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The Physicochemical Properties of Hemp Fibers and Their Applications in the Textile Industry

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Abstract This study explores the physicochemical properties of hemp fibers and their potential applications in the textile industry, including the effects of various chemical and physical treatments on the quality and performance of hemp fibers. The research found that after chemical treatments with sodium hydroxide and potassium permanganate, the fineness, flexibility, and tensile strength of hemp fibers were significantly improved. The combination of microwave energy and deep eutectic solvent treatments effectively removed non-cellulosic substances, increased cellulose content, and improved thermal stability. Processing hemp fibers using industrial flax equipment demonstrated high processing efficiency, with fiber quality comparable to flax. Economic analysis suggests that hemp fibers could become a more sustainable and cost-effective alternative to cotton in the textile industry. The results indicate that with appropriate chemical and physical treatments, hemp fibers can meet the quality standards required for high-performance textile applications. This study highlights the potential of hemp as a sustainable and economically viable alternative to traditional textile fibers, such as cotton and flax, promoting the use of green biomaterials in the textile industry.

Keywords Hemp fibers; Textile industry; Chemical modification; Sustainability; Fiber quality; Economic viability

1 Introduction

Natural fibers have been integral to the textile industry for centuries, offering a sustainable alternative to synthetic fibers. The growing environmental concerns associated with synthetic fibers, such as pollution and non-biodegradability, have led to an increased interest in natural fibers. These fibers, including cotton, flax, and hemp, are biodegradable and have a lower environmental impact compared to their synthetic counterparts (Gedik and Avinc, 2020; Schumacher et al., 2020; Malabadi et al., 2023). The textile industry, one of the highest polluting industries globally, is now exploring environmentally friendly textiles to mitigate its ecological footprint (Schumacher et al., 2020). Natural fibers are not only sustainable but also offer unique properties such as comfort, breathability, and biodegradability, making them increasingly important in the move towards sustainable production (Kocić et al., 2019; Gedik and Avinc, 2020).

Hemp, historically used for various applications including textiles, has seen a resurgence in recent years due to its environmental benefits and favorable properties. The cultivation of industrial hemp was recently approved in the United States through the 2018 Farm Bill, which has spurred renewed interest in its use (Schumacher et al., 2020). Hemp fibers are known for their strength, durability, and antibacterial properties, making them a valuable raw material for the textile industry (Musio et al., 2018; Malabadi et al., 2023). Unlike cotton, hemp requires fewer pesticides and less water, contributing to its lower environmental impact. The legal developments in hemp cultivation have further facilitated its re-emergence as a key textile material, offering a sustainable alternative to traditional fibers (Schumacher et al., 2020; Malabadi et al., 2023).

This study aims to explore the physicochemical properties of hemp fibers and their applications in the textile industry. By examining the sustainable production processes of hemp, fiber characteristics, and potential uses, the research seeks to highlight the advantages of integrating hemp into textile manufacturing. The study will cover the historical background of hemp usage, recent advancements in cultivation and processing, as well as the economic and environmental benefits of hemp fibers. It will also discuss the challenges and opportunities faced in adopting hemp in the textile industry, providing a comprehensive overview of its potential as a sustainable textile material.

2 Hemp Fiber Composition and Structure

2.1 Chemical composition: cellulose, hemicellulose, lignin, and pectin

Hemp fibers are primarily composed of cellulose, hemicellulose, lignin, and pectin. The cellulose content in hemp fibers is a critical factor influencing their mechanical properties and suitability for textile applications. Studies have shown that the cellulose content in hemp fibers can vary significantly, with values ranging from 64.2% to 70.5% (Zommere et al., 2013). This high cellulose content contributes to the strength and durability of the fibers. Hemicellulose content in hemp fibers ranges from 16.99% to 23.79%, while lignin content varies between 5.68% and 7.96%. Pectin, although present in smaller quantities (1.37% to 1.64%), plays a crucial role in the fiber's structural integrity and interaction with other components.

Chemical treatments, such as alkali treatment, can significantly alter the chemical composition of hemp fibers. For instance, selective chemical treatments have been shown to increase the α-cellulose content from 75% to 94% by removing non-cellulosic components like pectin and hemicellulose (Wang et al., 2007). This purification process enhances the fiber's crystallinity and mechanical properties, making them more suitable for high-performance textile applications.

2.2 Microstructure: fiber morphology and crystalline structure

The microstructure of hemp fibers is characterized by a unique morphology and crystalline structure. Microscopy studies have revealed that hemp fibers possess an interconnected web-like structure, with nanofibers forming bundles of cellulose fibers with widths ranging between 30 and 100 nm and lengths of several micrometers (Wang et al., 2007). This intricate morphology contributes to the fiber's mechanical strength and flexibility.

The crystalline structure of hemp cellulose is typically semicrystalline, as evidenced by wide-angle X-ray diffraction (XRD) patterns (Bonatti et al., 2004). The relative crystallinity of hemp fibers can be significantly enhanced through chemical and mechanical treatments. For example, the crystallinity of untreated hemp fibers, initially at 57%, can be increased to 71% after such treatments (Wang et al., 2007). This increase in crystallinity is associated with improved mechanical properties and thermal stability.

2.3 Comparative analysis with other natural fibers (e.g., cotton, flax)

When compared to other natural fibers such as cotton and flax, hemp fibers exhibit several distinct advantages and similarities. Both flax and hemp fibers have similar biological, physical, chemical, and mechanical properties, influenced by factors such as cultivation conditions and initial treatment methods (Zommere et al., 2013). The cellulose content in flax fibers ranges from 64.57% to 75.38%, which is comparable to that of hemp fibers. However, the hemicellulose and lignin contents in flax fibers are slightly different, with hemicellulose ranging from 12.97% to 26.07% and lignin from 4.78% to 7.44%.

In terms of mechanical properties, the high cellulose content and degree of polymerization in both hemp and flax fibers contribute to their strength and durability. However, the presence of non-structural components like pectin and the microfibril angle can influence the overall performance of the fibers (Marrot et al., 2013). For instance, hemp fibers have been shown to have a significant amorphous matrix polymer rate, which can affect their mechanical properties compared to flax.

3 Physicochemical Properties of Hemp Fibers

3.1 Mechanical properties: tensile strength, elasticity, and rigidity

Hemp fibers exhibit notable mechanical properties, making them suitable for various applications, including reinforcement in composite materials. The tensile strength and elasticity of hemp fibers are influenced by environmental conditions, particularly moisture. Studies have shown that water sorption significantly affects the tensile stiffness and strength of hemp fibers, with a remarkable increase in fiber stiffness of up to 250% under cyclic loading conditions (Placet et al., 2012). Additionally, the mechanical properties of hemp fiber composites can be enhanced through treatments such as alkali treatment, which improves tensile strength and impact resistance (Frącz et al., 2021). However, moisture absorption can lead to a reduction in mechanical properties, as observed in water-immersed hemp fiber composites (Dhakal et al., 2007; 2018).

3.2 Thermal properties: thermal conductivity and stability

Hemp fibers also possess favorable thermal properties, which are essential for applications requiring thermal insulation. The thermal conductivity of hemp fiber composites increases linearly with density, providing good insulating properties compared to traditional materials like glass wool (Sair et al., 2018) (Figure 1). Thermal stability is another critical aspect, with studies indicating that hybrid composites of hemp and polyethylene terephthalate (PET) exhibit improved thermal stability due to the presence of PET fibers (Ahmad et al., 2018). Moreover, cryogenic treatment of hemp fibers has been shown to enhance thermal stability by increasing cellulose exposure in the primary cell wall (Thomas et al., 2023).

3.3 Moisture absorption and retention capabilities

Moisture absorption and retention are significant factors affecting the performance of hemp fibers in various applications. Hemp fibers have a high cellulose content, leading to increased moisture uptake, which follows Fickian behavior at room temperature (Dhakal et al., 2007; 2018). The moisture sorption properties can be modified through chemical treatments. For instance, oxidized hemp fibers exhibit reduced moisture sorption and water retention capacity, making them suitable for advanced applications like sportswear (Milanovic et al., 2021). Additionally, the incorporation of compatibilizing agents in hemp fiber composites can mitigate the effects of moisture absorption (Dolza et al., 2022).

3.4 Biodegradability and environmental sustainability

Hemp fibers are highly regarded for their biodegradability and environmental sustainability. They offer an eco-friendly alternative to conventional, petroleum-based composites. Biocomposites made from hemp fibers and biodegradable polymers, such as polycaprolactone (PCL) and poly(butylene succinate-co-adipate) (PBSA), demonstrate enhanced mechanical properties while maintaining environmental efficiency (Dhakal et al., 2018; Dolza et al., 2022). The biodegradability of hemp fibers, combined with their ability to be processed into sustainable materials, underscores their potential for reducing environmental impact in various industries.

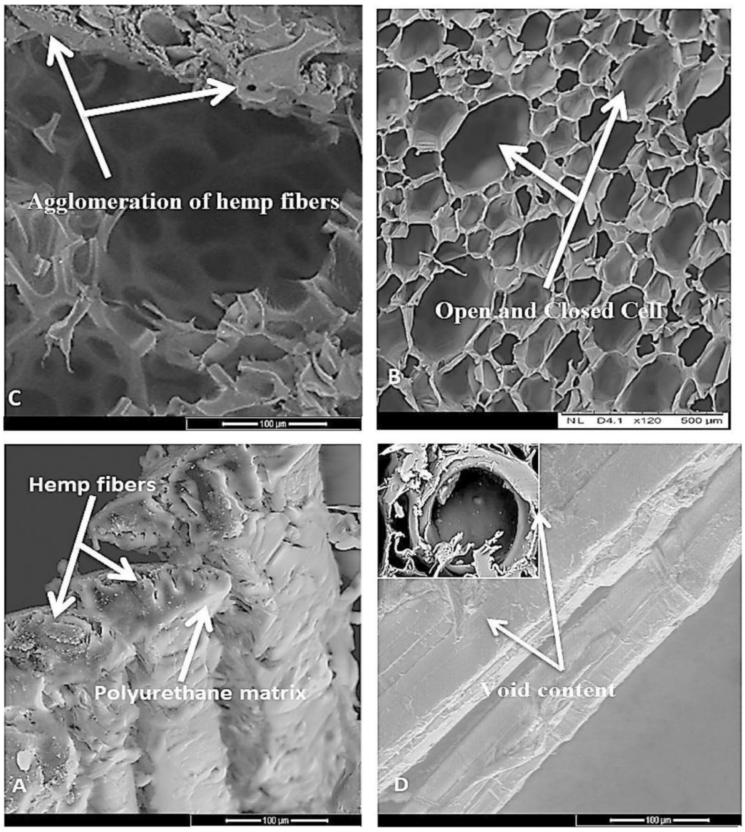

Figure 1 Scanning electron micrographs for hemp fibers (D), hemp fibers covered by the PU matrix (A), Polyurethane matrix (B) and composite at 30% in fiber content (Adopted from Sair et al., 2018)

4 Processing Techniques and Treatment of Hemp Fibers

4.1 Fiber extraction methods: traditional retting vs. modern techniques

Fiber extraction from hemp involves several methods, each with its own advantages and limitations. Traditional retting methods, such as dew retting and water retting, have been widely used. Dew retting, which relies on natural environmental conditions, is a common practice in regions with favorable climates, such as Northwest France and the Netherlands. This method can be effective but is highly dependent on weather conditions, which can lead to variability in fiber quality (Placet et al., 2017; Réquilé et al., 2021). Water retting, on the other hand, involves submerging hemp stalks in water to facilitate microbial activity that breaks down pectins, allowing fibers to be separated. While effective, water retting generates significant wastewater and can be time-consuming (Sadrmanesh and Chen, 2018).

Modern techniques aim to address these limitations. Enzymatic retting, for instance, uses specific enzymes to break down pectins more efficiently and with less environmental impact. Steam explosion and mechanical decortication are other modern methods that have been explored. Steam explosion involves treating hemp stalks with high-pressure steam, which disrupts the plant structure and facilitates fiber separation. Mechanical decortication uses mechanical means to separate fibers from the woody core, offering a faster and more environmentally friendly alternative to traditional retting (Sadrmanesh and Chen, 2018; Zimniewska, 2022) (Figure 2).

4.2 Chemical and enzymatic treatments for enhanced properties

Chemical and enzymatic treatments are employed to enhance the properties of hemp fibers, making them more suitable for textile applications. One innovative approach involves the use of combined microwave energy (MWE) and deep eutectic solvents (DES) for degumming hemp fibers. This method effectively removes lignin, pectin, oil, and wax, resulting in fibers with higher cellulose content and improved thermal stability. The treated fibers also exhibit a higher ultraviolet protection factor (UPF) compared to traditional alkali-treated fibers (Ahmed et al., 2022).

Enzymatic treatments, such as those using pectinases and other specific enzymes, can selectively degrade pectins and hemicelluloses, improving fiber fineness and flexibility. These treatments are often combined with mechanical processes to achieve optimal results. For example, bio-degumming, which uses biological agents to remove non-cellulosic components, has been shown to enhance the quality of hemp fibers for high-performance applications (Musio et al., 2018; Placet et al., 2018).

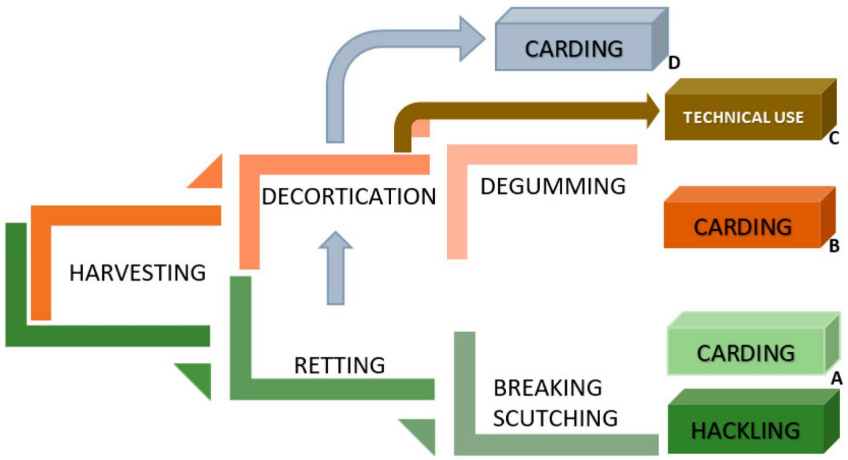

Figure 2 Schematic value chains of hemp fibre extraction for textile purposes (Adopted from Zimniewska, 2022)

Image caption: (A) (green line)—traditional order of processes including straw retting, (B) (orange line)—with use of decortication of straw excluding retting with use of degumming, (C) (orange-brown line)—decortication of raw non-retted straw for technical use of the fibres, (D) (green-grey line)—with use of decortication following retting aimed at preparation of fibre for cottonisation or woolenisation (own elaboration) (Adopted from Zimniewska, 2022)

4.3 Innovations in spinning and weaving hemp fibers

Recent innovations in spinning and weaving techniques have significantly improved the quality and applicability of hemp fibers in the textile industry. Traditional spinning methods, such as linen spinning, have been adapted to process hemp fibers, but modern techniques are pushing the boundaries further. For instance, the use of industrial flax equipment for processing hemp has shown promising results. This approach leverages existing technology to produce high-quality long fibers suitable for textile applications. Studies have demonstrated that field-retted hemp can be processed on flax scutching lines, yielding fibers with tenacity comparable to flax (Vandepitte et al., 2020).

Additionally, advancements in spinning technology, such as the development of natural binder systems and optimized spinning parameters, have enhanced the mechanical properties of hemp yarns. These innovations enable the production of finer and stronger yarns, which can be woven into high-quality fabrics. The integration of these advanced techniques ensures that hemp fibers can meet the stringent requirements of modern textile applications, including high-performance composites and sustainable fashion (Placet et al., 2018; Mazian et al., 2020).

5 Applications of Hemp Fibers in the Textile Industry

5.1 Apparel: clothing, footwear, and accessories

Hemp fibers have been traditionally used in the production of various apparel items due to their high strength, durability, and comfort. The fibers are particularly valued for their breathability and moisture-wicking properties, making them ideal for clothing, footwear, and accessories (Figure 3). Recent advancements in the chemical modification of hemp fibers have further enhanced their quality, making them finer, more flexible, and sometimes even improving their tensile properties (Kostić et al., 2008). This has allowed for the production of high-quality garments that are not only durable but also comfortable to wear. Additionally, the eco-friendly nature of hemp fibers aligns with the growing consumer demand for sustainable fashion (Peji et al., 2020; Promhuad et al., 2022).

5.2 Home textiles: upholstery, curtains, and bedding

Hemp fibers are also extensively used in home textiles, including upholstery, curtains, and bedding. Their high specific strength and stiffness make them suitable for heavy-duty applications such as upholstery. Moreover, the natural aesthetic of hemp fibers adds a rustic and organic feel to home decor items. The biodegradability and non-toxic nature of hemp fibers make them a safe choice for household textiles, contributing to a healthier living environment (Crini et al., 2020; Peji et al., 2020). The ability of hemp fibers to be combined with various polymers to create composites further expands their application in home textiles, providing enhanced durability and functionality (Shahzad, 2012).

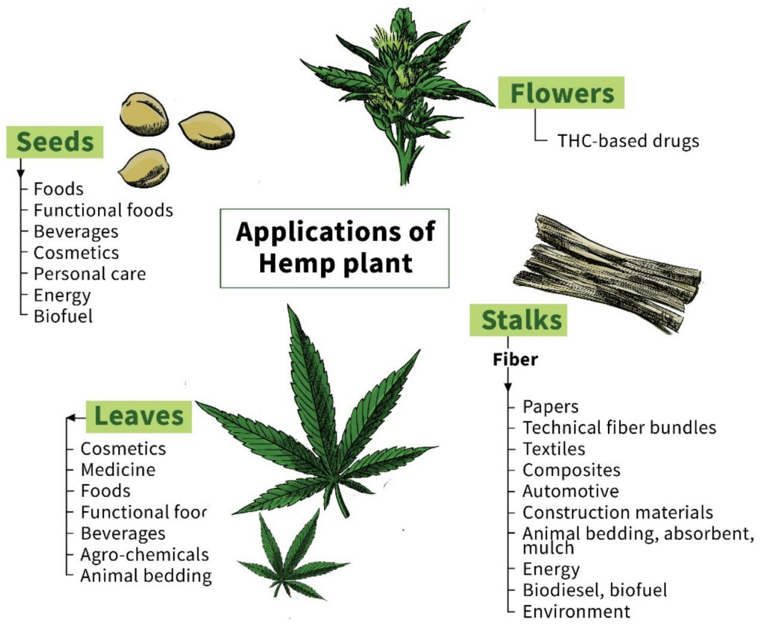

Figure 3 Applications of hemp plant components as seeds, flowers, leaves and stalks (Adopted from Promhuad et al., 2022)

5.3 Technical textiles: composite materials, insulation, and reinforcement

In the realm of technical textiles, hemp fibers have shown great promise, particularly in the development of composite materials, insulation, and reinforcement applications. The mechanical properties of hemp fibers, which are comparable to those of glass fibers, make them an excellent choice for reinforcement in composite materials (Shahzad, 2012). These composites are used in various industries, including automotive and construction, where high performance and sustainability are crucial (Musio et al., 2018; Kausar and Ahmad, 2023). Additionally, hemp fiber composites have been found to possess good insulating properties, making them a viable alternative to traditional insulation materials like glass wool and mineral wool (Sair et al., 2018). The ongoing research and development in the field of hemp fiber composites continue to unlock new applications and improve their performance (Manaia et al., 2019; Promhuad et al., 2022).

6 Case Studies

6.1 Success stories of hemp textiles in fashion brands

Hemp textiles have been increasingly adopted by various fashion brands due to their sustainable properties and superior performance characteristics. For instance, several high-profile brands have integrated hemp fibers into their product lines, showcasing the material's versatility and eco-friendliness. The resurgence of hemp in the textile industry is driven by its high yield and lower environmental impact compared to traditional fibers like cotton (Schumacher et al., 2020). Additionally, the superior strength and durability of hemp fibers make them an attractive option for high-quality garments (Promhuad et al., 2022) (Table 1). The global market for hemp textiles is expanding, with significant contributions from countries like China, Europe, and Canada, which are leading producers and exporters of hemp products (Crini et al., 2020).

6.2 Hemp fiber usage in eco-friendly textile products

Hemp fibers are increasingly being used in eco-friendly textile products due to their sustainable nature and minimal environmental footprint. The textile industry, known for its high pollution levels, is turning to hemp as a viable alternative to reduce its ecological impact. Hemp requires fewer pesticides, less water, and has a higher yield per hectare compared to cotton, making it a more sustainable option (Schumacher et al., 2020). Moreover, the combined physical and chemical modifications of hemp fibers enhance their mechanical and barrier properties, making them suitable for a wide range of eco-friendly textile applications (Promhuad et al., 2022). The use of innovative degumming processes, such as microwave energy and deep eutectic solvent treatment, further enhances the quality and sustainability of hemp fibers (Ahmed et al., 2022).

6.3 Comparative analysis of hemp with synthetic fibers in applications

When comparing hemp fibers with synthetic fibers, several key differences emerge in terms of environmental impact, performance, and applications. Hemp fibers are derived from a renewable resource and have a significantly lower environmental footprint compared to synthetic fibers, which are petroleum-based and contribute to pollution and waste (Schumacher et al., 2020). In terms of performance, hemp fibers offer superior strength, durability, and UV protection, making them suitable for a variety of textile applications (Ahmed et al., 2022). Additionally, the thermal stability and chemical composition of hemp fibers, which can be enhanced through advanced processing techniques, make them a competitive alternative to synthetic fibers. The holistic supply chain view of hemp production also highlights its economic viability and potential to reduce costs associated with agricultural activities (Schumacher et al., 2020).

7 Advantages and Challenges in Using Hemp Fibers

7.1 Benefits: sustainability, durability, and versatility

Hemp fibers offer numerous advantages that make them highly attractive for the textile industry. One of the primary benefits is their sustainability. Hemp is a high-yielding crop that requires fewer pesticides and less water compared to other traditional textile crops like cotton, making it an environmentally friendly option (Crini et al., 2020; Schumacher et al., 2020). Additionally, hemp fibers are known for their durability and strength, which are superior to many other natural fibers. This makes them suitable for a wide range of applications, from clothing to high-performance composites (Musio et al., 2018; Promhuad et al., 2022). The versatility of hemp fibers is another significant advantage. They can be used in various industries, including textiles, construction, automotive, and even food packaging, due to their mechanical, thermal, and acoustic properties (Pejić et al., 2020; Sahi et al., 2021).

Table 1 Related researches on application of hemp fiber in textile products (Adopted from Promhuad et al., 2022)

Types/Additive/Composite Material	Processing Technology	Fabric Characteristic	Reference
Yellow colorant (Buddleja officinalis)	traditional techniques of dyeing from communities of Yunnan, China equipped with natural mordant treatment	Optimum dying achieved at pH 5, 60 °C for 90 min. Natural mordant treatment improved the yellowness and color fastness was maintained, indicating a good combination process between natural mordant treatment and natural yellow dyeing.	Yan et al., 2021
Graphited knitting hemp fabric (GKHF)	Furnace filled with a nitrogen atmosphere, heating at 800 °C	GKHF showed a great air permeability, water vapor and moisture, as well as remarkable static stability in the range of 0.5 to 480 KPa.GHKF detected a variety of static pressure and physiological signals for health monitoring, rehabilitation, and convenience sport stuff.	Liu et al., 2021
Feretiko hemp fiber (woven)	Thermal comfort evaluated by thermal manikin	Clothing insulation of Feretiko was 0.20, very close to ASHRAE standard 55-2013 for clothing insulation of a long-sleeve (0.25 clo). The air permeability was also high (2600 L/m2 s).	Tama et al., 2020
Hemp fabric and epoxy resin composite	Composite technology: plate and Impregnated Fiber Bundle Test (IFBT)	The pores of composite are low observed in tomography with the similar fiber volume for all the composite. Untwisting reduced the tenacity at break of the rovings. Low-twisted rovings of composite resulting in similar tensile strength of best flax in the range of 150-200 MPa.	Corbin et al., 2020
Hemp fabric and vinyl ester composite	Chemical treated woven hemp fabric: NaOH and fire retardant (FR)	The treatment increase weight, thickness, density and yarn crimp, while decreased mechanical properties of woven fabric due elimination of hemicellulose and lignin by NaOH and hydrolyzation of cellulose by FR.The treatment increased thermal stability and limiting oxygen index values indicating fire retardant properties was improved.	Misnon et al., 2018
Hemp fiber, Lyocell and PLA composite	Wrap spinning process	Lyocell addition improve tensile strength of hemp/PLA composite-based fabric and lesser fiber pull-outs appears, but did not affect on water absorption.	Baghaei et al., 2016
PLA	Compression molding technique	Reinforcement improved flexural and charpy detected for fibre volume fraction of 20 and 30%, and decreased at 40%. The impact strength increased by increasing reinforcement content. 30% reinforcement showed the best creep behavior	Durante et al., 2017

7.2 Challenges: processing costs, fiber quality variability, and market acceptance

Despite the numerous benefits, there are several challenges associated with the use of hemp fibers. One of the primary challenges is the high processing costs. The extraction and processing of hemp fibers involve complex and often expensive methods such as retting, decortication, and degumming, which can be cost-prohibitive (Ahmed et al., 2022; Zimniewska, 2022). Another challenge is the variability in fiber quality. Factors such as the hemp variety, cultivation conditions, and processing methods can significantly affect the quality of the fibers, leading to inconsistencies in the final product (Musio et al., 2018; Vandepitte et al., 2020). Market acceptance is also a significant hurdle. Although there is a growing interest in sustainable materials, the adoption of hemp fibers in mainstream textile markets is still limited due to a lack of awareness and established supply chains (Schumacher et al., 2020).

7.3 Strategies for overcoming challenges and enhancing adoption

To overcome these challenges and enhance the adoption of hemp fibers in the textile industry, several strategies can be employed. First, optimizing agronomic practices and processing techniques can help reduce costs and improve fiber quality. For instance, using modern flax processing equipment for hemp can increase efficiency and yield (Vandepitte et al., 2020). Additionally, innovative methods such as combined microwave energy and deep eutectic solvent treatment have shown promise in producing high-quality hemp fibers more sustainably and cost-effectively (Ahmed et al., 2022).

Second, increasing research and development efforts to standardize fiber quality and develop new applications can help address variability issues. Selecting and breeding hemp varieties specifically for fiber production can also contribute to more consistent quality (Musio et al., 2018).

Finally, raising awareness and educating consumers and industry stakeholders about the benefits of hemp fibers can help improve market acceptance. Promoting the environmental and performance advantages of hemp over traditional fibers like cotton can drive demand and support the development of a more robust supply chain (Crini et al., 2020; Schumacher et al., 2020).

8 Future Prospects and Research Directions

8.1 Innovations in fiber treatment and processing

Recent advancements in hemp fiber treatment and processing have shown promising results in enhancing the quality and applicability of hemp fibers in the textile industry. For instance, the combined use of microwave energy and deep eutectic solvents (DES) has been demonstrated to effectively degum hemp fibers, resulting in higher cellulose content and improved thermal stability compared to traditional alkali-based processes (Ahmed et al., 2022). Additionally, the cottonization of hemp fibers through alkali treatment has been shown to produce textile-grade fibers suitable for cotton dry spinning systems, thereby eliminating traditional, time-consuming retting processes (Sahi et al., 2021). These innovations not only improve the efficiency of fiber processing but also enhance the mechanical properties of the fibers, making them more suitable for high-performance textile applications.

8.2 Potential applications in high-performance and smart textiles

Hemp fibers have shown great potential for use in high-performance and smart textiles due to their inherent mechanical, thermal, and acoustic properties. Studies have indicated that hemp fibers can achieve properties comparable to high-quality flax fibers, making them suitable for high-performance composite applications (Musio et al., 2018). Furthermore, the use of hemp fibers in technical textiles, such as load-bearing woven geotextiles and mid-range load-bearing composite reinforcements, has been explored, demonstrating their potential in various industrial applications (Grégoire et al., 2020). The development of smart textiles incorporating hemp fibers could also be a future research direction, leveraging their natural properties for applications such as UV protection and thermal regulation (Ahmed et al., 2022).

8.3 Role of hemp in sustainable textile manufacturing

Hemp is increasingly recognized as a sustainable alternative to traditional textile fibers like cotton. The cultivation of hemp requires fewer resources, such as water and pesticides, and yields higher fiber output per hectare compared to cotton (Schumacher et al., 2020). This makes hemp an economically viable and environmentally friendly option for textile manufacturing. Additionally, the use of hemp fibers in composite materials and packaging further underscores their versatility and sustainability (Promhuad et al., 2022). Future research should focus on optimizing agronomic practices and processing techniques to maximize the yield and quality of hemp fibers, thereby supporting the growth of a sustainable textile industry (Pejić et al., 2020; Vandepitte et al., 2020). The integration of hemp fibers into the textile value chain can significantly reduce the environmental footprint of textile production, promoting a more sustainable and eco-friendly industry.

9 Conclusions

The research on the physicochemical properties of hemp fibers has revealed several significant findings. Hemp fibers exhibit unique thermal properties, which are influenced by their capillary structure and surface characteristics, making them suitable for various textile applications. The use of industrial flax equipment for processing hemp has shown that hemp can yield high-quality fibers with tenacity comparable to flax, indicating its potential for high-value textile applications. Additionally, the combination of microwave energy and deep eutectic solvent treatment has proven effective in producing pure hemp cellulose fibers with enhanced thermal stability and UV protection. The mechanical and physical properties of hemp fibers can be significantly improved through various treatments, such as oxidation and alkali treatment, making them suitable for sportswear and other advanced textile applications.

The findings from this research have several implications for the textile industry. The superior strength and thermal properties of hemp fibers make them an excellent alternative to traditional fibers like cotton and flax. The ability to process hemp using existing flax equipment can streamline production and reduce costs, making hemp a more viable option for textile manufacturers. The environmental benefits of hemp, such as biodegradability and sustainability, align with the growing demand for eco-friendly materials in the textile industry. The development of advanced treatments to enhance the properties of hemp fibers further expands their potential applications, including sportswear and high-performance composites.

Future research should focus on optimizing agronomic practices and post-harvest processing techniques to maximize the yield and quality of hemp fibers. Genotype selection and harvest mechanization are critical areas that need further exploration to improve processing efficiency and fiber quality. Additionally, more studies are needed to fully understand the impact of various treatments on the mechanical and thermal properties of hemp fibers, particularly in the context of different textile applications. Research on the integration of hemp fibers into composite materials and their performance in real-world applications will also be valuable in expanding the use of hemp in the textile industry. Finally, exploring innovative applications and modifications of hemp fibers can lead to the development of new, sustainable textile products that meet the evolving demands of consumers.

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Conflict of Interest Disclosure
The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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