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REVIEW ARTICLE

Implications, challenges and prospects of industrial Hemp as a sustainable natural fiber in Pakistan: An overview

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Abstract

Industrial hemp (*Cannabis sativa* L.) is a sustainable source of fiber due to its fast growth rate and adaptability to diverse climates and low demand for pesticides and water. Additionally, hemp fibers are versatile and used for a variety of products, including clothing, textiles, paper and building materials. As a bast fibers with a high cellulose content, industrial hemp is both sustainable and resource-efficient sources. Considerations of environmental protection, as well as their intrinsic qualities like low density, high specific strength and stiffness, increased researchers' interest in hemp fibers. This review examines the current status and significance of hemp fiber in the textile sector, comparing it with cotton and synthetic fibers while discussing its processing and use. Although, industrial hemp shows great promise, further research is needed to improve its quality and expand its applications. Hemp fiber processing is a significant issue in the textile sector and thus this review provides comprehensive information on the complete value chain of hemp fiber, its challenges and future implications.

Keywords: Bast fiber, fiber processing, industrial hemp, sustainable fibers, textile sector

Introduction

Pakistan's economy is primarily driven by the textile sector, that serves as the heart and soul of the nation. As the eighth-largest textile exporter in Asia, Pakistan's textile industry plays as crucial role in job creation and foreign exchange earnings. Textile-related products account for more than 60% of country's exports and contribute 8.5% to the GDP (1). Climate change has significantly impacted the agriculture sector globally including Pakistan, leading to extreme weather events like droughts, temperature fluctuations, nutrient deficiencies, heavy metal contamination, diseases and pest outbreaks (2 - 4). Pakistan is among the top 10 most climate affected countries. Over the past few years, the cotton crop has been drastically damaged by climate change, including a rise in temperatures during sowing months coupled with water shortage, causing a severe heatwave and affecting germination and seedling establishment. Additional challenges, include land shrinkage, shortage of quality seed, disease and pest infestation (4 - 6). To mitigate these challenges, it is imperative to work on alternative sources of natural fiber crops that are climate-resilient, sustainable and cost-effective. Diversifying fiber sources will help meet the rising the demand for textiles, while supporting the economic growth of the country.

Industrial hemp (*Cannabis sativa* L.) has the potential to be sustainable, cost-effective and environmentally friendly source of natural fiber for the textile industry. It is an annual herbaceous bast fiber crop with low delta-9-tetrahydrocannabinol (<0.3% THC) (7-9). Given that hemp is native to western and central Asia, including Pakistan and has been used for various purposes for over 2 millenia, it could help reduce the country's dependence on cotton. The agro-climatic and edaphic conditions in Pakistan are ideal for the cultivation of industrial hemp (10, 11). However, no estimates of its production and cultivation are currently available across the country (12). In 2020, the Government of Pakistan conditionally permitted the cultivation of industrial hemp for industrial and medical purposes, to boost the country's economy. In 2024, the "Cannabis Control and Regulatory Authority Ordinance" was approved by the Government of Pakistan.

Hemp cultivation has become legalized in several countries such as China, the United States, Canada and some European countries leading to the development of new markets. Some of these countries have experienced significant growth in their hemp industries, with the number of industrial hemp licenses doubling in recent years, indicating a likely increase in hemp production in the coming

years (13-16). Beyond its diverse application, industrial hemp offers agricultural and environmental benefits, as it can withstand various abiotic stress conditions (17-19). Industrial hemp is increasingly recognized as a cost-effective and resource - efficient crop which can also improve soil health. Field retting in hemp cultivation can give back as much as 70% of the nutrients taken from the soil, ultimately lowering the expenses and environmental effects of field preparation (20). This results in a subsequent crop cycle requiring only around one-third of the initial fertilizing input, thereby reducing the environmental impact of field preparation (7). Hemp, a climate - resilient and resource-efficient fiber crop, offers unique chemical properties for the textile industry (21).

This review provides a comprehensive overview of industrial hemp as a sustainable natural fiber, covering its properties, production and processing. It also compares hemp fibers with cotton and other synthetic fibers while highlights challenges and future research directions.

Challenges of the textile industry in Pakistan

The textile industry in Pakistan has experienced fluctuations in recent years due to various factors such as limited raw material supply, high production costs, power shortages, outdated machinery, poor strategies and government policies (22-24). The production cost is primarily influenced by the raw material, which accounts for 35% of the total production cost of the textile industry. As a cotton-based industry, Pakistan sources a significant portion of its raw materials locally. However, the country faces a shortage of cotton, especially long soft cotton produced in Punjab and Sindh provinces (25, 26). The decline in cotton production, driven by multiple factors (Fig. 1), has forced the industry to import raw materials to meet domestic demand.

Globally, competition in the textile market is high; with strong demand for high-quality products at reasonable prices. Despite low wages and domestic cotton availability, Pakistani goods faces intense competition with Bangladesh, India and Vietnam, which offer cheaper and better-quality goods (27, 28). Over the past 20 years, pesticide use in Pakistan has increase by an average of 11.6% annually, with cotton cultivation accounting for more than 80% of total pesticide consumption (29, 30). Rising cost of production has stifled investment and export competitiveness. Moreover, the country is also facing a massive energy crisis, with a demand of more than 5000 MW. To manage this defecit, the government imposes daily power cuts, disrupting manufacturing, shutting down textile mills and reducing export orders. The garment sector is affected by continuous shifts in global fashion trends, requiring immediate response to market demand (30, 31). Moreover, inadequate marketing and advertising strategies also limit the demand for Pakistani textile products in the US and European markets (32).

The industry also faces a shortage of skilled labor, hindering its ability to compete with local and global standards. Technological advancements further challenge the workforce, as many struggle to acquire the necessary expertise. Additionally, inadequate knowledge of product development and design hampers the industry's ability to create high-demand products (33, 34). A lack of significant research and development efforts further weakens Pakistan's textiles sector, limiting its competitiveness in the global market. To address these issues, the industry needs sustainable and cost-effective solutions. Industrial hemp presents a promising alternative, as it reduces the cost of production, yield more fiber per unit area and serve various industrial applications.

Industrial hemp as a sustainable source of natural fiber

Textiles and clothing are highly polluting industries due to high energy, water and chemical consumption, generating substantial industrial waste, leaving a significant ecological footprint (35, 36). Cotton, a widely used natural fiber, requires extensive land and has high water and chemical demands. As the demand for raw materials grows, interest in sustainable and economical alternative natural fiber has increased (37). Currently, industrial hemp has emerged as a promising sustainable source of natural fiber due to its fast-growing nature, low water and pesticide requirements and high fiber versatility. Compared to cotton, hemp adoption may reduce

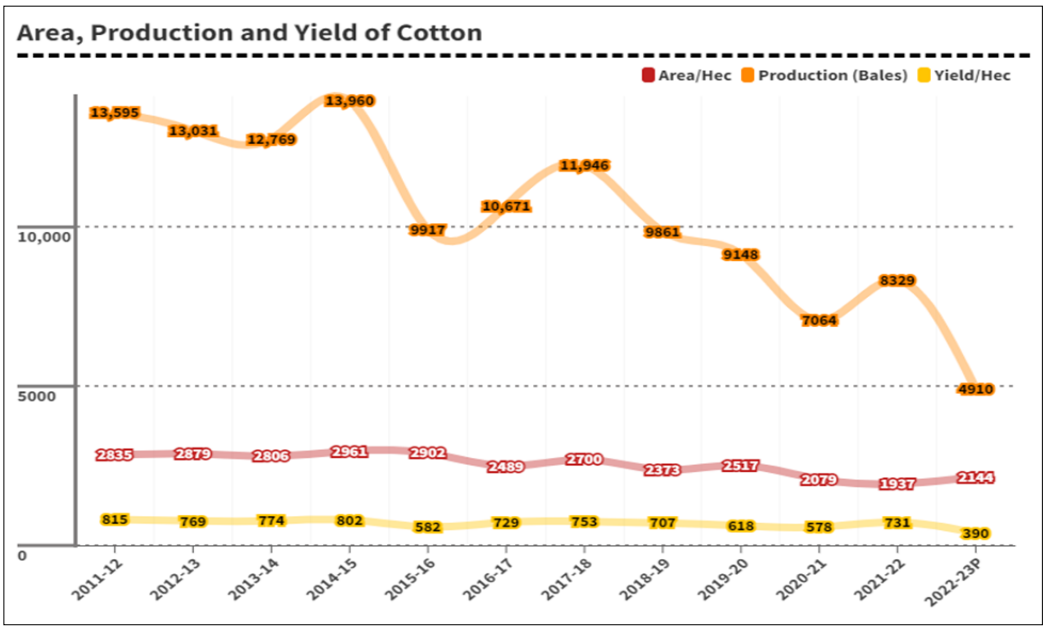


Fig. 1. The change in area/hectare, production/bales and yield/hectare of cotton in Pakistan due to various factors from 2011-12 to 2022-23 (86, 87, 88).

agricultural activity costs by 77.63% and reduction in production costs (7, 38). It thrives in various climates, requires fewer inputs (water, land and pesticides) and has low environmental footprints than other fiber crops (Table 1).

Table 1. Environmental footprints for producing one kg of hemp and glass fibers. Data taken (75).

Parameters	Hemp fiber	Glass fiber
Power consumption (MJ)	3.4	48.3
CO_2 emission (kg)	0.64	20.4
SO_x emission (g)	1.2	8.8
NO_x emission (g)	0.95	2.9

Hemp fiber is strong, durable and versatile, making it suitable for various applications (37, 39). Industrial hemp is a naturally resource - efficient and climate resilient crop capable of producing economic yield under various soil and environmental conditions such as drought, salinity, metals and temperature extremes (40 - 42). Fiber hemp seeds germinate at temperatures ranging from 5 -35°C, with the optimal germination rate of 95% at 20°C (42). Hemp plants can survive at low temperatures (0°C) and endure 6-week drought conditions (43). However, suboptimal conditions can reduce the stem dry matter content of the hemp plant. Hemp plays a crucial role in improving soil properties and climate through phytoremediation and carbon sequestration (44 - 46). Hemp requires a minimal amount of nutrition for maximum fiber production. It offers 50% nutrient reduction and improved water use efficiency, compared with cotton (7). Moreover, it produces three times more fiber per unit of water than cotton, making it a naturally cost-effective crop (7, 47). Hemp fiber is economically viable due to its low cost of production and high demand across various industries.

Processing of hemp fiber

Hemp provides an environmentally sustainable solution for fabrics and other materials. Hemp stalks consist of 2 fundamental components: long bast fibers and hurd. The bast fiber is a long, durable fiber used in textiles, paper and various other products, while the hurd is a non-fibrous solid material used in building materials such as insulation, bio-composites and particleboard.

Harvesting hemp fibers involves two main processes: collecting the plant's stalks and extracting fibers. Hemp plants are typically harvested during the early to mid-flowering stage, when the fibers are the strongest and the longest (17). However, the exact timing depends on the hemp variety, climate conditions and intended use (fiber, seed or both). Fiber hemp varieties are cultivated to produce long stalks and minimal flowering parts. Harvesting techniques vary and may include manual cutting with sickles or specialized machinery like combines adapted for hemp. The plants are normally cut at the base stem just below the lowest flowering branches and gathered in rows. The windrows are left to dry for a few days. At 12% moisture content, the stalk rows are baled and transported for further processing to strip and separate longer fibers and hurd. Longer fibers dominate in the bark of the stem, whereas hurd and lignin abound in the rest of the stem. As a result, larger diameter stems are required for higher fiber productivity. Common fiber yields, on the other hand, range from 15 to 22% of dry stem weight (17).

After harvesting and drying, the stems undergo retting to seperate the bast fibers from the inner hurd (48). This process relies on microbial activity to breakdown pectin that bind the fibers and hurd together. A variety of processes for retting hemp fibers have been implemented and explored depending on the environment and end use. Fibre extraction can be achieved through using enzymatic treatments, microbiological activity and physical and chemical techniques. However, none of these methods are cost-effective for large-scale industrial applications. As a result, dew retting and water retting are the most widely used and valued techniques (49).

Dew retting is a natural process that entails leaving the hemp stalks in the field and exposing the dew and elements. The pectin that keeps the fibers together is broken down by naturally occurring bacteria and fungi. This process is a time - consuming process, often lasting many weeks and requires frequent turning of the stalks to ensure even retting. The other method is water retting which includes immersing the stalk in water (ponds, tanks or slow-moving streams) for a set period, usually 7 days. Microorganisms in the water break down the pectins, making fiber separation easier. However, effectiveness of retting is influenced by crop maturity at harvest, retting procedure, ambient conditions and the type of bacterial and fungal populations. The retting process also affects the fiber composition because dew-retted hemp fiber contains less cellulose and hemicellulose content but more lignin and ash compared to water-retted fiber (49).

Both dew and water retting have drawbacks such as inferior fiber quality, variable fiber strength and significant polluted wastewater. To improve retting efficiency, crop varieties with higher cellulose contents and lower pectin and lignin elements may be preferable as they enhance yield, quality and fiber strength while while reducing labor and processing time. After the retting process is completed, the fibrous ribbon is separated from the stalk using specialized machinery like decorticators or hemp processing equipment. The fibrous ribbon is brushed, a process that crushes and scrapes the outer woody layer, releasing the fibers from the core.

The fibers must be dried after mechanical processing to reduce moisture content. Proper drying avoids mold growth and keeps the fibers in good shape for subsequent processing. Depending on their intended application, the recovered fibers may go through additional processing stages such as carding (to align the fibers), spinning (to make yarn) and weaving or knitting (to create fabrics) are examples of these steps.

Uses of hemp fabrics

Hemp is a viable sustainable raw material for the textile industry. China is generating massive amounts of hemp fibers and hemp yarns because of its well - established industrial infrastructure and greater export potential for textiles (50). Dry spinning processes with shorter drafting times are preferable over wet spinning processes for hemp yarn (51). Hemp fibers have high lignin and pectin contents, which make processing challenging. To address this, hemp is often blended with cotton to avoid spinning challenges. Blended fabrics offer superior moisture absorption, UV protection, anti

-mold, antibacterial and antistatic qualities. Increasing the hemp component in the blend such as using 50% hemp fibers with cotton in a rotor spinning machine, resulting in high-quality yarn. Hemp can also be vortex-spun and studies indicate that hemp/Tencel blended vortex-spun yarns outperformed Siro-spun yarns in terms of hairiness and evenness (52-54).

Knitted fabrics made with these yarns have a improved hand feel and are easier to process. Moreover, research suggests that employing folded yarns in hemp-knitted fabrics substantially improves air and water permeability. The moisture absorption and breathability of knitted fabric are improved by combining cotton/hemp/lyocell with a higher hemp ratio, while abrasion and pilling resistance remain unchanged. The evenness of hemp blended yarn is normally reduced as the hemp ratio increases; however, it can be enhanced with proper humidification by spraying mist in the ring-spinning frame. The GSM of hemp fabrics ranges from 270 to 540 gm^2 depending on the intended use (apparel or technical applications) and the composition of raw material such as hemp/wool/silk/synthetic fibers (55). Different natural fibers are utilized to make protective clothing, but hemp has some advantages. Union fabric made from hemp in weft yarn and cotton in warp yarn has higher breaking strength, resistance to flammability, pilling resistance and rigidity (51). While natural fiber-based textile fabrics often have greater comfort characteristics, but poor UV absorption. However, blended fabrics comprising hybrid yarns where hemp serves as the staple fiber and synthetic as filament - provide better UV protection.

The properties of hemp fiber can be improved by enzymatic and alkaline treatments. These treatments reduce lignin content, improve fabric hand, improve tensile strength and surface smoothness. Alkaline treatments also increase cloth dye ability by widening the amorphous regions. The application of liquid ammonia to fabric can improve its wrinkle resistance and softness. Enzymatic treatments on the surface of hemp cloth also make it softer, more elastic and smoother. Blending hemp with wool, on the other hand, improves the flammability of the blended fabric due to an increase in amorphous areas (51, 56). Antimicrobial fabrics have gained popularity in recent years due to their ability to prevent or minimize infection transmission in medical and healthcare settings. Hemp exhibits antibacterial properties making it effective against infections. The active antibacterial constituents of hemp include alkaloids, flavones and saponins. Hemp fibers are resistant to microorganisms such as *Staphylococcus aureus*, *E. coli* and *Pseudomonas aeruginosa*. Furthermore, hemp fabrics are hypoallergenic and have anti-mildew properties. Because of these characteristics, hemp fibers are widely used in odor -free socks (57-59).

Comparison of industrial hemp fiber with cotton

Cotton, an important crop for the textile industry in Pakistan, faces sustainability concerns due to high water consumption, pesticide use, fertilizer dependency and chemical inputs, all of which have negative environmental and economic impacts (43, 60). In contrast, hemp requires less maintenance and fewer inputs while yielding more fiber (7). It is also more sustainable, needing minimal chemical use for pest control (61, 62). Compared to cotton, hemp requires only only one- of the water to produce one kilogram of fiber, (63, 64). Hemp's stem bark produces 2 types of bast fibers: primary bast fibers which range from 20 mm to 50 mm long and secondary bast fibers which are approximately 2 mm long derived from the vascular bundles of the hemp stalk (65, 66).

Currently, hemp bast fiber is more expensive than cotton fiber due to its limited production. However, as its cultivation increases, the cost of hemp fiber is expected to decrease (67). Hemp fibers have a exceptional strength and modulus, comparable to man-made glass fibers, making them a excellent substitute for synthetic fibers in stiffness and lightness (68). They are longer, stronger and coarser than silk and are widely used in engineering fields like geo-textiles, sports equipment and structural components (69). Hemp fiber is a unique and versatile material with several distinctive properties It has anti-bacterial, anti-static, non-irritant and non-allergic properties (37, 70). Additionally, hemp fiber is hypoallergenic, resistant to mold and mildew, breathable, moisture-wicking and UV-resistant (50, 71). A comparison of industrial hemp and cotton fiber is given in Table 2 and Fig 2.

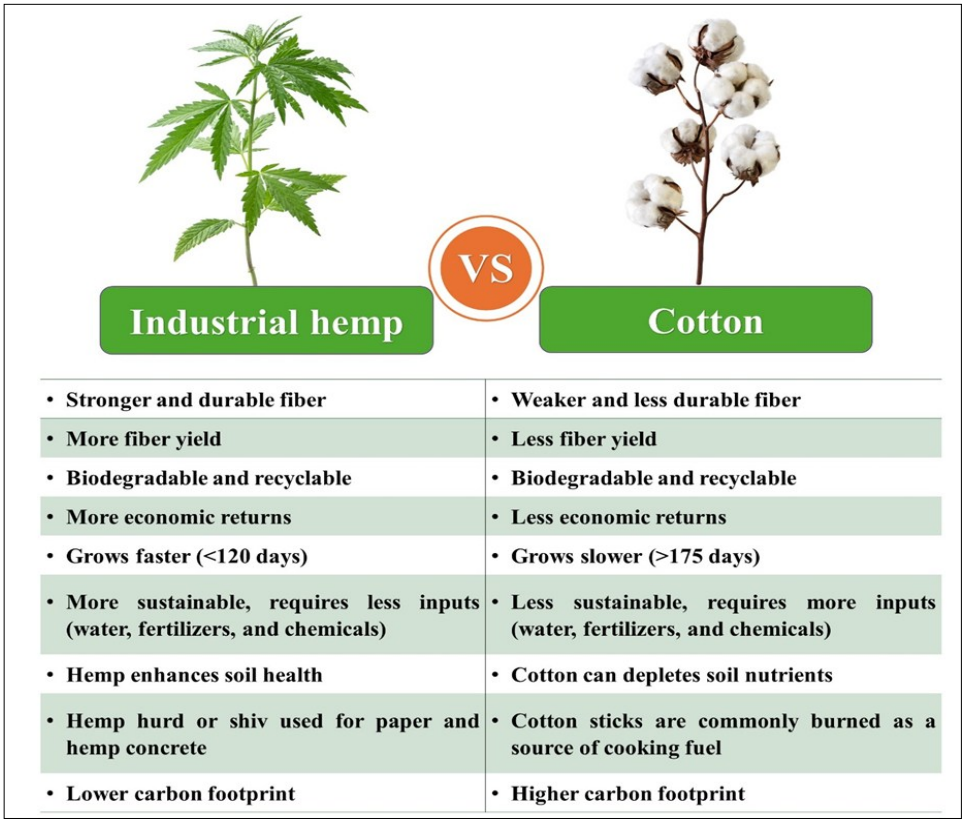
Industrial hemp fibers vs petroleum based Synthetic Fibers

In the textile industry, hemp and synthetic fibers represent two distinct groups of materials categories each with unique characteristics, manufacturing methods and environmental impacts. Hemp is a sustainable crop with low environmental impact (72). In contrast, synthetic fibers such as polyester, nylon and acrylics are manufactured from petrochemicals. Their production involves the extraction and processing of fossil fuels, which contribute significantly to greenhouse gas emissions, as well as water, air and soil pollution, leading to resource depletion. One of the notable attribute of hemp fibers is their biodegradability, as they degrade naturally in the soil without harming the environment. Conversely, synthetic fibers such as polyester persist contributing to microplastic pollution and environmental disruption. Additionally, hemp fibers are breathable and easy to wear, whereas synthetic fibers retain heat and moisture, causing discomfort and odor.

Both hemp and synthetic fibers are robust and long-lasting; however, the durability of synthetic fibers is dependent on the raw material used. Synthetic fibers are less expensive to produce due to the widespread availability of petrochemical goods (73). Hemp cultivation and processing are labor and expense-intensive activities that require adequate laws. Traditionally, hemp fibers have been used in textiles and ropes manufacturing. More recently, they have gained popularity in applications as a building materials and biofuels. Hemp's total biomass per ha is comparable to that of energy crops such as poplar and switchgrass. Hemp fiber has 73-77% cellulose, 7-9% hemicellulose and 2-6% lignin, whereas the hurd contains 48%, 21-25% and 17-19%,

Table 2. Comparison between hemp and synthetic fibers Data taken from (69, 75).

Property	Hemp	Synthetic Material
Strength	Strong	Strong
Durability	Durable	More Durable
Biodegradability	Biodegradable	Not biodegradable
Versatility	More Versatile	Less Versatile
Sustainability	Sustainable	Not sustainable



Industrial hemp	Cotton
• Stronger and durable fiber	• Weaker and less durable fiber
• More fiber yield	• Less fiber yield
• Biodegradable and recyclable	• Biodegradable and recyclable
• More economic returns	• Less economic returns
• Grows faster (<120 days)	• Grows slower (>175 days)
• More sustainable, requires less inputs (water, fertilizers, and chemicals)	• Less sustainable, requires more inputs (water, fertilizers, and chemicals)
• Hemp enhances soil health	• Cotton can depletes soil nutrients
• Hemp hurd or shiv used for paper and hemp concrete	• Cotton sticks are commonly burned as a source of cooking fuel
• Lower carbon footprint	• Higher carbon footprint

Fig. 2. Competitive performance of hemp and cotton crops. Industrial hemp, a naturally resistant crop, requires less water and pesticides, saving more water against cotton. Hemp also nourishes the soil, making it a valuable environmental asset (Based on information (7, 64).

respectively. The digestible cellulosic content in hemp fibers is higher than in other energy crops (74). As a result, hemp is a superior energy crop for biochemical-based biofuel applications.

In conclusion, hemp fibers are more environmentally benign and sustainable than most synthetic fibers (Table 2). They are biodegradable, require fewer chemicals for production and have a lower carbon footprint. However, synthetic fibers continue to dominate various industries due to their adaptability, cost-effectiveness and specialized performance qualities. The decision between hemp and synthetic fibers is frequently influenced by the intended application, environmental concerns and consumer preferences.

Hemp fiber-based composite Materials

Hemp is widely used as a raw material in composite synthesis because of its exceptional mechanical qualities and environmental benefits. Hemp-based natural composites are made by combining hemp plant fibers with a matrix material, usually a polymer, to create a composite with improved qualities. These fibers are lightweight and possess high tensile strength; making them ideal for reinforcement in composite materials (75). Several composite forming techniques using hemp fibers are under investigation, including film stacking, manual winding, resin transfer molding and hand layup. Hemp fibers have a high tensile strength of roughly 1110 Mpa, therefore thermoplastic, thermoset and biodegradable matrices have good mechanical properties (76). In comparison, thermoplastic matrices outperform thermoset matrix composites in terms of corrosion resistance, cost-effectiveness, high specific strength and recycling. However, a key challenge in using natural fiber as reinforcement in thermoplastic composites is the heat degradation of fibers; thus, the temperature is controlled below 230 °C (75, 77).

Natural fibers have a higher modulus than thermoplastics, resulting in composites with enhanced stiffness. Natural fiber-reinforced thermoplastic composites exhibit improved mechanical properties, flexibility and toughness. However, the random fiber orientation in these limits property enhancement compared to thermoset composites. Hemp fiber has specific applications in fiber composites, including automobiles, construction, golf clubs, tennis rackets and skis. These composites have the potential to enhance product performance and durability (78). Although still in its early stages of development, hemp fiber utilization in fiber composites is a promising area of research. As technology advances, its applications are expected to expand further.

Challenges in industrial hemp cultivation and fiber processing

The presence of the key photoactive component, THC, poses a substantial obstacle to the legalization and widespread use of hemp. This remains concern despite global discussions on the research, development and economic potential of hemp products. Hemp production is further complicated by its illegal use and difficulty distinguishing between drug and fiber types (79). Hemp plants contain two types of cannabinoids: THC and cannabidiol (CBD), both are pharmacologically active compounds (79). Most developed nations restrict industrial hemp cultivation to varieties with less than 0.3% THC content (81, 82), while European countries impose a stricter limit of 0.2% (81). Hence, high-standard laboratories are required to differentiate between drug and fiber-type plants (83). Cannabinoids are quantified using specialized techniques such as gas chromatography (GC), mass spectrometry (MS), GC-flame ionization detection, high-

performance liquid chromatography (HPLC) and liquid chromatography (84). These techniques, however, are costly and time - consuming, prompting recent research into reducing analysis time and sample quantity requirements.

China is the world's leading hemp producer, producing over 70% of global production followed France at nearly 25%. Globally, over thirty countries produce industrial hemp (80, 82). Pakistan has favourable conditions for high-quality growth of hemp without need of special interventions. Hemp is widely grown in most parts of the Northern Province, Potohar Plateau, some parts of upper Punjab and across Islamabad, the capital city (10, 84). Nevertheless, there is a lack of sufficient germplasm, site-specific production technology and hemp cultivation policy, which might limit its large production. Moreover, a lack of awareness and expertise among farmers and entrepreneurs regarding hemp cultivation and processing, as well as the insufficient infrastructure and technology for efficient extraction and processing of hemp fibers further hinder large-scale production. Moreover, low market demand and competition with other fibers remain significant challenges that need to be addressed in the near future.

Conclusion and future research directions

The textile industry, a highly polluting sector globally, requires a more sustainable alternative from fiber production to final product development. Hemp crop is a sustainable alternative to cotton in fiber production due to its ability to produce high-quality fiber. Furthermore, its superior resource efficiency, climate resilience and environmental benefits make hemp fiber particularly attractive to this sector. Hemp produces valuable biomass with the minimum cost of production in terms of fertilizer, water consumption and pest control. It can be used to make a wide variety of products, including clothing, textiles, construction materials and biofuels. As a natural fiber, hemp offers advantages over natural fibers, including greater resistant to harsh weather and UV rays and higher durability and anti-microbial properties. Pakistan's economy is in need of a long-overdue boost and recent research and recommendations on industrial hemp production and legalization present a promising opportunity. Investors, policymakers and researchers should learn from the experiences of other countries, especially China, Canada, France and other hemp exporting countries, while implementing strict control policies. Given its potential for sustainable growth and innovation, hemp research is essential. The low production cost of industrial hemp makes it affordable for small-scale farmers, particularly those seeking environmentally friendly cropping systems. However, the cultivation of hemp varieties suitable to local climate conditions and specific applications is pivotal for its success in the country. Moreover, germplasm screening for low THC content, variety development for higher fiber production and agronomic studies are highly recommended to ensure the large-scale cultivation and utilization of industrial hemp.

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Authors' contributions

SH and GMA conceived the idea and prepared outlines, MIFI, MAJ and AI gathered the data and wrote intial draft. SHGMA and AF. reviewed and revised the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of Interest: Authors do not have any conflict of interest to declare.

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