Reducing the carbon footprint of the textile sector: an overview of impacts and solutions

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Abstract

The clothing, footwear, and household textiles sectors play a significant role providing employment opportunities on a global scale. However, they are also associated with a considerable consumption of natural resources, leading to high levels of water pollution and emissions of greenhouse gases (GHGs), contributing to climate change. The carbon footprint (CF) of textiles depends generally on fabric types and production processes. Natural fibres such as cotton, wool, and silk generally have a lower CF, when compared to synthetic fabrics such as polyester and nylon, requiring more energy and chemicals during production. Additionally, fabrics manufactured through eco-friendly methods, such as closed-loop systems and sustainable production processes, have significantly lower CF than those produced using conventional means. Accordingly, there is a perceived need for comprehensive studies that investigate the environmental and climate implications of the textile sector. Considering these concerns, a study was undertaken on the topic, encompassing a literature review and data collection so as to present an overview of the environmental impacts and CF associated with the textile sector. The results from the research show that the resource consumption associated with the textile sector, particularly its CF, demands urgent action in order to reduce its impacts. Also, actionable measures are needed so as to reduce the CF of the textile industry. These are described in the paper, along with the obstacles that need to be overcome so as not only to reduce the CF of this sector, but also to pursue the objectives outlined in the sustainable development goals (SDGs).

Keywords: textile industry; carbon footprint (CF); greenhouse gases (GHGs); sustainable development goals (SDGs); environmental impact assessment

1. The Textile Industry: An Overview

The textile sector, including the fashion industry, operates within a complex supply chain structure[1]. The complex supply chain of textiles and clothing encompasses multiple stages, such as:

a) Raw material cultivation and harvesting

b) Fiber Processing

c) Dyeing and finishing

d) Garment manufacturing:

And entails the end of life, where garment is either discarded, donated, recycled, or upcycled.

Each of the aforementioned stages influences the carbon footprint (CF) of the final products. Understanding the specific links between this supply chain and carbon emissions involves examining key phases in raw material production, manufacturing and processing, transportation, garment production, retail and distribution, consumer use and end of life. It is widely acknowledged that this sector significantly impacts the environment, leading to an intensified CF[2–4]. Two studies, summarized by the International Labour Organization[5], attempted to map out a distribution of the CF in terms of emissions covering the complex value chain of garments. The results of these two studies (**Figure 1**) agreed on the prevalent impact of the wet treatment and finishing process, followed by fibre production. Nonetheless, it should be noted that all involved sectoral steps and processes remain highly emission intensive.

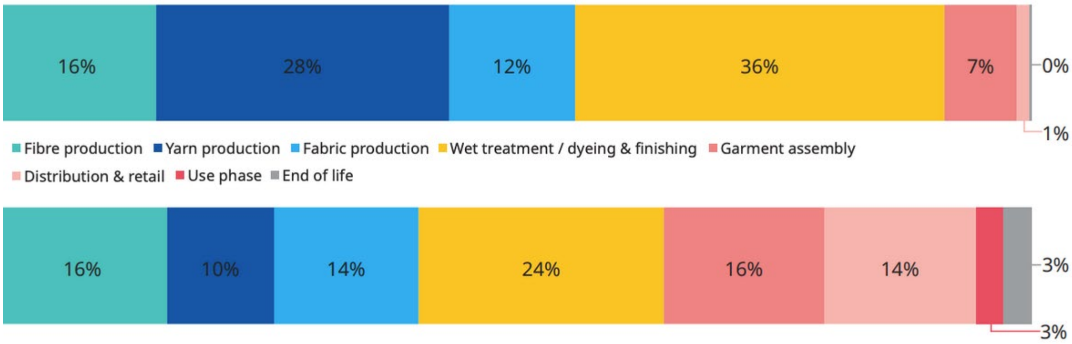

Figure 1. Emissions in the garment value chain by phase

Source: International Labour Organization[5].

The vast network of fabric and garment design, production, consumption, and disposal span the globe, involving approximately 430 million individuals who are part of the labour force, both willingly and sometimes involuntarily[6]. The immense profits generated by this highly industrialized model of mass production and consumption tend to benefit only a few, rather than the majority[7]. Projections indicate that by 2030, the global textile market will be worth an estimated 3 trillion United States (US) dollars in retail sales, with an expected annual growth rate of 5.8%[4]. However, there are growing calls for the industry to redirect these profits and take significant steps to "clean up" its practices. Consumers are being encouraged to shop more mindfully, opt for longer-lasting items, and avoid discarding them with each passing fashion trend. Waste and recycling issues are being addressed by promoting second-hand purchases, and brands are facing scrutiny regarding their environmental and ethical policies. The demand to eliminate polyester in favour of sustainable, organic, and natural fibres is gaining momentum, as consumers become more aware and accepting the need for sustainability. The challenge for the textile industry is to ensure that sustainability becomes a lasting trend, mainstream rather than a niche[8,9].

As the second-largest global industrial sector, the economic and social impact of the textile and fashion industry has been immense. However, questions about its environmental credentials and the sustainability of its operations, particularly in terms of technology and consumption[10], are being raised more than ever before. Reducing consumption at both the industry and personal levels is essential, but it poses challenges in a system where supply chain resilience is built upon producing more, rather than less[11]. Companies face pressure to keep producing, not only to meet demand, but also to remain profitable and stimulate new demand, which lies at the root of the problem. The interconnectedness within the textile and fashion industry is complex, with a strong focus on forward movement towards the product, often leaving materials and resources underutilized or contributing to generate more waste, along with the associated CF. While some waste might re-enter the system, these instances are typically small-scale and fragmented, making them negligible[12,13]. Concerning textiles, the connections between different types of textiles and their CF are significant and multifaceted. Cotton, as example, is one of the most commonly used natural fibres in the textile industry. Its cultivation is resource-intensive, requiring substantial amounts of water and pesticides, contributing to CF. Organic cotton has a lower impact due to the absence of chemical pesticides and fertilizers. Polyester and synthetic fibres are derived from fossil fuels, making their production particularly carbon intensive. The manufacturing process for synthetic fibres like polyester also releases significant amounts of greenhouse gases (GHGs). These materials are also non-biodegradable, contributing to long-term environmental issues. materials such as wool, linen, and hemp are energy intensive and manufacturing them often involves harmful chemicals, contributing to a higher CF. On the other hand, recycled fibres may significantly reduce the CF of textiles. Recycling textiles saves energy and reduces GHGs, emissions compared to producing new fibres, whether natural or synthetic.

The adoption of unsustainable and inappropriate practices in the textile industry has led to a technology gap, creating a pressing environmental challenge. It is crucial to explore both within and beyond current supply chains and traditional practices to identify more effective methods of communication and devise sustainable solutions for the future. The concept of a holistic supply chain network (HSCN) has been advocated, offering improved capacity for communication of health and disruption-related information and proactive resilience in uncertain circumstances[11]. A HSCN approach can shed light on building resilience and addressing uncertainties in reducing the CF of the textile industry[14]. To foster a sustainable and enriching industry and minimize shocks within the supply chain, critical voices against harmful practices play a pivotal role. Countries like China and Bangladesh face criticism for their excessive use of chemicals and poor labour conditions within the textile industry[15]. Sustainability challenges stem from weak ecological standards and interconnected social issues. The rapid turnover of garments and excess fashion consumption, popularly known as "fast fashion," exacerbates the problems of unsustainability and labour rights violations[16.] Fashion retailers and modern media encourage frequent purchases of trendy items, promoting a culture of disposability and unethical consumer attitudes[17,18]. The textile industry has expanded globally, seeking resources, cheap labour, and market opportunities, with China, India, and the US as significant players. China is the largest producer of textile products, while the US dominates raw material exportation and garment and textile importation. Essential European centres include Portugal, Germany, Spain, France, and Italy. The growing demand and new applications in textile products have led to a substantial increase in annual world fibre production, projected to reach 146 million tons (17.1 kg per capita) by 2030[19,20]. Natural fibres, such as cotton and wool, currently hold the majority of the global textile revenue, with synthetic fibres such as polyester and nylon expected to see a rise in demand[21].

Addressing waste in the industry requires more than just finding smarter waste processing technologies. The real challenge lies in re-evaluating the systems that generate waste in the first place, addressing issues of overproduction, consumption, and product design[22]. To tackle this, a focus on design, manufacturing, and marketing processes that consider waste re-appropriation is essential. Upscaling the deconstruction and reconstruction of garments[23], implementing reverse logistics systems[24], and adopting modular manufacturing approaches with new technology can all contribute to a sustainable approach[25], provided there is recognition of the complexities of the current supply chain and a clear design philosophy to guide outputs. However, government inertia is currently hindering the full potential of waste conversion, necessitating greater attention to funding and the establishment of appropriate spaces for re-manufacturing. Thus, due to mounting international pressure, the textile sector is actively seeking methods to reduce its CF both at the individual and industrial levels. One significant effort is increasing the lifespan of textile products and embracing the circular economy, which can lead to considerable reductions in carbon emissions within the industry. However, achieving this goal necessitates a systematic accounting of CF in production processes, showcasing their environmental performance, and engaging consumers in reduction efforts[26]. Currently, many practices within the textile and fashion system are unsustainable, with textiles and clothing manufactured and processed in ways that have negative consequences on the planet. Society then perpetuates over-consumption and a constant adherence to fashion cycles, leading consumers to involuntarily encourage the industry to produce new textiles, and consequently new emissions.

Acknowledging the complexity and intricacies of the supply chain, the authors recognize the need to address these issues in a comprehensive manner. Previous studies have examined the CF associated with the life cycle of certain products offered by leading textile organizations, proposed initiatives for reducing emissions in "fast fashion," and conducted bibliometric reviews of sustainability trends in textile companies[27–29]. A different study carried out by Mezatio at al.[30], pondered on the performance indicators that could help monitor the emissions performance of the logistic structure of a textile supply chain.

This study aims to offer an innovative and original approach to the challenges faced by the textile industry, encompassing alternative methods of production, consumption, disposal, associated policies, and material choices. Relying on extensive expertise on the topic, the study takes advantage of the authors guided critical review of the literature, as additional collected data, on the CF of the textile industry, adopting a holistic-systemic approach to study decarbonization in companies within this sector. It makes a crucial contribution to existing literature that has often focused on specific and narrow topics of textile and apparel decarbonization, rather than considering the broader perspective of supply chains as implied by their titles. This study aims to expand the existing literature by providing a broader range of perspectives on reducing the CF of the textile industry. It begins with an overview of the textiles sector within the context of supply chains, highlighting the major "hot spots" that require attention. The assessment does not limit itself to generic areas of unsustainability. Instead, it focuses on those areas significantly impacting the CF. The research investigates potential decarbonization solutions and categorizes them based on their nature of contribution. It examines the challenges of decarbonizing the textile industry and explores the achievable impacts of urgent decarbonization techniques once these barriers are addressed. The final part of the study features a selection of examples showcasing strategies adopted in various countries to decrease the CF for different types of textile products. The overall objective is to provide a comprehensive understanding of decarbonization within the specific context of the textile and apparel industry, offering insights to guide sustainable practices and policies for a more environmentally responsible future. The significance of this article becomes more apparent when one recognizes that the textile sector plays a substantial role in contributing to GHGs. Given the substantial impact of these emissions on the environment, addressing and curbing them within the textile industry holds paramount importance. Effective mitigation efforts in the textile sector can significantly contribute to broader climate change mitigation initiatives, making this article particularly relevant and timely in the broader context of environmental sustainability.

2. Methods

This study aims to analyse the impacts of the CF in the textile industry and propose measures for its reduction. To achieve this, a guided literature review was undertaken, drawing upon the authors' extensive expertise, relying on specialized knowledge, experience, and authoritative insights in sustainability within the textile field, combining this with other experiences from the literature and practical examples[31]. These approaches allowed for a variety of perspectives. The criteria for the selection of the publications/information were the following ones: relevance to the topic, focus on climate change and emissions, and actuality. It differs from normal literature reviews under the following main aspects: it identifies, examines and summarises the existing technical literature and it focuses on technical aspects, which are not necessarily in the scope of normal literature reviews. The collected findings were thoroughly analysed and discussed to unveil the connections between the textile industry and CF. While the literature review did not follow a systematic approach, it was guided by the collective knowledge and experience of the authors, resulting in a comprehensive assessment and reporting of key points identified in the literature and data. The study's approach was supported by a panel of 7 authors with expertise on the topic, facilitating a more streamlined assessment and examination of relevant information. Subsequently, a compilation of specific examples of products used in the textile industry was assembled, highlighting explicit measures to reduce CF. The objective was to gather evidence from around the world, highlighting different strategies employed to decrease the industry's CF.

Figure 2 illustrates the three phases employed in this study, encompassing the literature review, identification of sustainability dimensions, and the subsequent implementation of the research. These steps collectively contribute to a comprehensive understanding of the textile industry's CF and provide valuable insights to drive effective measures for CF reduction.

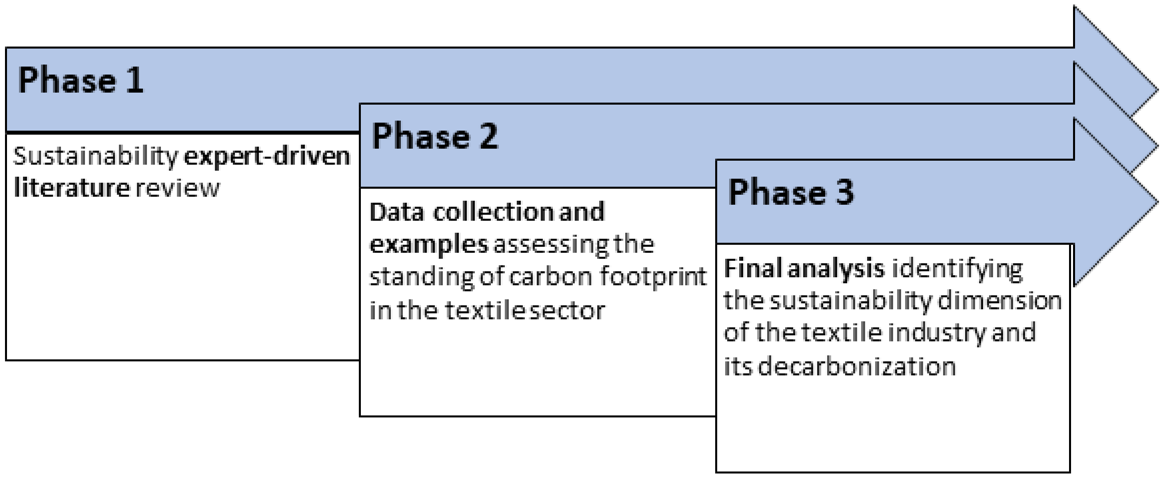

Figure 2. Methodological approach used in this study assessing the status of CF in textiles

Source: the authors.

3. Results and discussion

3.1. The environmental dimension of the textile industry

Apparel consumption is growing as a result of population increase and rising levels of living standards worldwide[32]. The CF reflects the GHGs emissions of human activities, and its assessment from a full lifecycle perspective[33] is of particular importance in the textile sector,[34] since the complex and wide-ranging supply chain in the textile and garment industry is largely responsible for such emissions[35,36] contributing to climate change[4]. In fact, the fashion industry is seen as one of the most polluting industries, being responsible for 10% of all carbon emissions and approximately 20% of all global wastewater[6]. Throughout the 15 years leading up to 2015, the consumption of clothing and footwear had an increased climate impact, going from 1.0 to 1.3 Gt CO_2eq, dominated by China, the world's greatest producer and consumer of textile and clothing[31], India, the USA, and Brazil[37]. This resulted in an exponential rise of both resource use and environmental pollution, including water[35] and textile waste production[32] the latter of which is a subject of significant concern having in mind the considerations raised by the Sustainable Development Goals (SDGs)[38]. A wasted opportunity of more than $100 billion (about $310 per person in the US) per year is caused by the fact that 87% of the clothes produced globally each year are landfilled or burned, instead of being used as resources according to the circular economy ideals[39]. Simply put, the rising costs associated with the textile and apparel industry, in terms of pollution, energy, raw material, and waste management are setting pressure on businesses across the globe[40].

The environmental and social impacts of the textile sector are even worse when considering the business of "fast fashion" since its growth has caused an overall rapid global increase in textile waste[40]. "Fast fashion" consists of transforming very up-to-date designs into products that can be bought by all consumers, who often buy more frequently when they have the opportunity to get a hold of cheaper items. Invariably, this leads to shortened market cycles and very flexible manufacturing processes[41]. Examining sustainable practices in the textile and apparel industry and analysing gaps and opportunities in sustainability implementation, the study from Li and Leonas[42] revealed a focus on environmental issues, involving fewer discussions on social and economic aspects. Gaps were identified in addressing microfibre pollution, enhancing consumer sustainability knowledge, CF offsetting, establishing transparent supply chains, and preventing animal cruelty, for example. The research offered valuable insights for industry practitioners and researchers to enhance sustainable practices. Industrialists can utilize these findings to identify opportunities for sustainable practices and enhance the management of sustainable supply chains. The life cycle of textile and apparel products encompasses various stages and stakeholders due to the extensive, complex, and globalized nature of the supply chain. The study by Zhang et al.[43] confirm that the textile industry is a very pollutant one, exceeding oil and gas, aviation and marine, combined. Key challenges within the textile conversion phase of the textile life cycle include minimizing energy and water consumption, as well as addressing chemical discharge. Through green science, new products can replace synthetic polyesters and nylon fibres. At the same time, technological innovation will allow to reduce energy or water use or advance mechanical recycling, contributing to reducing the environmental footprint. The review by Harsanto et al.[44] examined the current status of sustainability innovation in the textile industry, a sector facing significant challenges in integrating sustainability, as already mentioned. The study identifies and analyses sustainability practices. The researchers focused on sustainability innovation, increased recently. Addressed practices include product innovation (e.g., eco-design, eco-label, life cycle assessment), process innovation (e.g., cleaner production, waste handling), and organizational innovation (e.g., environmental management systems, business model innovation). The results highlighted a stronger emphasis on ecological innovation over social innovation. Considering the growing consumer demand for eco-friendly products and stricter regulations, collaborative efforts between businesses and policymakers are crucial for advancing sustainability innovation in the textile industry. The focus on decarbonization in dyeing processes seeks to diminish GHGs emissions. Additionally, according to Yousaf and Aqsa[45], utilizing innovative technologies such as solar and wind power, energy-efficient equipment, and process optimization, are crucial to minimize CFs in dye production. Circular economy principles are being applied in the denim industry, aiming to improve dye sustainability, thereby reducing waste generation and resource consumption, vital aspects to reduce the environmental impact of the textile industry.

The findings from a study carried out by Abbate et al.[29] reveal three primary research areas in the Textile, Apparel, and Fashion (TAF) context: consumers' behaviour towards sustainable clothing, circular economy initiatives, and sustainability challenges across the whole supply chain. This knowledge empowers TAF industry managers to innovate their business models and thrive in a competitive landscape by transitioning to environmentally friendly production systems and enhancing company performance. Stakeholders, including manufacturing firms and purchasing organizations, can then gain a comprehensive understanding of the issues, processes, predictors, barriers, and challenges related to sustainable practices, empowering them with the skills needed to mitigate environmental impacts, thereby gaining a competitive edge in the context of sustainability. Aligned with environmental sustainability, responsible consumption of Earth's resources is imperative. The textile industry strives to reduce CFs, packaging waste, and environmental impact, yielding financial benefits for corporations. With the sector being a major contributor to global economic growth and employment, wise resource use is crucial, as highlighted by Annapoorani[46]. Collaboration between brands and consumers is essential for a sustainable future, involving shifts to greener options and embracing the circular economy. However, the textile industry's heavy reliance on chemicals and water poses environmental threats, necessitating an urgent transition to eco-friendly production techniques. As the industry evolves to meet the demand for sustainable practices, corporate responsibility becomes integral to economic, social, and environmental stability. Government support and increased consumer awareness will further drive the transformation towards a more sustainable textile industry. The studies discussed above and summarised in **Table 1** contribute to highlighting the role of sustainability in the textile sector, demonstrating the importance of the different strategies being addressed in reducing the CF associated with this industry, and advancing sustainability at the global level. They all somehow underline the role of innovation.

Study topic	Context
Sustainability trends in the textile and apparel industry	Analyses practices and gaps in the textile and apparel Industry from 2013 to 2020[42]
Exploring Technological Innovation within textile life cycle sustainability	Analysing deployment of natural resources, energy and environmental impacts, in the context of the [43]
Overview of trends on sustainability in the textile sector	Outlines serious environmental and social concerns exist in the garment and textile industry[44]
Circular economy for sustainable textile dyeing	The effects of textile dyes on human health, ecosystems, water, soil, and air emissions[45]
Trends and gaps in sustainability within the textile, apparel, and fashion sectors	Assessing sustainability trends in textile, apparel, and fashion industries[29]
Innovative sustainable processes for the textiles and fashion industry	Navigating the realities and challenges of sustainable textiles[46]

Table 1. Studies contextualizing the challenges posed by sustainability in the textile industry

Source: the authors

Bearing in mind the above elements, it is noticeable that the textile industry faces an enormous challenge in achieving the SDGs and the cost of not implementing them[47–51]. Out of the 17 SDGs to be targeted by 2030, it is possible to emphasize the following ones that are most closely related to textile enterprises: SDG 6 on "Clean Water and Sanitation", which aims to reduce the negative impact of product manufacturing on water streams by using fewer chemicals; SDG 8 on "Decent Work and Economic Growth", which is related to the negative effects of mass production at lower costs, common in developing countries with insalubrious working conditions, as stated by Kumer and Radonjic[52]; SDG 12 on "Responsible Consumption and Production", which is related to environmentally friendly production, e.g., reducing the amount of textile waste, using circular fashion business models; and consumption, e.g., reusing, recycling, buying second-hand clothes; SDG 13 on "Climate Action", which aims to diminish the activities with more potential to provoke CO_2 emissions and global warming[53], affecting all activities of the fashion supply chain[40,54].

The solutions for the textile sector under SDG 6 include the implementation of water-saving technologies, including the adoption of advanced dyeing technology, low-liquor ratio machines, and water recycling systems to reduce water usage. They may also entail collecting and storing rainwater for industrial use to lessen the demand on freshwater resources and reducing the use of hazardous chemicals in dyeing and finishing processes to minimize water pollution. In respect of solutions associated with SDG 13, the textile sector, being one of the most resource-intensive industries, can deploy measures tailored to reduce greenhouse gas emissions. These include the use of solar panels and wind turbines to reduce reliance on fossil fuels and using energy-efficient machinery and lighting, and optimising production processes to lower energy consumption. Also, the use of organic cotton, recycled polyester, and other materials that have a lower carbon footprint compared to conventional raw materials, may help in the process, along with farming practices that capture CO2, improve soil health, and increase biodiversity.

In complement, the authors of this paper recommend including SDG 7 on "Affordable and Clean Energy", e.g., buildings' energy efficiency, use of renewable energy sources; and SDG 9 on "Industry, Innovation, and Infrastructure", e.g., development of innovative and environmentally friendly production processes, innovations in the circular economy, in this analysis. **Figure 3** summarizes the discussion presented in this subsection through an illustration of some of the main environmental impacts of the textile industry, the related SDGs, and some high-level solutions to mitigate climate change in particular.

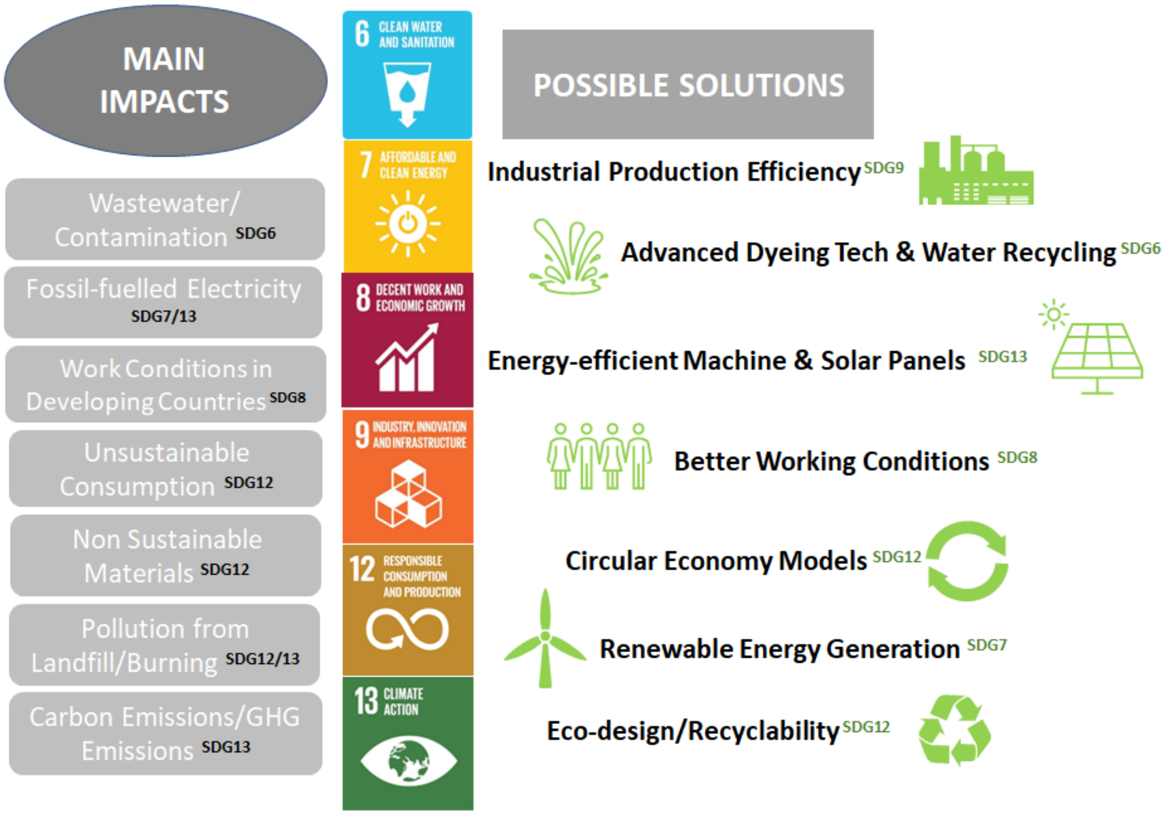

Figure 3. Environmental impacts of the textile industry, with the SDGs links and proposed solutions

Source: the authors.

It can be seen from **Figure 3** that the manifold impacts of the textile industry are not only related to climate change and GHGs emissions but also have ramifications across other environmental areas. The same applies to possible solutions. These have the potential to permeate various subsectors, while simultaneously considering the three sustainability dimensions, i.e., environment, society, and economy[42]. The following section delves deeper into the discussion of solutions for reducing the CF of companies operating in the textile sector.

3.2. Moving ahead: decarbonizing the textile industry

The primary distinction in decarbonization measures between the textile industry and other sectors lies in the unique challenges and processes associated with textile manufacturing. Unlike some industries, the textile sector faces specific complexities related to raw materials, production techniques, and product life cycles. Textile production often relies on diverse raw materials such as cotton, synthetic fibres, and dyes. The cultivation, processing, and transportation of these materials contribute to the industry's CF. Addressing this requires sector-specific strategies to optimize sourcing, reduce emissions in cultivation, and explore sustainable alternatives. Textile manufacturing involves various processes, each with its own energy and emissions profile. From spinning and weaving to dyeing and finishing, the industry demands comprehensive decarbonization strategies that encompass the entire production chain. This complexity contrasts with more streamlined processes in some other industries. Unlike certain sectors where products have relatively short life cycles, textiles often face challenges related to "fast fashion" and rapid turnover. Decarbonization in the textile industry necessitates addressing not only production emissions but also the impact of disposal and waste. Extending the life cycle of textiles through reuse, recycling, or sustainable design becomes a critical focus. The textile industry has intricated global supply chains, involving multiple stakeholders across different regions. Decarbonization efforts must account for the international movement of raw materials, semi-finished goods, and finished products. Collaboration and coordination on a global scale become imperative for meaningful impact. Consumer preferences and behaviours heavily influence the textile industry. Balancing decarbonization with meeting consumer demands for affordable and fashionable products presents a unique challenge. Educating consumers and encouraging sustainable choices without compromising industry competitiveness becomes a distinctive aspect of decarbonization efforts. Addressing these industry-specific challenges requires tailored approaches that acknowledge the intricacies of textile manufacturing. While general principles of decarbonization apply across industries, the textile sector's distinct characteristics demand nuanced strategies for meaningful and effective carbon reduction.

3.2.1. Potential decarbonization solutions

It is worth mentioning that the increasing industrial efficiency of the fashion industry is undoubtedly also linked to improvements in emissions per garment, with a reduction in carbon intensity among energy suppliers playing a smaller part. In fact, the absolute CF of the fashion industry can be greatly reduced by eliminating fossil-fuelled electricity sources, steam and coal[34], and the "fast fashion" business model, which was responsible for customers consuming 47% more apparel per person in 2015 than in 2000[37]. Taking China as an example, and considering it being one of the greatest contributors to the textile's industry CF, its domestic textile industry is under intense pressure to cut GHGs emissions, making it aim to achieve carbon neutrality by 2060. Promoting a renewable energy generation system, such as solar and wind power, is also advised as a way to control GHGs emissions[32].

Among the solutions, energy decarbonization, i.e., the provision of energy from renewable sources, as opposed to energy from fossil fuels as it is largely the case, combined with energy efficiency in textile production and re-use, can lower carbon emissions, along with enhancing industry interoperability. This may also create a suitable framework for textile recycling and encourage sustainable consumption via a multi-dimensional emission reduction approach in the textile sector[55]. This encouragement is crucial to the increase of sustainable clothing consumption, which involves the reuse of textiles, the buying of environmentally friendly pieces, made from recycled and organic materials, fair-trade production, or recyclables, and more care in their disposal by donating or selling/buying second-hand clothes[40,56]. Another way of minimizing the negative environmental impacts of the textile and clothing industry is implementing circular economy principles through innovative circular business models that allow for creating, delivering, and capturing value within closed material loops. Closed-loop production systems represent a paradigm shift in industrial processes, aligning with the overarching goal of sustainable development[57]. In the realm of textile materials, the concept of closed-loop systems is instrumental in achieving a harmonious balance between economic prosperity and environmental stewardship. In the context of textiles, a closed-loop system implies that materials can undergo usage cycles without experiencing significant degradation in their inherent properties. This highlights a transformative approach where textiles are not treated as disposable commodities but rather as valuable resources that can be continually utilized. The conversion of existing textiles into raw materials becomes a pivotal aspect of closed-loop systems, enabling multiple cycles of use and re-use. The essence of closed-loop production lies in its commitment to extending the life cycle of products[57]. This extension is realized through various sustainable practices, including durability enhancements, facilitating easy repair and upgrade options, and embracing modular design principles. By prioritizing these aspects, closed-loop systems strive to minimize waste and resource depletion while promoting a circular economy.

Durability is a key factor, ensuring that textile products withstand wear and tear, thus contributing to a longer lifespan. Additionally, the emphasis on reuse involves creating mechanisms for repurposing textiles, avoiding premature disposal. The repair, upgrade, and restoration aspects underscore the importance of maintaining and enhancing the functionality of textiles, reducing the need for constant replacement. Moreover, the incorporation of modular design principles allows for the selective replacement of specific components, promoting resource efficiency and minimizing overall waste. This modular approach aligns with the principles of sustainable development by offering flexibility in adapting to evolving needs and technologies[40,58,59]. Accordingly, closed-loop systems in textile production epitomize a holistic and forward-thinking approach. They champion the circular economy by prioritizing durability, reuse, repair, and modular design, thereby contributing significantly to the broader objectives of sustainable development in the textile industry [40,58,59] Thus, it is essential to use circular economy models to keep the textile and clothing industry committed to reducing GHGs emissions,[32,60,61] as seen during the recent COVID-19 pandemic[4,31]. Circular fashion can embrace several aspects of the circular economy including the management of product life cycles, from the selection of materials to the reuse or recycling of end-of-life products. Starting from an extensive literature review, Dissanayake and Weerasinghe[62], suggest four key strategies that can contribute to fashion circularity, i.e., (i) resource efficiency; (ii) use of renewable and sustainable raw materials; (iii) waste minimization; and (iv) reduction of resource consumption. To accomplish these requirements, it is necessary to invest in a circular design, i.e., design for longevity, design for customization, design for disassembly, design for recycling, and design for composting. Locating textile production in nations with low carbon electricity, striving for fewer unsold items, and consideration for the products' eco-design, including circular economy, would be the top priorities for lowering the CF of clothing and household linens, according to Payet[26], along with engaging consumer consciousness[63]. Therefore, monitoring the CF and advancing steps for GHGs emission reduction are crucial actions towards environmentally sustainable manufacturing in the textile sector[35,64] supporting the textile industry in pollution and thus CF reduction. It becomes clear that in the case of the textile industry, decarbonization caters for implementing energy-efficient machinery and processes, especially in dyeing and finishing, which are energy-intensive steps. Also, shifting to organic, recycled, or biodegradable fabrics reduces the CF associated with raw material extraction and processing.

3.2.2. Analysing decarbonization solutions through a contributive perspective

When discussing decarbonization solutions for the textile industry, it is also important to categorize them through a different dimension, one that would allow distinguishing between direct or indirect directions of intervention. In this perspective, the previously mentioned impact monitoring represents a transversal basis for assessing substitute manufacturing scenarios and highlighting the most efficient actions[26]. Some of the direct decarbonization solutions are highly technology-intensive – for example, production line optimizations for energy savings[65], adoption of renewable energy[66], replacements of conventional fossil fuel burners with biomass-based ones[67], improving wet processing by resorting to waterless dyeing[68] foam technology, supercritical dyeing or ultrasonic-assisted methods[69,70] among others. In addition, choosing materials obtained from renewable sources - with biodegradable properties, e.g., biopolymers in different textile processes[71,72] represents another valid possible solution to achieve a more contained CF, waste, and emissions levels, thus an overall sustainable textile industry.

There are also other approaches that may be implemented through other sustainable production expedients, avoiding high technological investments. These include, for instance, better maintenance of water pipes and fittings to avoid leakages, switching to drop-fill rinsing, and minimizing wastewater by reusing stenter, and singeing cooling water[40,69]. Moreover, adopting novel, circular business models can give new value to textile waste[68], as is the case of second-hand clothes or swapping, repurposing of materials, and the mechanical recycling of fabrics, i.e., shredding and spinning into new yarns. These represent energy-efficient ways to manage textile materials, compared with other techniques such as chemical and thermal recycling[73] which are more carbon-intensive. Furthermore, given the drastic nature of the transition required by the textile industry, other indirect, more macro strategies should be additionally considered in its support. For instance, value chain collaboration can help coordinate decarbonization efforts across several industry stakeholders and regions, additionally involving consumers in more sustainable habits[74]. It can also help to cultivate the best institutional context, i.e., transparency and traceability standards, guidelines for accountability of textile enterprises, stronger governance, and policies, to upscale the systemic sustainability transition of all textile enterprises, not limited to high-end players[68].

Figure 4 contributes to summarize the above discussion of the dimensions that textile organizations with the highest negative environmental impacts should leverage to mitigate and prevent externalities. Through this framework, the authors propose a logical process flow indicating the steps for minimizing the CF of the textile industry, including: (1) the initial assessment of the environmental impact; (2) a comparison of the resulting manufacturing scenarios against alternative solutions, and the selection of the solutions that are more appropriate to the context of the organization; (3) the available actions can be either direct, either technology-intensive or not, or indirect, allowing a leverage for a holistic transformation of the entire industry.

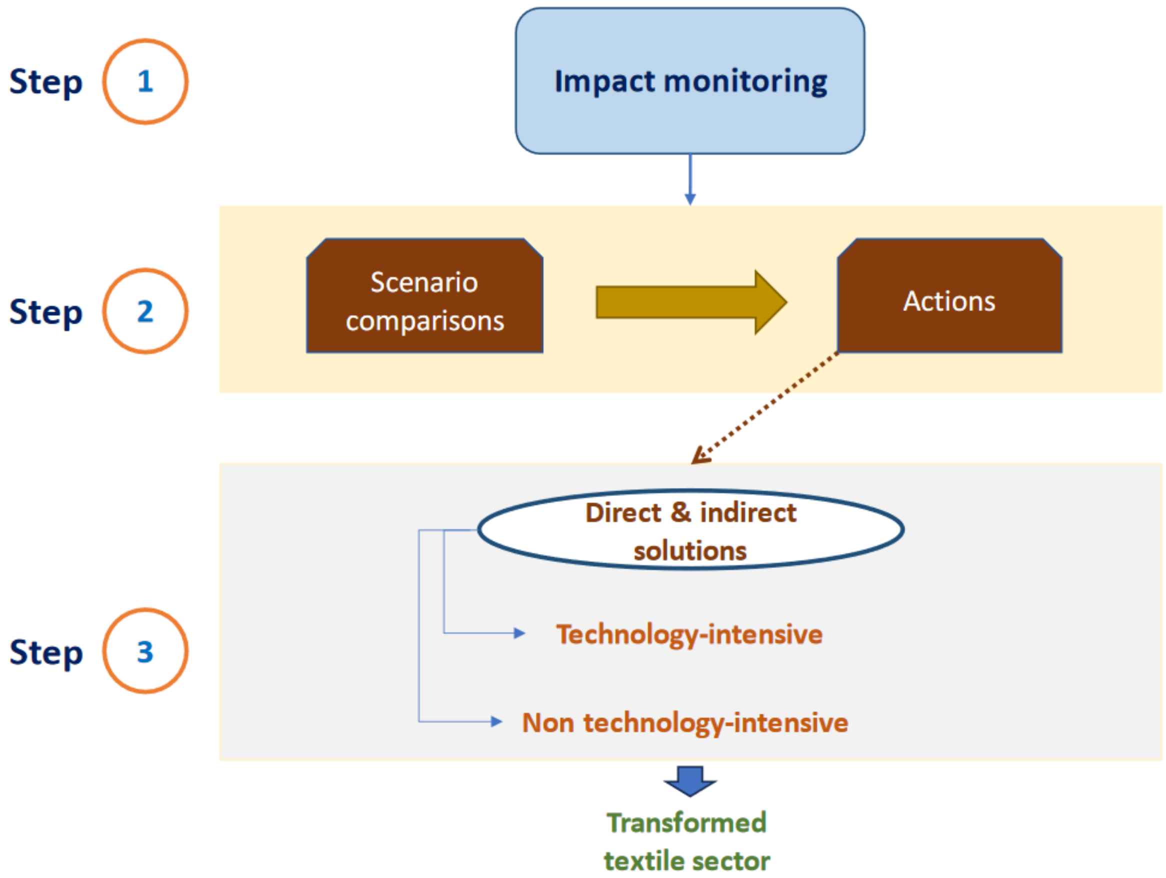

Figure 4. CF reduction dimensions in the framework of the textile sector

Source: the authors.

3.2.3. Barriers and challenges to the decarbonization of the textiles industry

One important aspect to keep in mind, however, is that the existence of barriers to the decarbonization of the textile industry could undermine the success of the above-discussed processes and actions. The most critical barriers have been found to be cause-based, permeating the entire textile supply chain and influencing other sector-specific barriers. They are insufficient regulatory and policy support and integration towards a more sustainable sector, scarce eco-literacy and training to various levels of textile companies in the supply chain, lacking reverse logistics practices, and inability to switch from conventional unsustainable infrastructure to novel clean technologies[75,76].

To facilitate the elimination of such barriers it is important to acknowledge them first, but also to foster a greater degree of awareness of and further elaborate on the solutions to the decarbonization of the textile industry, as per the latest stage of the process in **Figure 4**, particularly highlighting the most impactful ones that require a higher degree of attention. Firstly, the effectiveness of decarbonization highly depends on the scale of its application. Hence, ensuring that all organizations across the supply chain, not only manufacturers but also suppliers and distributors, are optimized for low-carbon operations will enable industrial change and ensure an impactful decrease in emissions across the sector[77]. Secondly, the choice of virgin fibres as primary materials increases both energy consumption inefficiencies as well as textile waste, causing major ecological risks. Minimizing the sectoral production and utilization of virgin materials through circular techniques, e.g., reuse of recycled material, will ensure an overall lower environmental impact of textiles[78]. When this practice is not viable and given the time it would take the textile industry to thoroughly operationalize it, the current focus should also be on cutting down the demand for fertilizers and pesticides in the cultivation of fibres. An action of this kind would help to secure the shrinking of CO_2 emissions normally stemming from their production[55]. Furthermore, not only raw materials but textiles themselves can be upcycled, i.e., textile waste acquiring a higher "green" value, into new input materials for other types of products. This will, in turn, decrease the need for novel materials in other sectors, subsequently reducing the pollution and CO_2 emissions associated with their production[79]. Another high-impact lever to be considered for decarbonizing the textile industry is technology. For instance, 3D printing has been recently found to carry a variety of applications in textile manufacturing, including for cleaner production, expanding the opportunities for waste prevention and energy efficiency compared to more traditional emission-intensive production methods[80,81]. Finally, organizations working with textiles should consider the ecological impact of both its main operations, as well as that of secondary processes and its facilities, e.g., energy-efficient lighting[82]. **Table 2** provides an original summary of possible decarbonization solutions for the textile sector.

Apparel consumption is on the rise due to population growth and increasing living standards globally. The CF of the textile sector is a crucial aspect to assess, given its complex and far-reaching supply chain, contributing significantly to climate change through GHGs emissions. The fashion industry ranks as one of the most polluting industries, responsible for 10% of all carbon emissions and about 20% of global wastewater[4]. ~~Over 15 years leading up to 2015, clothing and footwear consumption saw an increased climate impact, resulting in a rise in CO_2eq emissions from 1.0 to 1.3 Gt, with China, India, the USA, and Brazil being the major contributors.~~ The unsustainable practices of "fast fashion" further exacerbate the industry's environmental and social impacts, leading to a rapid increase in textile waste worldwide. To advance the SDGs by 2030, the textile industry must clearly ~~address key objectives like "Clean Water and Sanitation" (SDG 6), "Decent Work and Economic Growth" (SDG 8), "Responsible Consumption and Production" (SDG 12), and "Climate Action" (SDG 13). i~~mplement circular economy principles and innovative business models can help extend the lifecycle of products, minimize waste, and reduce emissions.

Decarbonization solutions for the textile industry vary in their directness and scope of intervention. Direct solutions involve technology-intensive approaches like optimizing production lines for energy savings, adopting renewable energy, and using biodegradable materials. Indirect strategies focus on sustainable practices, better maintenance, circular business models, value chain collaboration, and supportive institutional frameworks. However, several barriers hinder the decarbonization process, including insufficient regulatory support, lack of eco-literacy, and difficulties in transitioning to cleaner technologies. Addressing these barriers requires greater awareness and engagement from all stakeholders across the supply chain, including manufacturers, suppliers, and distributors. A comprehensive approach encompassing circular techniques, waste reduction, and innovative technologies can significantly contribute to reducing the industry's environmental impact and achieving sustainable manufacturing.

In conclusion, the textile industry faces a considerable challenge in reducing its CF. By adopting sustainable practices, embracing circular economy principles, and leveraging technological advancements, it can make substantial progress towards achieving environmental sustainability and meeting the SDGs. An Overview of such possible decarbonization solutions for the textile sector, along with the potential impacts resulting from them, based on the extensively discussed considerations above is provided in **Table 2**.

Measure	Potential impact
Optimizing textile supply chains (low-carbon textile chain)	Since supply chains account for more than 20% of global emissions, rationalizing emissions in supply chains could make an important contribution toward meeting the global CO_2 emission-reduction targets[83]
Optimizing material use	Minimizing the need for more virgin materials reduces CO_2 emissions in processing. For example, it is estimated that substituting polyester with its recyclable counterpart, rPET, would reduce GHGs emissions by up to 40%[84]
Reducing the use of fertilizers and pesticides	Lowering demands for chemicals, the production of which increases emissions. An 80% reduction in carbon emissions can be reduced by 2050, by using less fertilizers[85]
Upcycling textiles	Decreases in the need for new materials, and, in turn, the emissions associated with production. Reusing 1 kg of clothing saves 25 kg of CO_2[86]
Use of technologies such as 3D printing	Studies have shown that 3D printing can help reduce carbon emissions by up to 50% and reduce waste by up to 90%, making it a highly efficient

Measure	Potential impact
	way to produce parts and components. It prevents wastage in conventional production methods, which tend to be emission-intensive[87]
Investing in sustainable production practices such as energy-efficient lighting	More efficient energy use, and lower emissions from operations. LED lighting achieves energy savings of 50%-70% compared to the old technologies[88]

Table 2. Possible decarbonization solutions for the textile sector

Source: the authors

The list of items in **Table 2** represents by no means a comprehensive account of all possible solutions but offers a summary of which effective measures can be carried out to move towards the decarbonization of the textile sector. Mitigating carbon emissions in the textile industry is crucial for addressing climate change and reducing the environmental impact of textile production. Other techniques and strategies that can be deployed to reduce carbon emissions in this industry may include sustainable fibre selection, implementing water recycling and reuse systems which can reduce the energy required for water treatment and heating, lowering emissions, and reducing the distance materials travel in the supply chain, which can decrease transportation-related emissions. Also, promoting sustainable consumption and educating consumers about responsible clothing care can help extend the lifespan of textiles and reduce emissions from disposal.

3.2.4. Overcoming challenges and barriers

The discussed above barriers and challenges can be also illustrated through the four examples of specific textile products and corresponding strategies aiming at reducing the impact of the industry on the environment and society, involving different countries and textile contexts. As observed in **Table 3**, the main focus of the current decarbonization strategies is related to the reuse and recycling of polyethylene terephthalate (PET), which evidences a considerable effort of the textile sector on the way to circularity.

Another point is the reduction of energy and/or use of clean energy aiming at reducing the emissions of CO_2. Innovation in production and education of the consumer is also considered of crucial importance to this sector. The examples provided in **Table 3** are clear sign of hope in this sector, but also a sign of alert, highlighting the fact that the textile industry, having a significant impact on the global CF of the planet, needs to move towards effective sustainability, at a global level.

Product (Country)	**Decarbonization strategy**
All types of textiles (China)[55]	• Using discarded polyethylene terephthalate (PET) bottles as raw materials, promoting circularity and lowering the unit emission of raw material. • End-of-life (EOL) management improvement, i.e., waste circularity and renewability, significantly reduces CF. • Innovation, through sustainable consumption habits change and awareness.
Recycled yarn and fill (Chile)[32]	• By using recycled PET production, the global warming potential (GWP) is avoided due to waste recovery (textile waste not disposed of in sanitary landfills). • Usage of textile waste (between 27% and 48% of the entire CF created by the manufacture of textile recycling is saved in emissions). • Try to produce locally the recycled PET.
Sold clothes and household linen (France)[26]	• Installing the most energy-intensive production processes in a nation with a low carbon electricity mix. • Avoiding unsold goods. • Implementing eco-design methods. • Increase the value of EOL products through reuse or recycling. • Promoting eco-design through circular economy.
Virgin and recycled polyester textiles (Australia)[89]	• Promote the use of recycled polyester (there is a reduction of 79% of energy consumption, and less emissions of CF, compared to virgin (new) polyester).

Table 3. Examples of specific textile contexts and strategies to reduce CF

Source: the authors

The substantial GHGs emissions originating from the textile industry, when juxtaposed with global energy production, serve as a clear environmental warning signal, emphasizing the imperative to diminish the overall impact of textile production on global climate change[4]. As resulting from the above analysis and discussion, it is possible to state that the core link in the textile decarbonization production process is often centred around the adoption of sustainable and low-carbon materials, coupled with advancements in manufacturing technologies. The integration of eco-friendly and innovative materials, such as recycled fibres or organic textiles, contributes significantly to reducing the CF of the textile industry. Additionally, the implementation of energy-efficient and cleaner production methods is crucial for achieving substantial carbon reductions. Predicting the exact amount of carbon reduction can be challenging due to the variability in production methods, technologies, and the specific strategies employed by individual companies. However, it is common for textile decarbonization initiatives to target significant reductions, often measured in terms of emissions per unit of output (e.g., carbon emissions per unit of fabric produced)[4]. Achieving a specific reduction amount may depend on factors such as the degree of renewable energy integration, improvements in energy efficiency, and the extent of circular economy practices adopted. To offer a more precise estimate of the predicted carbon reduction amount, it becomes necessary to refer to industry-specific studies, initiatives, or benchmarks that outline quantitative goals and outcomes. These figures can vary based on the scale of implementation, the level of technology adoption, and the overall commitment of the textile industry to sustainable and decarbonization practices. In any case, there seems to exist will by leading textile producer countries to achieve high levels of CO_2 emissions reduction targets by 2023. It is the case of China (60-65%, compared to 2005)[90,91], Germany (at least 65%, compared to 1990)[92], India (33-35%, compared to 2005)[93], Hong Kong (65-70%)[94] and others[4].

4. Conclusions

The links between the complex supply chain of textiles and clothing and carbon emissions can be better understood, if one considers that that textile-related emissions occur in the production for fibre creation, and extend themselves through manufacturing, logistics, and retail. The intricate network of suppliers, subcontractors, and manufacturers adds complexity to the supply chain. This chain is not only lengthy but also energy intensive. Managing and coordinating this complexity can result in inefficiencies, leading to increased emissions. To mitigate carbon emissions within the textile supply chain, sustainable practices such as using eco-friendly materials, adopting energy-efficient technologies, optimizing transportation routes, and promoting circular economy principles are crucial. Understanding these specific links allows for targeted interventions and the development of comprehensive strategies to minimize the environmental impact of the textile and clothing industry. This article aims to contribute to existing research on sustainability in the textile industry by focusing on the nature and scale of its CF, as well as on providing potential solutions to mitigate it. Through the information collected in the authors' guided literature review, relying on specialized expertise and authoritative understanding on the topic, and selected data, namely the summarized CF reduction dimensions and examples presented, this study demonstrates how important it is to further address specific measures aimed at tackling the decarbonization challenges embedded in the textile sector, characterized by very specific issues, barriers, and priorities. In this respect, the fostering of consumers' knowledge of sustainability in general and textiles sustainability in particular, beyond the offsetting of the CF, is crucial for the improvement of the efficiency and eco-friendliness of the textile industry, as highlighted by Li and Leonas[42] and Leal et al.[95] The results of this articles show that there are some specific steps which may help in reducing the CF of the textile sector, some of them being:

i. Utilizing sustainable materials. One highly impactful strategy for mitigating emissions in textile supply chains involves the adoption of sustainable materials. This entails a shift towards employing natural fibres like organic cotton, wool, and hemp, renowned for their eco-friendly cultivation practices. Additionally, embracing synthetic materials derived from recycled sources contributes significantly to reducing the environmental footprint. By prioritizing the use of these sustainable materials, the textile industry can actively contribute to lowering emissions, promoting responsible sourcing practices, and fostering a more environmentally conscious and sustainable approach within its supply chains.

ii. Investing in energy-efficient technologies. Investing in and adopting energy-efficient technologies within the production process emerges as a crucial strategy for mitigating emissions and promoting sustainability. This involves the implementation of innovative solutions such as solar and wind-powered systems, which harness renewable energy sources to power operations. Additionally, incorporating LED lighting not only reduces energy consumption but also extends the lifespan of lighting systems. Furthermore, directing investments towards more efficient machinery enhances overall production processes, curbing energy waste and lowering emissions. By integrating these advancements, industries can not only streamline their operations but also contribute significantly to environmental conservation efforts and the pursuit of a greener, more sustainable future.

iii. Reducing water usage. The textile production process is known for its significant water consumption. Implementing water-efficient technologies, such as waterless dyeing and other innovative water-saving methods, emerges as a crucial strategy to not only conserve precious water resources but also to mitigate emissions associated with the textile industry. By adopting these advanced technologies, the textile sector can play a pivotal role in promoting sustainable practices, reducing environmental impact, and contributing to overall water conservation efforts. This approach aligns with a broader commitment to responsible resource management, fostering a more sustainable and environmentally conscious textile production landscape.

iv. Streamlining logistics: Enhancing the efficiency of the supply chain logistics presents a viable strategy for mitigating emissions. This involves a multifaceted approach, encompassing the optimization of transportation routes, consolidation of shipping methods, and the implementation of warehouse efficiency measures. Streamlining these logistical processes not only contributes to the reduction of carbon emissions but also promotes resource optimization and sustainability across the entire supply chain. By strategically managing transportation networks, minimizing the use of trucks and ships, and incorporating warehouse improvements, organizations can make significant strides toward fostering an environmentally responsible and resource-efficient supply chain ecosystem.

v. Reducing waste. Minimizing waste throughout the production process emerges as a pivotal strategy in mitigating emissions. This entails not only the conscientious reuse and recycling of materials but also the adoption of more streamlined and efficient production processes. By implementing these measures, a dual benefit is achieved: a reduction in emissions and a more sustainable utilization of resources. This approach aligns with the broader goals of environmental conservation and sustainable manufacturing practices, contributing positively to the industry's overall ecological footprint.

The study has some limitations. The first one is the fact that the literature assessment was undertaken over a limited period of time, restricting definitive conclusions to be drawn. Secondly, the focus of the paper was on the carbon footprint, without dwelling in-depth on aspects of resource consumption. Finally, the work did not tackle in-depth phases of the life-cycle, such as the CF, of raw material cultivation and harvesting, fiber processing or garment manufacturing.

The study provides nonetheless a relevant contribution to the literature since it has analysed and documented trends related to the environmental and climate impacts of the textiles sector. It offers a profile of the extent of the problem and outlines some of the measures which may be deployed to address it, helping to foster a broader understanding of the international implications of this important topic. As to the future, it is clear that the textile industry requires a drastic change, so as to reduce its CF and allow it to become truly and thoroughly sustainable. Navigating the way through these challenges successfully will depend on the holistic approaches undertaken, recognizing the coexistence of different scales of production and the sharing of information. In order to yield the expected results, attempts to reduce CO_2 emissions should be paralleled by implementing transparency and traceability standards, promoting guidelines for accountability, and stronger governance across the entire sector, not only being limited to high-end players.[68] The collected examples show that concrete actions are being pursued - or may be pursued - to reduce the CF in specific contexts of the textile industry. By means of the implementation of strategies such as adopting renewable energy sources, optimizing raw material and water consumption, and increasing the utilization of recycled fibres, the CF of this pivotal economic sector can be not only enhanced but also aligned with sustainable practices. These measures may not only contribute to environmental conservation but also reflect a commitment to responsible resource management, marking a positive step towards achieving a greater sustainability in the sector.

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