



ISSN: 3062-3235

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## Sustainability Assessment of Natural Fibers Used in the Textile Industry: A Literature Review

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**Abstract.** The textile industry uses natural or synthetic fibers, or both, as raw materials. Global climate change affects the production potential of natural fibers by increasing pressure on air, soil, and water resources. Consequently, the production of these fibers, which the sector requires, faces significant sustainability challenges. This literature review comparatively examines the natural fibers commonly used in the textile sector—cotton, jute, flax, and wool—based on environmental, economic, and social sustainability criteria. Each fiber's production process was evaluated, along with factors such as water consumption, chemical input requirements, carbon and water footprints, biodegradability, soil health impacts, and production conditions. The findings indicate that the sustainability performance of fibers varies significantly depending on fiber type, production method, and geographical conditions. This review aims to assess the impact of natural fibers on sustainable fashion and circular textile systems and to provide guidance for future research and industrial applications.

**Keywords:** Natural Fibers, Global Climate Change, Water Footprint, Carbon Footprint

### 1 Introduction

Textile industry, which meets the most important basic need in human life after food and water (Madhav et al., 2018; Mostafizur Rahman et al., 2023), covers an integrated process that includes a series of complex stages such as yarn production using natural and/or artificial fibers, weaving, knitting, washing, bleaching, dyeing-printing, finishing and apparel (Turkes et al., 2024). The textile industry, which provides employment to tens of millions of people worldwide (Harsanto et al., 2023), produces products with various properties for use in agriculture, automotive, construction, geotextile, industrial, medical, sports, etc. fields (Sun et al., 2018; Roy et al., 2020; Harsanto et al., 2023). As one of the largest manufacturing industries in the world economy, the sector is expected to reach a turnover of 2.25 trillion US dollars in 2025 (De Felice et al., 2025). The textile and apparel industries cause a range of environmental problems, including chemical use, high water/energy consumption, air pollution, solid waste, and odor generation at every stage of production, from the cultivation of raw materials to the



disposal of finished products (Islam et al., 2022). Fiber production accounts for approximately 12% of the total environmental impact of textile products (Sigaard and Laitala, 2023). The United Nations Environment Programme (UNEP)'s sustainable development goals, which provide global guidance and cooperation to address significant environmental and socio-economic challenges, such as achieving sustainable development for the world, combating climate change, reversing environmental degradation, and managing resource use for a growing population, and to implement transformations and actions on the ground, provide a path to follow to shape a sustainable future for the world (Cordella et al., 2023).

Considering the textile sector's employment, economic scale, and environmental impacts, evaluating resource use in production is crucial for the sector's sustainability. The main raw materials of the sector are natural and synthetic fibers (Nayak et al., 2023). Global synthetic and natural fiber production increased from 57 million tons in 2000 to 111 million tons in 2020. It is expected to reach 145 million tons by 2030 (Periyasamy and Tehrani-Bagha, 2022). The declining global reserves of petroleum, the raw material for synthetic fibers, its exorbitant prices, and its environmental impact are accelerating the shift towards green products as a fiber source (Dhir, 2022). Rising environmental concerns and the depletion of petroleum resources are increasing the importance of natural fibers and encouraging researchers and industries to use sustainable fibers instead of traditional synthetic fibers (Ahmed and Mondal, 2021). Natural fibers are primarily obtained from plants and animals. Additionally, natural mineral fibers with specialized uses are considered in this category, but their use is limited (Jabbar and Shaker, 2016). The classification of some natural fibers of plant and animal origin used in the textile industry is presented in Table 1 (Jabbar and Shaker, 2016; Nayak et. al., 2023).

**Table1.** Classification of natural fibers

Natural Fibres					
From Plants				From Animals	
Seed Fibres	Leaf Fibres	Grass Fibres	Bast Fibres	Wool and Animal Hair	Silk Fibres
Cotton	Sisal	Bagasse	Flax	Sheep	Bombyx
Coir	Pineapple	Bamboo	Jute	Alpaca	Eri
Oil Palm	Banana	Canary	Hemp	Angora	Muga
		Corn	Ramie	Camel	Mulberry
		Sabai	Sisal	Cashmere	Tussar
				Rabbit	Spider Silk
				Yak	



Natural fibers are used in apparel and technical textiles across various sectors. However, they also exhibit negative characteristics that limit their application in textiles, including their hydrophilic structure, swelling due to water absorption, increased susceptibility to microbial attack, poor mechanical strength, lower color fastness, and non-uniform distribution compared with synthetic fibers (Ahmed and Mondal, 2021). Furthermore, the use of plant-based natural fibers such as cotton, linen, sisal, hemp, jute, and pineapple is more environmentally friendly than synthetic fibers due to their renewability, biodegradability, better specific properties, non-corrosiveness, natural availability, and photosynthetic activity during cultivation (Nayak et al., 2023). These characteristics necessitate consideration of the limitations of natural fibers as well as the opportunities and risks they present for environmental sustainability.

This study aims to examine the role of natural fibers in sustainable fashion and circular textile systems and to assess their environmental advantages and disadvantages. In this context, the production processes for cotton, linen, jute, and wool, the most commonly used natural fibers in textiles, were evaluated on the basis of data from the literature with respect to parameters such as water and energy consumption, levels of chemical use, carbon and water footprints, biodegradability, soil health impacts, and renewability. The study employed a comparative analysis method, and the contributions of different fiber types to sustainable fashion and technical textile applications were discussed from the perspective of environmental compatibility, product life cycle, and circular economy.

## **2 Material and Method**

An effective literature review provides a solid foundation for the development of knowledge. It supports the development of a theoretical framework, reveals intensively studied areas, and clarifies topics requiring further research (Hussain and Wahab, 2018; Leite et al., 2019). When a topic is approached and logically integrated on the basis of the reviews and findings from previous studies, further progress can be made in that field (Yıldız, 2022). In this study, the environmental impacts and sustainability dimensions of the production processes for natural fibers, the basic raw materials of the textile industry, were assessed using environmental metrics. Environmental metrics are quantitative measurements used to assess the environmental impact of human activities (Zarea et al., 2019; Mirmoradi et al., 2025). These metrics help track trends, evaluate performance, and guide decision-making processes toward more sustainable practices and policies (Alishah et al., 2019; Mirmoradi et al., 2025). Monitoring these environmental metrics can help identify areas for improvement, set reduction targets, and monitor



ISSN: 3062-3235

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progress toward sustainability goals (Mirmoradi et al., 2025). In this study, carbon footprint and water footprint, widely used environmental metrics that reflect the impact of human activities on the planet, were used to assess the sustainability of fibers. Furthermore, various environmental metrics used in the literature on the sustainability of natural fibers are included for informational purposes. This study investigates the sustainability of natural fibers and uses data from the literature. For this purpose, 157 articles published in online databases and high-impact research journals were searched, and after reviewing their abstracts, information was collected from 68 research articles and several reports and book chapters. The keywords used to search the databases were as follows: textile, textile fiber, cotton, linen, jute, wool, water footprint, carbon footprint, sustainability in agriculture, agricultural inputs for natural fibers, waste minimization in agriculture, and pollution prevention in agriculture.

### **3 Results and Discussion**

#### **3.1 . Global Status of Fiber Use**

According to Textile Exchange's latest Materials Market Report, global fiber production reached an all-time high of 124 million tons in 2023. Natural fibers constitute approximately one-quarter of this amount. The percentage distribution of global fiber production from the 2024 Textile Exchange Materials Market Report is shown in Figure 1, and the fiber production and forecasts for 1975–2030 are presented in Figure 2 (Textile Exchange Materials Market Report, 2024).

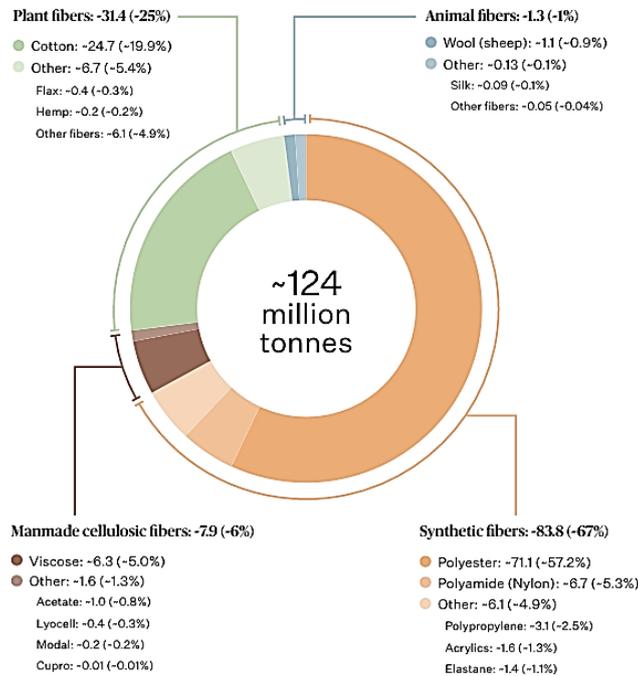


Fig.1. Global fiber production in 2023 (in million tonnes and % of global fiber production)

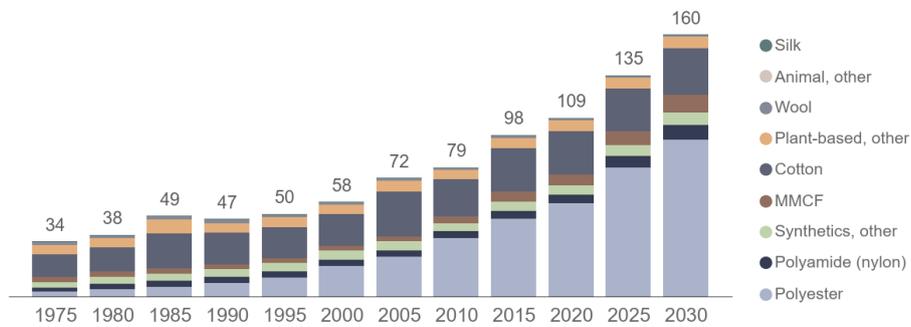


Fig.2. Global fiber production (million tonnes)

An examination of Figures 1 and 2 reveals that cotton has by far the largest share among natural fibers, accounting for approximately 20% of total global fiber production. Other plant fibers, such as flax, jute, hemp, and sisal, account for approximately 2–3% of the total, while animal fibers, such as wool, silk, and mohair, account for approximately 1%. These fibers play a significant role in textile and technical textile applications owing to their properties, such as comfort, moisture absorption, breathability, and biodegradability. The production of natural fibers is affected by environmental factors such as climate conditions, agricultural productivity, water use, and carbon emissions, and these factors impact the



environment (Gonzalez et al., 2023), necessitating their evaluation from both an economic and an ecological perspective.

### 3.2 Environmental Sustainability Assessment of the Natural Fibers Considered in the Study

Considering the data in Figures 1 and 2, this study evaluated the sustainability and environmental impacts of natural plant fibers such as cotton, linen, and jute, and animal fibers such as wool, all used in the textile industry. General information on these fibers is provided below under various headings.

#### Cotton

Cotton (*Gossypium* spp.), although botanically a perennial plant, is generally grown as an annual in agricultural production and is the world's most important source of fiber. Cultivated primarily for fiber production, cotton also contributes to animal feed through the oil obtained from its seeds and the oil cake remaining after extraction (Constable and Bange, 2015; Huang et al., 2022). The production cycle of cotton is 150–180 days (Dristy et al., 2024). It is estimated that cotton, cultivated on an area of  $31.92 \times 10^6$  ha in approximately 80 subtropical and tropical countries, has an annual turnover of US\$5.68 billion (Vitale et al., 2024). In areas with irrigation facilities, Cotton yield averages 800 kg/ha and increases by 10–20 kg/ha annually (Constable and Bange, 2015). The cumulative energy requirements for producing 1 kg of cotton fiber (growing) and 1 kg of textile (yarn) are 68.5 MJ and 368 MJ, respectively (La Rosa and Grammatikos, 2019). Cotton accounts for one-fourth of the global fiber market (Yu and Yang, 2025). Approximately 25 million tons of cotton are produced annually worldwide. The top ten cotton-producing countries are India, China, the United States, Pakistan, Brazil, Australia, Uzbekistan, Türkiye, Turkmenistan, and Burkina Faso (Khan et al., 2020). The harvesting of some traditional natural fibers, such as cotton, requires substantial amounts of water and pesticides (Nayak et al., 2023), thereby necessitating an assessment of the environmental impacts of cotton production. Given the socioeconomic value of cotton, it has been reported that it can help reduce extreme poverty (SDG 1) and achieve the Zero Hunger target (SDG 2) of the UNEP 2030 Sustainable Development Goals (SDGs) (Kang et al., 2023). The results of the literature review on the environmental impacts of cotton production are presented in Table 2.



**Table 2.** Environmental impacts of cotton production

Cultivation Area	Green Water Footprint (m <sup>3</sup> /ton)	Blue Water Footprint (m <sup>3</sup> /ton)	Total Water Footprint (m <sup>3</sup> /ton)	Ecological Footprint (m <sup>2</sup> ·anual/ton)	Carbon Footprint(kg CO <sub>2</sub> eq/ton)	Source
Türkiye	205	1,641	1,846		715	Muratoğlu (2024) Yu and Yang (2025)
Greece	~320	~1,700	2,020			Tsakmakis et al. (2018)
Kazakhstan	962	1,462	2,424			Chapagain et al. (2006) Yu and Yang (2025)
Kyrgyzstan	665	2,384	3,049			
Tajikistan	388	5,858	6,246			
Turkmenistan	191	6,875	7,066		971	
Uzbekistan	255	4,171	4,426		1,021	
USA	1,673	576	2,249		904	
Brazil	2,575	46	2,621		693	Chapagain et al. (2006) Yu and Yang (2025)
Benin					303	
Pakistan	1,054	3,860	4914		1,366	
India	6,512	2,150	8662		1,080	
China	1,258	760	2018		747	Mehmeti et al. (2024) Korol et al. (2020)
Egypt		2,171.8			2,622.6	
		2,070		31,320	2,950	

As shown in Table 2, the impacts of cotton grown in different regions, such as the water and carbon footprints, vary. Therefore, planning for the sustainability of cotton production should be conducted on a global scale while considering local resources. The ecological footprint assessed in the study by Korol et al. (2020) estimates the amount of biologically productive land and water surface required to compensate for the resources consumed for consumption, development, treatment of some waste, storage of other waste, and absorption of emissions from fossil fuel and nuclear energy consumption. Thus, the impact of cotton on productive land and water surface per unit of production can also be quantitatively assessed. The values of 1 ton of cotton textile production in the environmental impact categories of Water Resource Depletion, Acidification, and Eutrophication were reported as 1,736 m<sup>3</sup> water eq, 165 kgSO<sub>2</sub> eq, and 70.84 kg PO<sub>4</sub> eq, respectively (La Rosa and Grammatikos, 2019).

### Flax

Flax (*Linum usitatissimum L.*) is an economically important fiber crop cultivated for both its long, cellulose-rich fibers and its seeds. Archaeological findings from the Neolithic period reveal the use of flax fiber in early cultures. It is also known that the plant was cultivated in Egypt approximately 6,000 years ago (Chabi et al., 2023). It has also been reported that flax was used as a wound dressing in ancient times (Gębarowski et al., 2022). Flaxseed contains 37–42% oil and is classified as a drying oil due to its



high alpha-linolenic acid content. It is beneficial to human health due to its content of omega-3 fatty acids, lignans, and fiber (Zare et al., 2021). Flax fibers are an important raw material for industrial applications such as textiles, paper, and composite materials (Huang et al., 2021). Whether the primary selection criterion in flax breeding is based on seed oil content or stem fiber yield remains a matter of debate (Chabi et al., 2023). The flax production cycle is 90–120 days (Fenart et al., 2010). Currently, flaxseed is produced primarily in Eastern Europe, Central Asia, and North America, and the main producers are the Russian Federation, Kazakhstan, Canada, and China. Cultivated areas in Eastern Europe increased by 74.6% between 2011 and 2021. The highest yields are achieved in France (1.9 tons/ha), representing a threefold increase since the early 1970s. Europe is the world leader in flax fiber production, with France as the leading producer. The highest quality fiber is produced in an area extending between France and the Netherlands due to the mild climate and the availability of well-drained land. The area under fiber flax cultivation is increasing annually in Europe. Because every part of the flax plant can be used in many areas, such as animal feed, oil production, textiles, paper, heating sources, chipboard production, etc., flax is a waste-free product (Moyses et al., 2023). The energy efficiency of flax fiber production was found to be the lowest among those of jute, kenaf, and sunn hemp fiber production. It has also been reported to consume more chemical fertilizers, diesel fuel, pesticides, and seed energy than other fibers. Fertilization and fiber processing are estimated to be the largest contributors to greenhouse gas emissions (Singh et al., 2018).

A literature review on the environmental impacts of flax production found that the green, blue, and total water footprints are 2,637, 443 and 3,481 m<sup>3</sup>/ton, respectively (Mekonnen and Hoekstra, 2011). Carbon footprint has been calculated at different values in different studies as 520 kg CO<sub>2</sub>eq/ton (Singh et al., 2018), 1,100 kg CO<sub>2</sub>eq/ton (Dissanayake et al., 2009).

## Jute

Jute (*Corchorus* spp.) is a herbaceous, deciduous, perennial plant that generally grows up to 1.5 meters tall. Jute plants cultivated for fiber can grow up to 4 meters tall (Rahman and Rahman, 2024). The jute production cycle is 110–120 days (Ahmed et al., 2023). Jute fibers have been used throughout history for the production of rope, clothing, and sacks (Jarín et al., 2024). Today, they are used across various fields, including the textile industry, packaging materials, geotextiles, composite materials, paper production, food, medicine, and construction (Rahman and Rahman, 2024). Jute is known as the "golden fiber" due to its color and significant material value, and it is the most important and cheapest textile



fiber after cotton (Gangarde et al., 2024). India, Bangladesh, China, Myanmar, Nepal, and Thailand are the primary jute producers in the world (Islam and Alauddin, 2012). India is the largest producer of jute, and with technological advances, jute productivity has increased from 1.04 tonnes/ha to 2.56 tonnes/ha since independence (Kar et al., 2023). The cultivation phase of jute fiber production has the most significant environmental impact. This impact becomes particularly evident when assessed in terms of carbon footprint. Fertilizer and pesticide use in the production process accounts for approximately 23% of the total environmental impact. This stage, which typically involves the highest level of mechanization, uses electrically powered machinery and equipment to process the fibers. Furthermore, because irrigation is included in the cultivation phase, the cultivation phase is the largest contributor to the total water footprint of jute production. In contrast, the transportation process, which does not require specialized equipment, has the lowest environmental impact (Korol et al., 2020).

A literature review on the environmental impacts of jute production has yielded impact assessments in different categories. In the water footprint assessment, the blue water footprint was reported as 1,550 m<sup>3</sup>/ton and the ecological footprint as 4,730 m<sup>2</sup>·annual/ton (Korol et al., 2020). The carbon footprint was calculated to be 565 kg CO<sub>2</sub>eq per ton (Singh et al., 2018). The cumulative energy requirements for producing 1 kg of jute fiber (cultivation) and 1 kg of jute textile (yarn) are 29.55 and 97 MJ, respectively. The values in the environmental impact categories of Water Resource Depletion, Acidification, and Eutrophication were reported as 188 m<sup>3</sup> water eq/ton, 41 kgSO<sub>2</sub> eq/ton, and 14.93 kg PO<sub>4</sub>eq/ton, respectively (La Rosa and Grammatikos, 2019).

### **Wool (Sheep)**

Wool is a proteinaceous fiber sheared from sheep. Wool fibers have unique biological, physical, and chemical properties and are becoming increasingly important as demand for natural products increases (Zhou et al., 2024). Wool is a renewable resource, and the average sheep produces 2.3 to 3.6 kg of raw wool per year (Koyuncu, 2024). 4.5 kg of wool is equivalent to more than 10 meters of fabric. This amount of fabric is sufficient to make six sweaters; three suits and trousers; or a large sofa cover (International Wool Textile Organization, 2024). It is valued for its insulation, moisture-buffering properties, flame resistance, and biodegradability (Corscadden et al., 2014). These properties stem from its unique fiber architecture and specialized protein composition, which distinguish it from other natural and synthetic fibers. According to data from the International Wool Textile Organization (IWTO), the number of sheep is reported to have reached 1.296 billion head in 2022, with greasy wool production



reaching 1977.3 million kilograms and clean wool production reaching 1051.2 million kilograms (Zhou et al., 2025). China has the largest sheep population. Other leading sheep producers include India, Australia, Mongolia, Türkiye, the United Kingdom, South Africa, and New Zealand (International Wool Textile Organization, 2024).

A literature review of the environmental impacts of wool production yielded assessments across various categories. Research indicates that preparing each ton of wool fiber consumes 2.3–2.5 tons of water (Duan, 2010; Li et al., 2022). Various studies have reported that the carbon footprint of wool is between 10 and 70 kg CO<sub>2</sub>eq/kg (Brock et al., 2013; Wiedemann et al., 2015; Wiedemann et al., 2016; Dougherty et al., 2018; Bech et al., 2019; Bianco et al., 2023). The cumulative energy required to produce 1 kg of belly wool fiber is 91.8 MJ. The values in the Water Resource Depletion, Acidification, and Eutrophication environmental impact categories have been reported to be 12.7 m<sup>3</sup> water eq, 1.59 mol H<sup>+</sup> eq, and 0.0171 kg PO<sub>4</sub>eq, respectively (Bianco et al., 2023).

### 3.3 Discussion and General Evaluation

Natural fibers play a central role in the textile industry's sustainability transformation due to their renewable origins, biodegradability, and lower carbon footprint than that of synthetic fibers. According to life cycle assessment (LCA) studies, bast fibers such as flax, hemp, and jute typically have 20–50% lower carbon footprints than those of synthetic fibers such as polyester or nylon (Singh et al., 2018). On the other hand, despite being noted for its durability and low production costs, polyester contributes significantly to terrestrial ecotoxicity and microplastic pollution. Recycled polyester fibers have been reported to release approximately 2.3 times as many microplastics as virgin polyester fibers due to thermal degradation during the recycling process (Özkan and Gündoğdu, 2021).

While the environmental performance of natural fibers is lower than that of synthetic/polyester fibers, it is not uniform; it varies significantly depending on agricultural inputs, regional growing conditions, and processing technologies.

Among bast fibers, jute offers significant environmental advantages over conventional cotton. Jute cultivation requires significantly less irrigation and fewer chemical inputs and achieves lower values in environmental impact categories such as human toxicity, eutrophication, and acidification (Bhalla et al., 2018; Gonzalez et al., 2023). Similarly, flax stands out as a sustainable alternative, requiring less water and energy in production processes while providing higher yields per hectare (Moazzem et al., 2021).



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To better utilize the agricultural and nutritional potential of flax, brown-seeded genotypes are recommended for cultivation under water-stress conditions (Zare et al., 2021). Because the environmental burden of flax production is particularly concentrated during the agricultural phase, fertilizer and pesticide use, as well as fuel consumption for agricultural machinery, accounts for a large portion of these impacts.

Although cotton is one of the most important textile crops globally, it contributes significantly to the depletion of freshwater resources and to greenhouse gas emissions due to its dependence on intensive irrigation and nitrogen fertilizers (Yu and Yang, 2025). Studies show that modern irrigation technologies, such as drip irrigation, can reduce the total water footprint by 5–12% compared to traditional sprinkler systems (Tsakmakis et al., 2018). Similarly, increasing nitrogen use efficiency and using renewable energy in agricultural equipment can significantly reduce the carbon footprint of cotton production. Ammonium nitrate production and its use for fertilizing plants has been reported to be the most significant contributor to global warming potential (Le Duigou et al., 2011). However, both the heavy reliance on herbicides and pesticides and the environmental risks associated with genetically modified (GM) cotton still pose significant sustainability challenges (Vitale et al., 2024).

Wool, an animal-derived fiber, has higher environmental impacts per unit of fiber than those of plant fibers. This is particularly due to processes associated with animal production, such as feed production, methane emissions, and pasture use.

Therefore, sustainability assessment should not only consider the carbon and water footprints but also focus on factors that occur throughout the life cycle, such as biodegradability, recyclability, and social and ethical impacts. As emphasized by Sandin et al. (2019), there is no “inherently sustainable or unsustainable” fiber type; sustainability depends on context-specific management styles and decisions made throughout the life cycle. New materials, such as bio-based fibers derived from citrus pulp, mushrooms, or industrial waste, have the potential to expand the range of sustainable textiles; however, the lack of standardized LCA data on this topic hinders comparative analyses.

#### **4 Conclusion**

This review has revealed that natural fibers generally have lower carbon and water impacts than synthetic fibers; however, their sustainability performance is closely linked to cultivation methods, input



intensity, and processing. Among plant fibers, flax, hemp, and jute have the most positive environmental profile, while traditional cotton and silk have the most negative impacts due to their high resource use and environmental burden. Methods such as precision agriculture practices, use of organic fertilizers, integration of renewable energy, and environmentally friendly flax processing technologies (e.g., bioretting) can significantly reduce the environmental footprint of natural fiber production.

However, achieving sustainability in the textile industry is not possible solely through correct fiber selection. True sustainability requires a holistic lifecycle approach encompassing all stages from raw material procurement to the end of the product's lifecycle. Increasing product durability, developing recycling systems, and making decisions based on accurate environmental data are key elements of this transformation. Consequently, the transition to sustainability in the textile industry requires both technological innovations and systemic transformations throughout the supply chain, placing natural fibers at the center of a circular and low-impact textile economy.

**Acknowledgment:** This study was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) with project number 2244-119C178. The authors thank TÜBİTAK for their support.

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