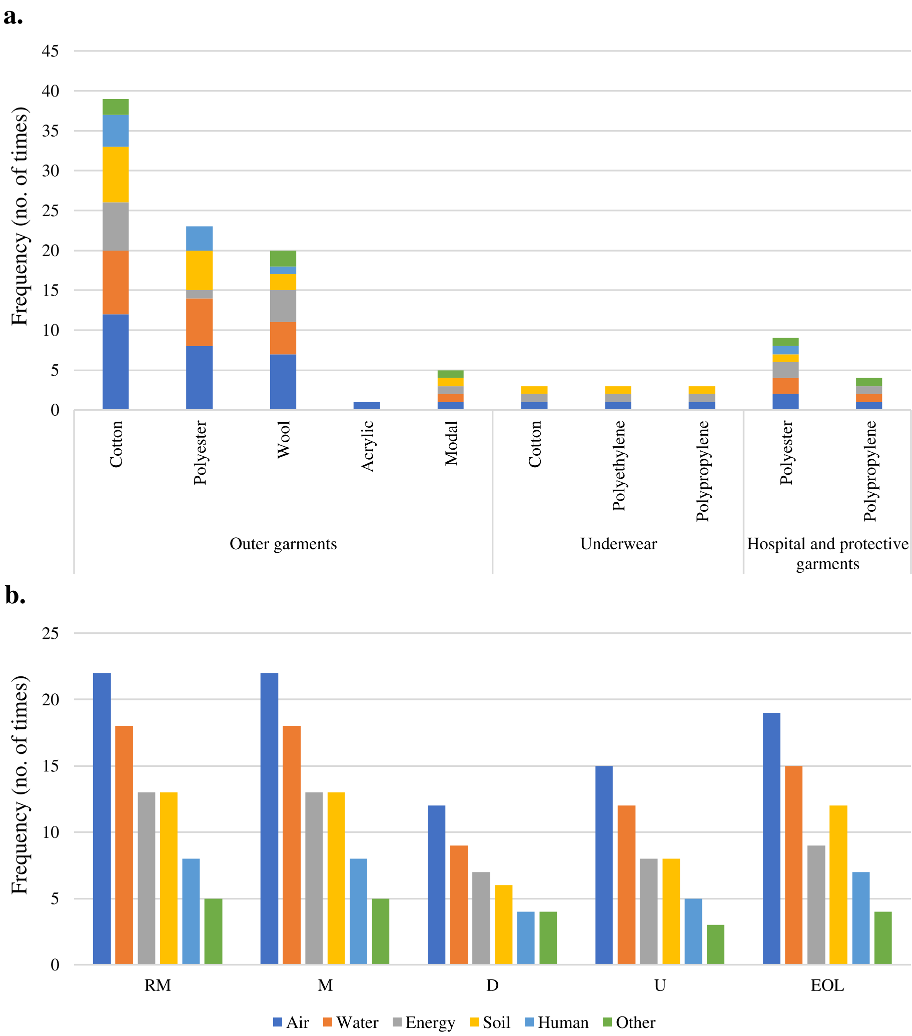

Fig. 6. Frequency in investigating the type of item (a) and the LC stages (b) related to the scope (RQ2). Source: Personal elaboration by the authors.

et al., 2021). Activities related to cotton fabric and garment manufacturing also show considerable impacts, particularly yarn spinning, dyeing, and finishing. Cotton fabric manufacturing mainly affects ADP – fossil, HTP, and MAETP for about 70 %, plus ODP for around 90 %; cotton cultivation, yarn production, and fabric production together contribute to the highest GWP value, for an overall total amount of emissions equal to 3–4 $kgCO_2eq$ per *t*-shirt production (Kazan et al., 2020; Schmutz et al., 2021). A share of 40 % of impacts is attributable to consumer use-related activities, mainly EP and CC (Zhang et al., 2015; Moazzem et al., 2021a), with the GHGs emissions that can equal those of the production phase of a cotton item (Baydar et al., 2015). Also, in the case of polyester and wool garments the production and the use stages contribute largely to the CC, with the wool fiber production that stands out for its greater impact than cotton and polyester (Moazzem et al., 2018). Wool production is not only responsible for most of the GHGs emissions, but also to a large extent for Water stress, Freshwater consumption, and LO impacts (Wiedemann et al., 2020). According to Wiedemann et al. (2021), to the total GHGs of a wool sweater weighing 0.3 kg and used in Western Europe, fibre production contributed 57 %, manufacturing 29 %, and use phase 12 %. Use phase demonstrates to be a hotspot also for water stress (38 %) and fossil energy demand (30 %). Minimizing care practices (reduced use of machine dryer, using more efficient washing machines, washing less frequently) and specially maximizing use (reuse by multiple users and increased number of wears) leads to a decrease of up to 75 % of the impacts (Wiedemann et al., 2021). However, the impact of a wool garment depends mostly on the complexity of the supply chain, therefore on the selling-point localization, on the transportation mode and on the choice of the suppliers. Considering the CO_2eq, the transportation is the main contributor. Bevilacqua et al. (2011) estimated an average value of 1,947 kg CO_2eq for a sweater with net weight 264.85 g, considering the delocalization of the different life cycle phases all around the world.

In the case of polyester, the fiber production is responsible for a lower percentage of the impacts attributable to the production-related activities of a jacket, which causes impacts ranging from 60 % up to over 80 % related to CC, AP, ALO, and WD (Moazzem et al., 2021a). Instead, the consumer use stage contributes around 60 %–85 % of water scope impacts for polyester jackets and shirts (Agnhage et al., 2016; Moazzem et al., 2021a). End-of-life management of polyester garments is primarily responsible for Human health effects if incinerated (50 %) (Braun et al., 2021). Generally, the end-of-life stage contributes very little to the other impact categories, together with distribution and transportation, which affects mainly Respiratory inorganics, ODP, and Photochemical ozone formation (Braun et al., 2021).

It follows that for clothes, the most critical life cycle phases are the production and use stages. Among the studies listed here, there are some solutions for the mitigation of the overall impacts. For instance, if substituting primary by secondary materials, a circular polyester jacket shows a reduction in impacts between 50 % and 80 % in the categories of Respiratory inorganics, Photochemical smog formation, HT, and Water scarcity, and achieving reductions of more than 30 % in GHGs emissions (Braun et al., 2021). The use of recovered fibers as substitute of virgin cotton (conventional or organic), avoids all the costs and impacts related to the cultivation and dyeing phases. Nevertheless, the recovered fiber needs a cutting/shredding process involving the use of electricity, plus other EIs associated with raw material transport, whose total incidence remains low (Esteve-Turillas et al., 2017). Overall, Esteve-Turillas et al. (2017) estimated an impact reduction in the categories GWP – 26 %, AP – 79 %, EP – 93 %, and WU – 79 %. In the case of wool sweaters, by using waste wool, GHGs emissions are halved, going from about 14 kgCO_2eq to about 6 kgCO_2eq per item (Martin and Herlaar, 2021). Some authors assessed the EIs of those types of products available in reusable and disposable versions, comparing for example diapers and pants for adult incontinence, concluding that the latter have a very low impact when considering GWP, LO and nuclear energy use; obviously the absorbent insert to be used in conjunction increases it, but it remains a less impactful option compared to diapers (Muthu et al., 2013). With reference to medical and protective devices, a reusable polyester coverall emerged to have significant environmental benefits compared to disposable versions in polypropylene and high-density polyethylene (HDPE) nonwoven, thanks to the decrease of the impact related to manufacturing, transport, and packaging. Vozzola et al. (2018) estimated a reduction between more than 20 % to up to almost 60 % in process energy and CO2eq emissions, in the range of 70 % in water consumption, and in an average of 95 % in solid waste generation.

As regards the use phase, the impacts can be mitigated by sustainable consumer behavior, which take care of fullness of the washing machine, washing temperature, numbers of wear events or frequency in the replacement of garments (Moazzem et al., 2018; Wiedemann et al., 2020; Schmutz et al., 2021). Reductions in the number of launderings can be achieved by manufacturing clothes with odor reduction thanks to fabrics enabled with silver, which has antimicrobial properties. However, it could be difficult to achieve even environmental benefits related to reducing the number of washes since silver has environmental costs too. The losses during laundering, together with silver mining and refining, affect almost all the impact categories, considering that the high content of silver in fabrics causes significant non-carcinogens impacts due to silver release (Hicks and Theis, 2017; Temizel-Sekeryan and Hicks, 2021). However, Krishna Manda et al. (2015) estimated that antibacterial *T*-shirts have 20–30 % lower impacts concerning CC, FW toxicity and EP compared to non-antibacterial. The reagent and energy usage for the attachment of the nAg to the textile also have the greatest environmental impact, even higher than the synthesis of nAg itself, but in the study of Hicks et al. (2016) considering hospital gown, the energy consumption was lower using the reusable than disposable ones. Regarding the end-of-life phase, the reuse and recycling of discharged clothing seems to help reduce the EIs compared to incineration and landfill, thanks to the credits of avoided processes. Particularly, the reuse of cotton clothing leads to a substantial decrement in GHGs emissions compared to incineration, performing better than the recycling of cotton, polyester, and blended garments (Semba et al., 2020). In general, the end-of-life management of cotton apparel leads to greater environmental benefits than the polyester one, which requires more energy and resources to be recycled and generates less methane gas from landfilling compared to natural fibers (Moazzem et al., 2021b).

4.3. *Environmental concernss related to the life cycle stages of textile made up articles, other than clothing (RQ3)*

Table 5 summarizes the seven selected articles related to the RQ3, highlighting explored fibers and items, FUs, investigated life cycle stages, scopes of the research and research focus.

Among the results in line with the purpose of this research, four articles assessed the EIs of household and hospital textiles (carpets, curtains, and outer covers), and two compared the reusable and disposable options of different items (face masks and grocery bags). Most conducted a full LCA (n = 5), while others focused only on the gate-to-grave phases, which turn out to be the most examined in contrast to

Table 5
RQ3 publications' main features.

References	Fibers	Items	FU	LC stages	Scopes	Research focus
Ahamed et al. (2021)	Cotton, Polypropylene	Grocery bag	820 million plastic bag equivalents	RM, M, D, EOL	Air, Water, Energy, Soil, Human	Comparing the single-use and reusable grocery bags EI in Singapore.
Schmutz et al. (2020)	Cotton, Polypropylene, Polyurethane	Face mask	1 week wearing	RM, M, D, U, EOL	Air, Water, Energy	Comparing the surgical masks and 2-layered cotton masks EI.
Yasin and Sun (2019)	Wool, Polyester	Curtain	kg wool curtain, 1 kg polyester curtain	U, EOL	Air, Water, Soil, Other	Evaluating the EI of a flame retardant treated wool curtain and a AgNPstreated polyester curtain.
L'Abbate et al. (2018)	Polyester	Mattresses' outer cover	1 kg	RM, M, D, U, EOL	Air, Water, Energy, Soil, Human, Other	Evaluating the potential EI of a PET outer-cover for bed mattresses.
Sim and Prabhu (2018)	Wool, Nylon	Carpet	0.09 m^2	RM, M, D, U, EOL	Air, Energy	Evaluating energy consumption and carbon emissions on a wool carpet and a nylon carpet in the U.S.
Yasin et al. (2018)	Cotton	Curtain	1 kg/25 launderings	RM, M, D, U, EOL	Air, Water, Soil, Other	Evaluating the EI for a FR cotton curtain before and after an eco-path disposal treatment.
Zamani et al. (2015)	Cotton, Polyester	Household textile	1 t	EOL	Air	Evaluating the potential environmental benefits of three recycling techniques for household textile.

Notes: FR = Flame retardant; AgNPs = Silver Nanoparticles; U.S. = United States. Source: Personal elaboration by the authors.

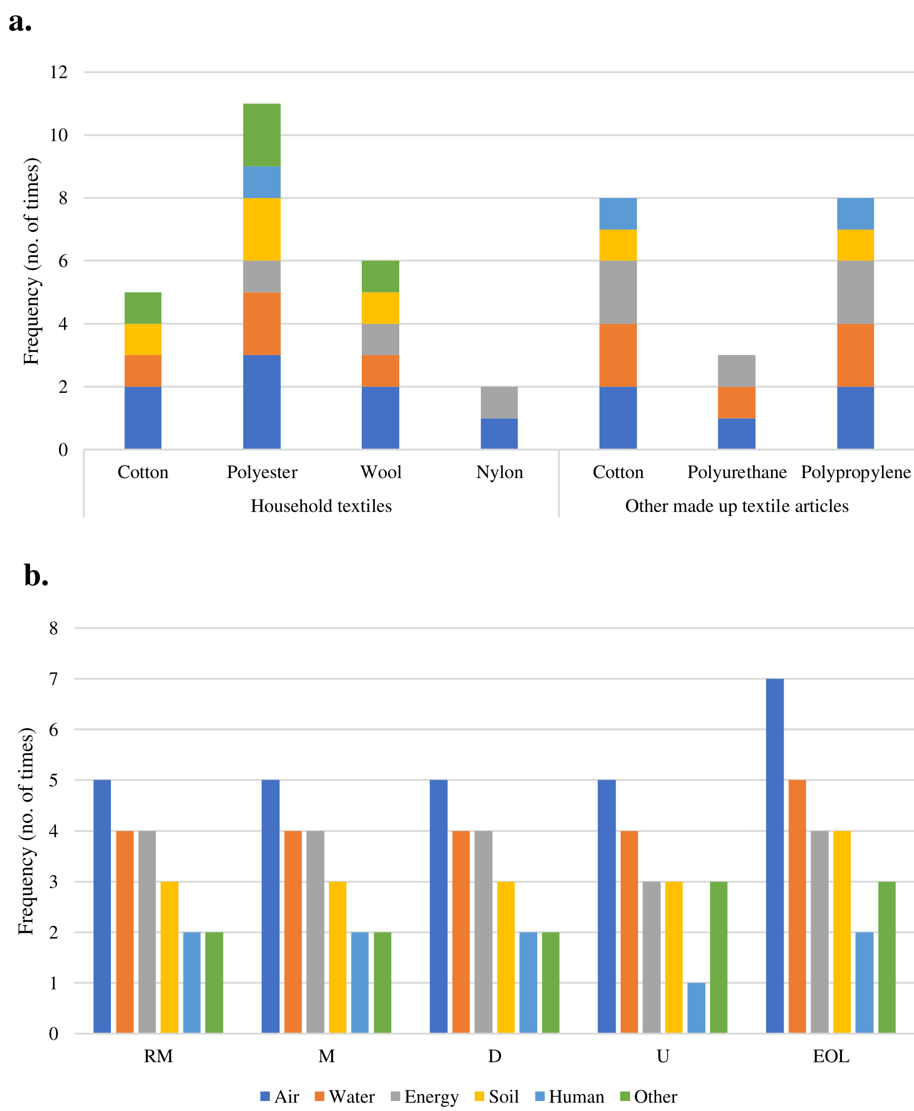

Fig. 7. Frequency in investigating the type of item (a) and the LC stages (b) related to the scope (RQ3). Source: Personal elaboration by the authors.

what was found for RQ1 and RQ2. The "air" scope is once again investigated in all the studies, followed by the "water" scope (five studies). (Fig. 7).

The EIs related to household textiles are difficult to compare, since the functionalities and purpose of use can be very different. Even a change in product's material composition can determine different impacts. For instance, in the production, consumption, and end-of-life of a carpet, carbon emissions can settle on around 4 kgCO_2eq and 6 kgCO_2eq for a nylon and a wool carpet, respectively (Sim and Prabhu, 2018). According to Sim and Prabhu (2018) the production of raw material for a nylon carpet is the most impactful phase contributing around 70 % of the total energy consumption and carbon emissions. In the case of wool carpet, it is the use phase that seems to have the greater impact, accounting for almost 70 % of the total energy consumption and generating more than 40 % of carbon emissions; on the contrary, raw material production stage consumes less than 20 % of energy and produces almost 60 % of emissions (Sim and Prabhu, 2018).

The type of fiber affects not only the production phase, but also the use one, since the resilience of the fiber determines a specific treatment during washing, which can take place at different temperature and time, as Yasin and Sun (2019) pointed out. Consequently, the energy consumption and emission values linked to washing, drying, and ironing can change considerably. The behavior in the use phase also changes with the type of product considered and the contest in which it is used, as is in the case of curtains with antibacterial activities in a hospital environment. This kind of technical textile is certainly washed more, therefore it has greater EIs, not only due to a significant use of energy and consequent emissions but caused by the release of applied functional chemical materials. Yasin and Sun (2019) assessed the EIs of two technical textile products, a silver nanoparticle (AgNPs) treated polyester curtain and a FR treated wool curtain in gate-to-grave phases. They conclude that WD, GWP, FEW, and Air toxicity (AT) were the greater impact categories for both. Some uncertainties arise concerning the end-of-life phase due to the lack of data related to the emissions of potentially toxic substances from the incineration; however, landfill seems to have higher EIs than incineration with or without energy recovery (Yasin and Sun, 2019). A technical textile product has greater impacts than conventional fabrics since it also uses more raw materials and requires additional manufacturing processes. Yasin et al. (2018) found that the manufacturing together with the use phases of a cotton curtain treated with FR substance were the most impactful phases, while landfill or incineration were responsible for a small fraction of the impacts. L'Abbate et al. (2018) established that incineration is a better solution than disposing in landfill for a polyester outer cover for bed mattresses, whose yarn production is responsible for most impacts and around 60 % of CO_2eq emissions, while the dyeing process consumes around 70 % of water used. As an alternative to incineration, Zamani et al. (2015) evaluated the potential environmental benefits of various recycling techniques for household textiles made of cotton and polyester. The material reuse (transforming waste into a new product) had the best performance when compared to cellulose/polyester separation process and repolymerization, for both GHGs emissions and PED, thanks to the avoided production of textiles; however, the effectiveness of these recycling techniques with respect to incineration depends on the quality of the textile waste inflow (Zamani et al., 2015).

Also for textile made up articles other than clothing, some authors assessed the EIs of those types of products available in reusable and disposable versions.

As for the face masks, reusable cotton masks have impacts related to the washing, but it plays only a minor role compared to the production (Schmutz et al., 2020). An important part of the impact is due to cotton fiber production, which contributes especially to the WD (almost the totality), while GWP and non-renewable CED are affected by dyeing step, fabric production, and yarn production in a range of 15 %–25 % (Schmutz et al., 2020). Even in the case of surgical masks, most of the impacts are attributable to the production of polypropylene layers, while incineration contributes to a large part of CO_2eq emissions (Schmutz et al., 2020). In this case, it is not possible to determine an environmental convenience of the reusable option, because a lot depends on the actual use behavior (number of changes and washes). In addition, this kind of comparison might not be appropriate since community masks are not produced following standardized norms that guarantee their effectiveness, therefore the comparison on environmental convenience between two items with the same performance would fail. Reusable cotton options do not show environmental benefits even in the case of grocery bags, which proved to be an impactful alternative when compared to reusable polypropylene non-woven (PNB) and single-use HDPE plastic bags (HPB), with GWP up to 29 times higher, up to 680 times more water, and the ECPs categories highly affected by pesticide and heavy metals emissions to soil and freshwater (Ahamed et al., 2021).

4.4. Theoretical and managerial implications

This systematic literature review sought to put together the evidence regarding environmental concerns of textiles production and consumption but the difficulty in drawing strong implications is substantial. The variables (e.g., FUs, system boundaries, fibers typologies, technologies applied, impact categories) involved in each research are many, and the interpretation is even more difficult due to the scarce chances of comparing evidence coming from each research. Overall, it is possible to identify some critical issues, as follows.

1. Non-matching or not properly defined FUs (lack of information on fibres composition or weight) do not allow to compare quantitative results based on the general amounts of emissions or resources consumed.
2. Arbitrary system boundaries provide incomplete data resulting in improper comparisons between fibres produced differently (i.e., natural and synthetic fibres). In addition, most of the studies only assess cradle-to-gate phases, excluding those gate-to-grave which are crucial in estimating the overall impact.
3. Global average values from databases do not take into account differences between the world regions; from place to place the impacts can change significantly considering different conditions.
4. The choice of one impact category over another, or the lack of specific indicators (e.g., the spread of microplastic for synthetic fibres), give misleading and incomplete results.
5. The allocation methods and the modelling approaches are decisive but are often not even mentioned in the methodology.

As regards managerial implications, it must be considered that textile products' impacts are case dependent, due to the variability of many factors such as production and disposal methods, energy mix, geographical boundaries, and consumers behavior (Terinte et al., 2014; Wiedemann et al., 2016; Peters et al., 2019; Schmutz et al., 2021). However, the present review shows that raw materials production, manufacturing, and use are the most impactful phases. That is why the choice of the life cycle stages to be included in the system boundaries is crucial, as much as the impact categories to be assessed, since a product could negatively affect a certain impact category or a specific phase of the life cycle (e.g., cotton production most affect WD). Therefore, excluding or including them would lead to different results. For instance, not considering the consumption phase can lead to inaccurate estimations, as consumer behavior can strongly influence the impact (Wiedemann et al., 2021) and common care practices can change significantly according to the textile product considered (e.g., some household textile is washed much less than clothes). Else, the end-of-life of textile products generally has a small contribution to the overall impact (Yasin et al., 2018; Braun et al., 2021), but reuse and recycling can lead to more environmental credits, avoiding virgin materials production in the system expansion (Semba et al., 2020). Finally, the emergence of new consumption trends (e.g., sharing and renting platforms) makes it necessary to collect more data on the distribution and use phases, which can make the difference in estimating the environmental convenience of new ownership and business models (Levänen et al., 2021). Therefore, assessing several impact categories throughout the whole life cycle of a textile product is an essential requirement when using the LCA method as a decision-making tool. According to these few results, circular practices seem to be able to bring benefits with regard to textile EIs (e.g., substituting primary materials by secondary materials/recycled materials). The limit is that to define and estimate these advantages there is the need for more evidence from full LCA studies, able to evaluate the shift of impacts from one life cycle phase of another, as can happen in the case of renting or sharing.

5. Conclusions

The present research performed a systematic literature review considering 54 scientific articles assessing the EIs of textiles and extracted from Scopus and WOS databases, in order to investigate their environmental concerns. Overall, the research has investigated three research questions, as follows: (i) Which are the environmental concerns related to the life cycle stages of fibers, yarns and fabrics? (ii) Which are the environmental concerns related to the life cycle stages of clothing? (iii) Which are the environmental concerns related to the life cycle stages of textile made up articles, other than clothing?

The paucity of studies in the literature together with the diversity in the choice of FUs, impact categories, boundaries and allocation methods by researchers makes it difficult to compare the results to draw appropriate conclusions about the environmental concerns associated with the production and consumption of textiles. The impact categories most assessed are those relating to air and water scopes, while those pertinent to human scope are less frequently examined. The cradle-to-gate phases are those most taken into consideration, on the contrary the distribution and the use phases are investigated in fewer studies. Cotton and polyester are of interest in many publications, followed by wool, while the studies examining the other fibers are far fewer. Raw materials production, manufacturing, and use phases affect the environment the most and CE practices can mitigate related impacts. More studies comparing the use of different fibers, manufacturing technologies, care practices, and disposal processes, together with different ownership models, for the same FU are needed, since these results, in addition to giving approximate information about the most impacting life stages on which operate interventions, do not offer useful tools to decision-making level in product design.

CRediT authorship contribution statement

Vera Amicarelli: Conceptualization, Investigation, Resources, Writing – review & editing, Supervision. **Christian Bux:** Conceptualization, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing. **Maria Pia Spinelli:** Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing. **Giovanni Lagioia:** Conceptualization, Supervision.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors have no relevant interests to disclose.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2022.07.032.

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