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(REVIEW ARTICLE)

Industrial *Cannabis sativa*: Role of hemp (fiber type) in textile industries

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Abstract

This review paper highlights the importance and role of hemp fibre in textile industries. In recent years, there has been a resurgence of interest in hemp as a sustainable and versatile textile fibre in fashion and textile industry. Hemp is a sustainable and environmental friendly crop that can provide valuable raw materials to a large number of industrial applications. Hemp fibre is very strong compared with other natural fibres such as cotton, flax and nettle. The cultivation of hemp has significantly less environmental impact compared to cotton. The industrial hemp contains primary and secondary fibres of which the primary fibres are utilisable for the textile end use. Hemp has been the mostly blended with cotton and synthetic fibres due to barriers in the industrial process of the production of full hemp-based textiles. Hemp clothing is stronger and more durable than cotton clothing and does not deform as easily. Apparel made from hemp merges easily with dyes and does not discolour easily. Hemp has outstanding antibacterial properties that surpass those of cotton and also any other natural fibre. Hemp textile fibre is hypoallergenic and has natural antimicrobial properties, making it an excellent choice for individuals with sensitive skin. However, despite its many benefits, hemp is still relatively expensive in India compared to other cellulosic fibres such as cotton, linen, and rayon etc. Hemp has a great cultural and historical value in India because it has been grown and used here for thousands of years. This cultural history can be conserved and honoured by using hemp in the fashion and textile business.

Keywords: Bast fibres; Biodegradable; Cotton; Hemp fabric; Hemp Fabric Lab; Industrial *Cannabis sativa*; India; Textile

1. Introduction

Industrial *Cannabis sativa*-Hemp (fibre type) is a herbaceous annual plant (family *Cannabaceae*) that has a 4- to 8-month life cycle, is naturally dioecious, reproduces via seed propagation grown for the production of fibre, seed and oil [1-39, 40]. Hemp seeds are used as a functional food and medicine since it contains Cannabidol (CBD), and very low levels (0 to 0.3% dry wt) of Λ9-tetrahydrocannabinol (THC) [1-37]. The growth and reproductive cycle progression of hemp is photoperiod-sensitive. Hemp (*Cannabis sativa* L.) is a multi purpose crop that has been investigated for its potential use in phytoremediation of heavy metals, radionuclides, organic contaminants, as a feedstock for biochar and bioenergy production [1-65]. Hemp plant also provides many raw materials that are valuable to various industries perhaps even more so than cotton [1-68]. In fact, it is estimated that hemp currently has over 20,000 different uses [1-45]. The plant is grown extensively to make textiles, rope, food, paper, personal care products, environmentally friendly building materials, hempcrete and fuel [1-68]. Hemp fibres have several promising features [1-39]. Specifically, they are set apart from other fibres by their aseptic properties, high absorbency, protection against UV radiation, and no allergenic effect [1-69]. Hemp is a valuable raw material for the textile industry, as well as for other industries [1-40]. It is a robust plant that needs almost no pesticides and less water compared to cotton when cultivating [1-40]. Hemp is durable, breathable and very tear-resistant [1-40]. At first glance it seems that hemp does not have any disadvantages compared to other natural fibres. It even shows benefits over cotton as a raw material when it comes to several factors, such as higher UV-

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resistance [1-40]. Hemp fabrics are known to be highly absorbent, breathable, warm and long lasting [1-69]. Hemp fibre has served humanity for thousands of years to create textiles, fabrics, ropes, yarns, rugs, and canvas [1-68]. The fibre can be spun, then woven or knitted into many fabrics suitable for durable and comfortable clothing [1-69].

Traditionally, hemp as a fibre plant has been used for the production of apparels, fabrics, papers, cordages and building materials [1-40]. The hurds, as waste by-product of fibre production, were used for bedding of animals, the seeds for human nutrition, e.g., as flour, and the oil for a wide range of purposes, from cooking to cosmetics [1-40]. Hemp has also been an important crop throughout human history for medicine [1-40]. Other more recent applications include materials for insulation, furniture, automotive composites for interior applications, motor vehicle parts, bio-plastics, jewellery and fashion sectors, animal feed, animal bedding, energy and fuel production [1-40]. Foods containing hemp seed and oil are currently marketed worldwide for both animal and human nutrition [1-40]. They also find applications in beverages and in neutraceutical products [1-38]. Hemp oil is also used for cosmetics and personal care items, paints, printing inks, detergents and solvents [1-40]. Currently, the construction, insulation sector, paper, textile industries, food, nutrition domains are the main markets while the cosmetics and automotive sector are growing markets [1-40]. Innovative applications, e.g., in the medical and therapeutic domains, cosmeceuticals, phytoremediation, acoustic domain, wastewater treatment, bio-fuels, bio-pesticides and biotechnology, open new challenges [1-69].

In recent years, man-made fibres have been largely replaced by natural fibres as a reinforcement in polymer composites [1-69]. Hemp fibre has the ability to be used as reinforcement in polymer composites due to its biodegradability, and abundance [1-40]. Natural fibres offer high specific strength, stiffness, relatively low density, low cost, produce minimal pollution during processing and production, resulting in very few health concerns, hence a smaller carbon and ecological imprint [1-40]. Natural fibres are used in a wide variety of industries, including furniture, automotive, aviation, construction, marine, and aircraft [1-69]. Among natural fibres, hemp is one of the most durable, strongest, and its chemical composition makes it a best choice for use as a reinforcement in polymer composites [1-69]. Additionally, hemp fibre has a long fibre length, a high absorbency, and antimicrobial characteristics [1-69]. Hemp-hybrid materials can be easily created by combining hemp with other fibres [1-40]. This hemp-hybrid approach preserves the strength of hemp fibres while providing the comfort of a soft and refined fibre [1-69]. In the following section, the importance and superiority of hemp over cotton has been discussed.

2. Hemp Fibre Botany

The hemp plant *Cannabis sativa* Linn, referring to industrial hemp, is a high-yielding annual industrial crop grown providing fibres from hemp stalk and oil from hemp seeds [1-40]. Although hemp is a niche crop, hemp production is currently undergoing a renaissance [1-40]. Hemp plants can grow to heights of up to 5 m and can develop a tap root penetrating up to 2 m into the soil [1-40]. Under optimal weather conditions, the hemp plants grow from 6 to 10 cm per day. Industrial hemp plants can stand cold and heat. They have the ability to grow under mild and cool climates, preferably having a humid atmosphere for fibre production [1-40]. The plant endures light frosts, which outlines advantages towards other crops, e.g. corn, being able to survive cold temperatures down to -8 to -10 C° for a shorter time [1-40]. The fibre yield increases in rainy years during the growth phase of the hemp crop [1-40]. For an increase of the total growing time, early sowing is frequently done [1-40]. This fast growth is beneficial for the weed control, since the hemp crop is suppressing the weeds [1-40]. This is the reason why hemp is one of the only crops where no herbicides and pesticides need to be utilised in the cultivation [1-40]. They grow on almost every soil, taking into account that the preferred soil for hemp cultivation is sandy loam or clay loam having a pH of 6.0 to 7.0 [1-40]. The plants root system additionally has a positive effect for farmers, as it aerates and improves the soil structure [1-40].

The majority of above ground hemp biomass comes from the tall lignocellulosic plant stalk, which has been used for fibre for thousands of years [1-40]. The hemp varieties largely differ in their fibre content [1-40]. Therefore, the variant needs to be well chosen [1-40]. Often, monoecious hemp plants are used for the fibre production, as they showed an advanced uniformity in growth [1-40]. Monoecious hemp plants are plants, which have male and female organs on the same plant, but in different flowers [1-40]. On the other hand, male plants are frequently preferred for fibre use, since they grow taller, the stems are thinner, and their fibre composition is superior compared to female plants [1-40].

The hemp stalk has two main fibre types: long **bast fibres** and short **hurd fibres** [1-40]. The outer bast fibres surround the vascular tissue of the hemp stalk, whereas the hurd makes up the woody core [1-40]. Hemp is a **bast fibre**, which means fibre is extracted from the stalk of the plant [1-40]. Conventionally, hemp fibres have been extracted in a long fibre (50–60 cm) form, with a significant quantity of short fibres [1-40]. Hemp fibre, as lignocellulosic raw material, shows similarities to other bast fibres due to the comparable chemical composition of this fibre group [1-69]. Fibres extracted from fibrous plant stalks contain cellulose, hemicellulose, lignin, pectin, waxes, fats and ash [1-40]. The bast fibre, as a lignocellulosic material, consists of mainly cellulose, hemicellulose and lignin in its chemical composition [1-

40]. Hemp fibres, similar to other natural fibres, have several bottlenecks resulting from their nature, the most significant is the lack of homogeneity [1-40]. The lack of repeatability of fibre properties in batches delivered from farmers year by year is an essential disadvantage, the unevenness of fibre linear density, diameter and properties creates difficulties in the detailed design of processing the fibres and the planning of the quality of hemp products [1-40]. Hemp fibres showed a high ability for moisture absorption from surrounding areas, similar to other hydrophilic cellulosic materials [1-40]. The amount of bonded moisture by bast fibres depends on the surrounding air humidity [1-40].

Hemp fibres are found in the plants outer stem tissues, referred to as bast fibres [1-40]. This is in comparison to cotton, whose textile is found in the boll or fruit [20-40]. Bast fibres are made **of primary** and **secondary fibres** [1-40]. Primary fibers are longer and larger compared to secondary fibres [1-40]. Secondary fibres are shorter and thinner with heavily lignified cell walls [1-40]. These characteristics make the former desirable for textile use rather than the latter [1-62]. Due to their characteristics, secondary fibres are mainly used for cordage, pulp, and recycling additive purposes [1-40]. The presence of secondary fibres decreases along the stem and increases with plant age [1-40]. As bast fibres qualities change with plant age, due to the increasing presence of secondary fibre, plant harvesting time is key to increase fibre extraction quantity [1-40]. Hemp offers robust bast fibres, which are divided in primary and secondary fibres [1-40]. The primary fibres are longer and finer, whereas the secondary fibres are shorter and coarser [1-40]. For the textile use, only primary fibres can be processed, since the size of the secondary fibres makes it impossible to process and spin them into homogenous yarns [1-40]. These primary fibres are produced during the so-called vegetative growth phase of the plant before flowering [1-40]. The flowering generally occurs between 70 to 90 days after sowing, the harvest of the seeds normally happens 4 to 6 weeks later [1-40]. When cultivating fibre crops, the sowing density is higher than for seed crops, as the plants are primarily growing in height and less in width [1-68]. This leads to a higher stem yield, even if not necessarily to a higher bast fibre yield [1-40].

Nevertheless, the secondary fibres are valuable for other end-uses [1-40]. In general, the fibres have a length from 5 to 55 mm and their diameter varies from 16 to 40 μm[1-40]. They are highly moisture absorbent, offer a good breathability and thermal insulation [1-40]. The separation of secondary fibres from primary fibres has not been accomplished effectively during fibre decertification [1-40]. However, the quality variability can be reduced with the use of biological or physiochemical processing allowing for future reliable methods for industrial processing of hemp fibre [1-40]. In general, a high dry matter yield with high primary bast fibre content and low secondary bast fibre is ideal for the extraction of fibre for textile uses [1-62].

The amount of European hemp fibres used for clothing only amounts to 0.1% [1-40]. When cultivating hemp, no waste arises, since all the parts of the plant can be used for different purposes [1-40]. The shivs are a by-product during the separation of the fibre from the core [1-40]. Since the shivs are highly absorbent, the biggest market for them is in the field of animal bedding, having a share of 63 % [1-40]. Other application areas are in the use for garden mulch (19 %) and steadily growing in the construction area (16 %), e.g. as hempcrete [1-40]. Another profitable market for the farmers of industrial hemp is in the field of hemp seeds and oil [1-62].

3. Hemp and Cotton Fibre in Textile Industries

Hemp is a sustainable and environmental friendly crop that can provide valuable raw materials to a large number of industrial applications. Traditionally harvested at full flowering for textile destinations, nowadays hemp is mainly harvested at seed maturity for dual-purpose applications and has a great potential as multipurpose crop [1-64]. From the beginning of the 19th century, when the mechanical cotton thresher was invented, cotton became real competition for hemp fibres [40-64]. Cotton was naturally softer than the strong, raw hemp-linen fabrics and was considered a more luxurious fibre. As cotton production became cheaper because of labour-saving technologies, it almost completely replaced hemp in textile application by the 1920s [40-63]. With the arrival of the petroleum era and the development of the first cheap, man-made fibres, like viscose and especially nylon in 1937, hemp was effectively vanished from use in textiles [40-63]. By now cotton comprises 39% of the entire European textile market, while all man-made fibres combined comprise around 54% of the market [40-63].

Hemp is an annual plant characterised by a well-developed leaf system and is one of the fastest growing plants on Earth. Hemp fibre was indeed a common material for clothing because of its durability and versatility until the cotton industry grew stronger all over the world gained [25-50]. Hemp fibre is very strong compared with other natural fibres such as cotton, flax and nettle [1-50]. So, historically, the fibre has also long been widely used in ropes, rigging, net, and sail production [10-50]. Other advantages are its flexibility, strength, and resistance to water damage. Thus, in past centuries, hemp was extremely important to the Navy, the shipping trade, and also fishing [10-50]. Christophe Columbus sailed to America on ships rigged with hemp [10-50]. Cotton is the most used natural fibre in the textile and apparel

industry. Like hemp, its cultivation and processing has long tradition in the human history [10-50]. Over the last several decades, *Cannabis sativa* L. has become one of the most fashionable plants [10-50]. The huge ecological potential of the plants, and the diversity of raw materials that can be delivered by the plant, makes industrial hemp interesting for agriculture, medicine, food, textiles, construction and other industries [10-50]. The additional benefits of hemp growing are the suppression of weed growth, anti-erosion, reclamation properties, the ability to drain the soil of poisonous substances and heavy metals [1-50]. The ability of hemp plants to kill tough weeds results from several factors such as the tall height of the hemp plants, its thick leaves, and fact that hemp can be densely cultivated [10-50]. All the stages of the total value chain of *Cannabis sativa* L. e.g., growing, processing, use and finally recycling/ reuse/bio-refination/waste management, fulfil the principles of the above-mentioned strategies and can contribute to the fight against climate change [10-62].

The textile and clothing industry is one of the most polluting industries in the world [10-50]. Industrial hemp fibre is economically viable and has the potential to be a more environmentally friendly alternative material than cotton within the textile industry [10-50]. Currently, one of the highest produced natural fibres is cotton, which requires intensive use of water and chemicals (i.e., pesticides and fertilizers) [10-50]. Hemp fibres have several promising features. Specifically, they are set apart from other fibres by their aseptic properties, high absorbency, protection against UV radiation, and no allergenic effect [10-50]. Cotton is an extremely versatile fibre, fodder and commercial crop and grows in tropical and subtropical regions around the world [25-50]. Cotton textiles are used to make, among many other things, clothing, bed sheets, and tents [10-50]. They also make up almost the entire towel and washcloth market [25-50]. Cotton can also be used in the form of oil. For this purpose, cotton seeds are pressed to make cottonseed oil [10-50]. This oil is also a common ingredient in the production of candles, soaps, detergents and cosmetics [10-50]. The husks and shreds of cotton are also useful as a source of fertilizer, fuel, as well as animal feed [25-50]. Due to the growing demand for clothing, environment protection needs, raw-material resource requirements, and ecological implications, a sustainable and economical alternative natural fibre is required[10-62].

Hemp has been the mostly blended with cotton and synthetic fibres due to barriers in the industrial process of the production of full hemp-based textiles [10-62]. Due to the substantial lack of innovation in the industrialization of hemp fibre production, opportunities for improvements in the different stages in the production process exist [10-50]. On the other hand, cotton has been industrialized for many years, which makes it the leading natural fibre but also limiting the likelihood of process improvement [10-50]. The demand for product quality for both fibres requires a high operational production to ensure profitability [10-50]. Cotton has mass economies of scale, enabling its high productivity rate [10-50]. The requirement for a high input of hemp stalks to produce fibre has led to the investment of high straw input processing lines to allow for economies of scale [10-50]. Currently, hemp fibre extraction has long processing lines related to a high investment cost, with low mass flows and with well-known operational problems[10-69].

Textiles are easy to produce, durable, breathable, versatile, biodegradable, having strong thermal qualities. Fabrics have the best capacity ratio compared to other fibres, meaning they keep the wearer cool in the summer and warm in the winter [10-69]. Preference for hemp textiles in summer is often associated with their excellent hygienic properties [10-64]. However, natural fibres without modification do not provide good UV protection. The fabrics are also antimicrobial and hypoallergenic, as well as resistant to mould [10-62]. Fibres are also more resistant to weather and ultraviolet rays than cotton and silk. Hemp clothing is stronger and more durable than cotton clothing and does not deform as easily [10-64]. Apparel made from hemp merges easily with dyes and does not discolor easily. No difference between hemp and cotton fabrics in terms of color fastness to crocking, oily stain release, flammability, tearing strength, breaking strength and elongation [10-64]. Fibres can also be mixed with other materials to create clothing hybrids, e.g., fibres can be blended with cotton or linen for specific textures and performance [10-64].

For all these reasons, hemp is also an eco-friendly fabric for upholstery and furniture: home furnishing textiles, seating, tables, fashion accessories, mirrors, wall decorations, and decorative objects, etc [10-62]. Finished goods such as clothing, shoes and hats are made from 100% hemp or combined with other natural or synthetic fibres [10-62]. Hemp is also a viable and excellent fibre for making rugs, pure hemp carpets, and similar textiles. However, two main problems often cited are their primarily higher cost and the need for manufacturing machinery to be adapted. Cordage is an age old use for hemp fibre [10-62]. While its use in the marine world has largely being replaced by cheaper, long-lasting and lighter synthetics, and hemp rope still has its uses [10-62]. It is well known that, due to its coarser texture, hemp rope can bind against itself for better knot stability, and this is useful in some situations [20-62]. Hemp yarn is used for crafted jewellery because it is smooth, consistent, strong and comfortable in contact with the skin. Hemp twine is also interesting in crafting, gardening and landscaping [10-62].

Cotton has been the most used worldwide natural fibre due to the comfort ability and breathability of the resulting fabrics [20-50]. However, the main drawback of cotton use is that, currently, the availability of land for its cultivation is

quite limited and it is insufficient to cover the world market demand, which has an incremental tendency due to the growing sensitivity of customers on sustainable goods [10-50]. Some other drawbacks of cotton are the high amount of water consumed during cultivation, the necessity of using pesticides and the proper conditions for harvest (can only be grown in temperate-hot climates) [10-50]. For these reasons, the use of alternative natural fibres such as hemp can be blended with cotton to achieve similar or even better properties as cotton in the final product will contribute to an increase in the sustainability of the textile process [10-50, 52-60].

Hemp fibres are employed in a variety of industries, from everyday items to military uses. Rope, cordage, rugs, towels, hats, canvas, apparel, home furnishing textiles, autos, insulation products, erosion control mats, boat hulls, yachts, surfboards, military uniforms, antibacterial deodorizing function socks, construction materials such as foam concretes, and cement-based mortars are just a few of the applications [10-50]. Hemp is more sustainable, environmentally friendly and higher yielding than cotton. Even automotive giants have been using hemp plastic bio-composites to make body panels and interior components of their cars for many years [10-50]. Hemp, on the other hand, is an extremely sustainable and environmentally friendly plant and can actually fulfill many of the same roles as its cotton derived alternatives [10-50].

Hemp is actually one of the fastest growing crops in the world and can fully grow within four to 18 weeks. Cotton, on the other hand, requires much more time to complete its growth cycle - around 21 to 25 weeks [10-50]. Hemp is definitely the superior crop when it comes to reducing water consumption. In fact, cotton required more water for growth [10-50]. In many countries that rely heavily on cotton as an export product, over-cultivation of cotton has even led to desertification [10-50]. A study conducted by the Stockholm Environment Institute found that cotton takes up to 10,000 litres of water to produce 1 kg of cotton - the equivalent of a single T-shirt [20-50]. Hemp, on the other hand, requires less than half that amount of water to grow - around 2,123 litres per kilogram of usable fibre [20-50]. In conclusion, estimates suggested that for every 20 litres of water, cotton needs to grow, and hemp needs only around five [20-50]. Fabrics made from hemp can last up to 30 years on average, while fabrics made from cotton can usually last up to 10 years [10-50]. This is partly due to their high tensile strength and resistance to temperature changes and humidity [20-50]. Consequently, repeated washing does not damage hemp fabric as much as cotton. Cotton fabrics, on the other hand, gradually become thinner with each wear and wash and are more prone to tearing [20-50]. In addition, hemp fibre does not stretch out of shape, making it a suitable upholstery fabric[20-50].

Fabrics made from hemp fibres can be pulled taut and remain taut for the life of the furniture. Cotton fabrics, on the other hand, are more suitable for garments where a little stretch is desired [20-50]. Hemp and cotton are highly breathable fabrics and can reduce perspiration by effectively absorbing moisture from the skin [20-50]. In fact, fabrics made from hemp fibres are even more water absorbent than cotton, making them the best choice for the summer season [20-50]. But they can also provide warmth on cool winter nights, especially since they have better insulating properties. Thus, hemp fabrics can help keep the body cooler during summer and warmer during winter [20-50]. Even though fabrics made from hemp are not as soft as those made from cotton right from the beginning, they become softer and more comfortable with each wear and wash [20-50]. In fact, unlike cotton, hemp fibre fabrics retain their strength even when wet and do not degrade nearly as quickly [10-50].

Hemp has outstanding antibacterial properties that surpass those of cotton and also any other natural fibre [10-50]. This is due to its natural richness in terpenes and cannabinoids [10-50]. Consequently, hemp (fabric) is extremely resistant to mould, mildew and fungi. Hemp is able to sequester more CO_2 than it creates during its crop cycle, therefore, hemp is known as a carbon-negative plant [10-50]. As researchers suggest, each ton of hemp grown can remove around 1.63 tons of CO_2 from atmosphere [10-50]. Consequently, the plant can be used to mitigate emissions from the farms on which it is grown [10-50]. Cotton cultivation, on the other hand, causes extraordinarily high CO_2 emissions - with 2 to 4 tons per hectare [10-50]. Largely due to its slender shape, the hemp plant requires significantly less land to produce much higher yields compared to cotton [10-50]. In fact, only half the acreage of cotton is needed for hemp to produce one ton of finished textiles. Cotton producers, on the other hand, have a higher land requirement for the same yield and consequently generate less income per hectare [10-50].

The hemp plant can be grown on the same land for several years in a row without depleting the soil or reducing the yield [10-50]. On the contrary, hemp is known to be a powerful phytoremediation agent and was also grown in Chernobyl to draw radioactive material and other toxins from the soil [10-50]. The leaves and shavings of the hemp plant can also be ploughed back into the soil as a natural fertilizer without crop rotation[10-50]. Cotton, on the other hand, drains the soil and can severely deplete its fertility if continuously sown in the same fields [10-50]. Cotton is an extremely pesticide-intensive crop and is therefore, anything but soil-friendly: 25% of insecticides and around 10% of all agrochemicals come from the cotton industry [10-50]. Extensive use of toxic chemicals along with other fertilizers and herbicides on cotton crops not only harms soil quality but also the overall environment [10-50]. Farmers as well as

surrounding communities, streams and rivers are affected [10-50]. Some farmers have therefore, switched to growing organic cotton. Hemp, on the other hand, requires hardly any herbicides and far fewer pesticides or fertilizers [10-50]. This is largely due to the plants dense canopy, which acts as a natural weed suppressor, reducing the need for herbicides during growth [10-50]. Some farmers even refrain from using any synthetic pesticides altogether, as the hemp plant is also naturally resistant to most insects and plant diseases. As growing number of people are currently making the switch to more sustainable practices, hemp will only increase in popularity and reclaim its position as the plant of future [10-52].

Significant factors provide proof of hemp sustainability and strengthen the chance for the development of the hemp textile sector as a part of holistic hemp business [10-52]. These include the multi-perspective environmental benefits concerning hemp cultivation, such as the absorption of CO_2 from the atmosphere, improvement of soil quality and enhancing biodiversity, helping to mitigate the effects of climate change and restore healthy ecosystems, as well as the possibility of using every part of the hemp plant for different purposes and waste less industrial hemp processes, where each by-product is a valuable raw material for many sectors of the bio-economy[10-64].

4. Dyeing Properties of Hemp Fibre

Although the abundant of synthetic fibre, cotton (*Gossypium hirsutum L.*) is still most popular and versatile textile fibre in world market [20-52]. It is used for a variety of textile applications such as apparel fabric, upholstery, carpets and curtains, etc [40-52]. Cotton fibre is smoother, stiffer and straighter than hemp fibre [40-52]. Cotton can be dyed easily and the color of dyed cotton often remains fast to repeated washings and to prolonged wear as well. Whereas hemp fibre is coarser than cotton which is dark in color and difficult to bleach because of lignin [10-52]. For the dyers, it is really challenging task to dye hemp fibre [10-52]. Even though many studies have reported the dyeing of hemp fibres with direct dye [10-52]. Also basic dyestuff provide bright shades when hemp is mordanted with antimony and tannin. There has been a limited researches reporting the dyeing properties of hemp fabric dyed with reactive dye [10-52].

One of the study confirmed that the dyeing properties of hemp fibre were found to be excellent in comparison with that of cotton fibre [10-52]. The dye yield for the two cellulosic fibres upon using mixed bi-functional reactive dye confirms the interrelation between the molecular rearrangements with the dyeing properties [10-52]. Cotton fibre exhibits higher exhaustion and better levelness properties than hemp fibre, presumably due to the lower crystallinity and degree of orientation [10-52]. However, the build-up properties of both fibres are almost identical. Salt and alkali addition enhances the color strength of hemp fibre because of lower crystal size which enhances the surface area of the fibre [10-52]. Fastness properties of reactive dyed cotton and hemp fabrics were found to be almost similar [10-52]. Therefore, the results suggest that hemp fibre could be used as an alternative to cotton fibre as a cellulosic fibre [10-52].

Fabrics made from cotton fibre, on the other hand, break down over time the more often they are washed [10-52]. Hemp fibre is more absorbent than many other natural fibres and requires less pre- and post-treatment [10-52]. Because of these properties, it is also easier to dye than cotton. The results of one of the study showed that dyeing of a non-textile residual hemp substrate is possible, and that Calendula is a good option for dyeing it with tap water, tannin-alum set in a meta-mordanting process, and rinsing after 24 h [30-52]. In addition, hemp fabrics also retain their color longer and are less likely to fade. This is also largely due to hemps superior ability to block most of the suns UV rays. Common madder (*R. tinctorum* L.) grows in the west, south, and southeast parts of Europe, Africa, and South America [10-52]. It has been used for dyeing textiles since 2000 B.C. Pigments can be extracted from the roots of common madder. Their main dye components are anthraquinones with alizarin (1, 2 dihydroxy anthraquinone), the hydrolysis product of ruberythric acid [30-52]. These pigments produce useful colors that have distinctive heat and light resistant properties [30-52]. Pot marigold, common marigold, garden marigold, English marigold, or Scottish marigold (*Calendula officinalis*) is native to Asia and southern Europe [30-52]. It has been used due to its large number of helpful properties such as antibacterial, antifungal, antiviral, anti-inflammatory, and wound healing, etc [30-52]. The coloring matter is in its bright orange or yellow flowers that contain lutein (a carotenoid pigment), which includes alpha- and beta-cryptoxanthin and hydroxyl groups [30-52]. Typically, dyes obtained from plants have no affinity for cellulose, so they need a mordant to permanently fix to the textile fibres, resulting in improved color and color fastness [30-52]. Consequently, environmentally friendly mordants such as tannins and alum are necessary to make the dyeing process more sustainable and eco-friendlier [30-52]. Fabrics made from hemp fibre can be naturally green, brown, gray, black or creamy white - without the use of chemical dyes [20-52]. The color of hemp fibre largely depends on the method by which it is removed from the stalk. Cotton fibres, on the other hand, mostly occur in white tones in their natural form [20-52].

5. Cottonization of Hemp fibre

To improve hemp fibres in terms of quality, feel and easier processing, different methods were developed in the past [37]. All of these methods are generally known as cottonization of hemp [20-52]. The goal of these processes is to decrease or eliminate the lignin or pectin content of the hemp fibre [20-52]. Pectin is part of the plants cell wall and important for the binding of the cells, whereas lignin fills the spaces within the cell wall, between pectin and other components, like cellulose and hemicellulose [20-52]. Therefore, both components are essential during the growth of the crop, although these components are highly unfavourable for high-quality fibre processing, as they make the fibres stiffer, coarser and hence more difficult to process [10-52]. The cottonization process primarily performed in China aims at decreasing the lignin content from 8-10 % to 0.2 % through a physical chemical degumming technique [20-52]. Firstly, the hemp fibres are immersed in acid for an hour at 50° C [20-52]. Secondly, the fibres are boiled in an alkaline solution for three hours at a temperature of 100° C [20-52]. After that, the fibres are dried, opened and stretched and have a cotton-like feel [20-52]. Another method that is applied, is the so called steam-explosion. It was invented at the Hochschule Reutlingen, and further developed by the Dutch company StexFibers in collaboration with the University of Wageningen (StexFibers BV) [20-52]. In this process the fibres are put in a container with a warm aqueous alkaline solution. The container is put under pressure up to 15 bar [20-52]. After opening the pressure valve and the followed pressure drop, the water in the fibres vaporizes and the fibres bundles are opened [20-52]. In this way, the fibres become cleaner, finer, better separated, and more uniform [20-52]. The third method is the CRAILAR technique, developed by an US American company in collaboration with the Canadian National Research council [20-52]. After decades of research, the company developed a patented method that removes all pectin in the hemp fibre [20-52]. It is an enzymatic process through which the fibres become softer and are able to be spun and further processed on conventional cotton machinery [20-52]. The company already works together with companies like IKEA and Adidas [20-52].

The most feasible direction for the development of hemp yarn production is the adaptation of the cotton spinning system to cottonised hemp fibre features [10-52]. This is conditioned by commonly available machines, which are usually used for cotton and cotton-like fibre processes [10-52]. The quality of yarn made of cottonised hemp fibres is lower in comparison to yarn spun from long hemp fibres in terms of yarn uniformity and its mechanical properties which result from huge differences in fibre length [10-52]. The cottonisation of hemp and the applied cotton spinning system causes hemp to lose its inherent properties like high tensile strength, cool touch, resistance to pilling and bioactivity [10-52]. Alternatively, textiles made of cottonised hemp can be more resistant to wrinkling [10-52]. The productivity of the cotton spinning system is much higher than productivity of the traditional linen spinning system but only on the condition that the cottonization of hemp fibres is conducted with high accuracy [10-52]. In this case, there is a chance to develop the production of hemp textiles for relatively low costs in the near future [20-52]. The production of the best quality hemp yarn from long fibres will be dedicated to exclusive premium clothing with high prices due to the high cost of production [20-52].

The economic value of hemp can be maximized if all plant biomass (stems, inflorescences and seeds) is exploited and delaying harvest until the generative phase is completed [64]. For the production of high-quality fibre for industrial applications, fineness is another desirable trait. Hackled fibre bundles, as expected, are finer than scutched ones [64]. The main purpose of scutching is to remove the shives from the bast fibre bundles, while the refining of bast fibre bundles is carried out during hackling [64]. One of the study results obtained at industrial level confirmed that yellow stem varieties have higher fibre extraction efficiency than conventional ones [64]. The fineness of hackled fibre bundles was affected by genotype, and was highest in the yellow variety Carmaleonte, but it was not affected by the retting treatment and harvest time [64]. The IFBT technique was used to determine hackled fibre bundle properties by back-calculation from hemp-epoxy composites [64]. Strength and stiffness were higher at full flowering than at seed maturity in both analyzed varieties [64]. The results on composites and back-calculated fibre properties are comparable with those obtained from other authors with long hackled flax and hemp fibre bundles [64]. In this study long hemp fibre bundles, having properties comparable to those of flax, proved to be suitable for high performance composites applications [64]. In particular, these results were underscored for yellow varieties that had the highest decortication efficiency [64].

6. Hemp fibre in Fashion Industry

According to the study conducted by Kramer (2017) [37], hemp as well as cotton are natural fibres, they have many similar properties, such as good breathability and thermal insulation when wearing [20-52]. First of all, cotton generally has longer fibres than hemp [37]. Moreover, a major disadvantage of hemp fibres towards cotton fibres is their lack of uniformity [20-52]. The hemp fibres highly vary in length and diameter, which makes it more difficult to process and

spin them into uniform yarns [20-52]. Furthermore, cotton fibres are finer, leading to a softer feel of the garment on the skin. On the other hand, hemp fabrics become softer and more lustrous through laundering and therefore, comfortability is increased with time [20-52]. The cotton fabric degradation occurs faster and hemp fabrics turn out to be more durable and wear-proof than cotton fabrics [20-52]. Despite higher durability, hemp fabrics are less flexible but their tensile strength is better in comparison with cotton [20-52]. In terms of heat resistance, hemp shows outstanding results over cotton. Additionally, hemp is superior to cotton regarding moisture absorption and dissipation [20-52]. The stated values for hemp are almost twice as high in comparison with cotton. This absorbency rate is also beneficial for dying processes, where hemp fabrics are more capable to absorb and retain the dyes being applied[20-52]. Furthermore, it was found that the mechanical properties of hemp/cotton blends are generally 15 to 20 % better compared to pure cotton fabrics [20-52].

According to the study conducted by Kramer (2017) [37], the slow progress in improved cultivation and processing methods in hemp fibre production would keep hemp in a niche market within the fashion industry [20-52]. The market value would be far too low compared to work and energy input [20-52]. As already mentioned, a high potential to substitute cotton with hemp is perceived, under the condition that fine and high quality fibres, equal to cotton, can be produced [20-52]. The low competitiveness, also due to the much higher price is further emphasized. The high competition in the fashion sector with different raw materials being cheaper would complicate a broader prominence within the industry and the consumers [20-52]. Therefore, there would be few brands interested to implement hemp in their products, further leading to a lack of investments from the industry [20-52]. It is said that high financial means would be needed to make hemp easier to process and to market the fibre [20-52]. Some respondents ask for the industry's own impulse taking more risks and volition to invest in the prospective profitability in order to get a sustainable raw material for the future in fashion [20-52]. Others intend continuing on their own projects to be able to convince the industry with newly developed machinery and processes being ecologically and economically sustainable [20-52].

7. Hemp Fabric in India

The Indian textile industry is a pillar of the national economy and a major source of export revenue for India. Indian economy is heavily influenced by the textile and apparel industry [65-67]. The Indian textiles and apparels industry plays a pivotal role in contributing to employment generation, industrial output and export earnings. India has a noteworthy position as a major exporter of natural fibres like silk and cotton [65-67]. India currently commands a share of about 4.5 per cent in the world exports of textiles [65-67]. This is still a very nominal share despite the textile sector in India being one of the oldest sectors and has witnessed revolutionary changes in transforming the industrial and economic landscape of the country [65-67]. Rigorous efforts have been made to establish the ambitious 'Make in India' programme that is wishing to make India as a 'manufacturing' and 'sourcing hub' in the coming times [65-67]. Natural fibres are appealing to the classes, due to the rise in prices of natural fibres. This makes it challenging for India to offer competitive pricing in the market and reach a wider audience [65-67]. With micro-plastic being one of the biggest issues right now, natural fibre seems to be the only answer to solve this issue. Brands are going through the process of realisation and do wish to be better (**Neha Rao**, **Head of Hemp Fabric Lab**) [65-67]. While hemp is currently more expensive compared to other cellulosic fibres, its application has the potential to fundamentally change Indias fashion and textile position[65-67]. India can take benefit of its cultural and economic potential to develop a more sustainable and ethical fashion business by raising awareness of and investing in the production and processing of hemp [65-67].

In recent years, there has been a resurgence of interest in hemp as a sustainable and versatile textile fibre in fashion and textile industry [1-67]. However, despite its many benefits, hemp is still relatively expensive in India compared to other cellulosic fibres such as cotton, linen, rayon etc [1-67]. The high cost of hemp in India and the capability of hemp to change the fashion and textile industry of the country is one of the interesting topic in the textile industries [65-67]. **Hemp Fabric Lab** in India makes innovative textiles that are either 100 percent hemp or blend hemp with fabrics like organic cotton, Tencel, silk, and wool [65-67]. Over the past half a decade, the interest in and demand for hemp-based products is on the rise, as may be seen with the increase in the number of women artisans and weavers in rural Himalayan villages [65-67]. These Himalayan villages have increased the quantity and quality of indigenous hemp handloom products, such as shawls, stoles, and accessories [65-67]. Every inch of **hemp fabric** or hemp clothing comes from **beautiful remote Himalayan villages of State of Uttarakhand**, India made by love and care by these hard-working women [65-67]. These women from the mountains are very beautiful at heart and now they are making the world a better place by promoting the most sustainable plant on earth [65-67]. UKHI has beautifully combined all of its hemp fabrics into one album called the **Hemp Fabric Swatch Book** [65-67]. There are approximately 60 Fine Hemp fabrics included in the swatch book. It mostly contains pure hemp fabrics but it also has hemp cotton blends, hemp and Lycra, and Lyocell etc. These products are beautiful organic hemp fabrics and other sustainable fabric products [65-68].

Hemp Fabric Lab is a brainchild of **BOHECO** (Bombay Hemp Company). Hemp Fabric Lab are dedicated to providing 100% hemp fabric and blends with other sustainable fibres like organic cotton, Tencel, wool, silk, yak hair, nettle, Bamboo, Lyocell [65-67]. Being a product of BOHECO, Hemp Fabric Lab's core mission is to educate and encourage brands, designers and consumers to adopt hemp and banish any myths surrounding it [65-67].

Bombay Hemp Company, incorporated in 2013, is an Agro-based enterprise reimagining the future of Indian agriculture and sustainable living with hemp as their lens [65-67]. Their design fuses this very potential with the existing industries of agriculture, technology and medicine, to bring together Community, Impact and Value [65-67]. Hemp Fabric Lab is a textile division under the Bombay Hemp Company (BOHECO) specifically dealing with 100 per cent hemp fabric and fabric blends [65-67]. Hemp Fabric Lab vision is to become the foremost players in the hemp textile industry in India and create an ecosystem for designers, consumers and innovators to come together in a collaborative spirit and find interesting new ways to use hemp [65-67].

But the biggest challenge is on the other side, that have to source the hemp fibre from outside India and that adds to the cost [65-67]. This is one aspect that stops most of Indian manufacturers and brands from offering a good price on hemp clothing[65-67]. In order for retail to accept the hemp products, it is believed that the concept needs to get more acceptable within India and just for to create awareness or give washing guide is not enough [65-67]. The Indian market still has the stigma of comparing hemp with marijuana [65-67]. However, hemp is an extremely durable and versatile fabric that uses 50 per cent less water as compared to cotton [65-67]. In fact, there are two sides of the coin; on one side of it, there is 'Marijuana' that has so many medicinal uses and on the other side have 'Hemp', which can use to make more than 20,000 products [65-67]. The entire hemp plant from seed to foliage can be used purposefully [65-67]. Hemp is versatile and biodegradable and this is one of the few plants whose by-products can either be eaten, sat on, written on, worn, slathered on your body, painted on a wall or squirted into a machine [65-67].

There are various factors that contribute to the high cost of hemp in India compared to other cellulosic fibres [65-67]. One of the main factors is mass hemp cultivation is banned in India. Although hemp has been grown in India for centuries, its cultivation is restricted to certain states due to legal and regulatory barriers [65-67]. In 2021, India has legalized hemp as food and licences have been sanctioned for growing hemp throughout India. While it is often confused with marijuana, hemp is a distinct variety of the same plant species, *Cannabis sativa* and contains only trace amounts (0 to 0.3%) of THC (Δ9-Tetrahydrocannabinol), the psychoactive compound found in marijuana [1-60, 65-67]. This causes limited supply of hemp in India, so mostly hemp-based businesses are run by importing hemp yarns, fabrics or hemp extracts from other countries like China, Italy, Canada and USA etc [65-67].

Hence, the cost increases as the raw materials are imported. The absence of processing infrastructure also contributes to the high price of hemp [65-67]. To transform hemp into useful fibres, yarns, and fabrics, specialized machinery and knowledge are needed [65-67]. However, Indias existing lack of infrastructure for processing and producing hemp products can drive up production and distribution costs [65-67]. Additionally, the cost of hemp products increases due to the need for certifications and conformity with international standards [65-67]. For instance, hemp products must adhere to tight criteria for THC levels and other quality indicators in order to be exported to the EU or USA [65-67]. This requires additional testing and certification procedures, raising the production cost [65-67]. Despite the high cost of hemp in India, the use of this eco-friendly and sustainable fibre can have a transformative impact on the fashion and textile industry of the India. Here are some ways in which it can change the Indian fabric industries.

- Hemp is a highly sustainable crop that can grow in a variety of climates and soil types [1-65-67]. It requires less water and can be grown without the use of pesticides or herbicides. In contrast, cotton requires a lot of water and is often heavily sprayed with pesticides and herbicides to control pests and weeds [1-67]. It is also biodegradable, making it an eco-friendlier alternative to synthetic fibres such as polyester [65-67]. As hemp fibre is naturally resistant to mildew, mould, and pests, it is an ideal choice for organic farming practices. Hemp is a carbon negative fibre because it absorbs more carbon than it produces while cultivating [1-65-67].
- Hemp fabric can be used for a variety of applications, from clothing and accessories to home textiles and upholstery [1-65-67]. Hemp fabric has a unique texture and appearance that sets it apart from other natural fibres [65-67]. It can be made into a wide range of weights and textures, from lightweight, breathable fabrics to heavy-duty canvases [1-67]. Due to its high absorbent property, hemp is highly used to make towels. It can be blended with other fibres such as cotton, linen and silk to create unique fabrics with a range of properties [1-67].
- Hemp textile fibre is hypoallergenic and has natural antimicrobial properties, making it an excellent choice for individuals with sensitive skin. Hemp fabric is also highly breathable, which can help to regulate body temperature and keep the wearer cool and comfortable in the Indian climate [1-65-67]. Hemp fibres are known

for their durability and strength, making them ideal for use in products that required high durability and resistance to wear and tear [65-67].

- The cultivation and processing of hemp can provide economic benefits, as India's climate is very much suitable for its cultivation [65-67]. Now hemp farming is made legal in India since 2021 and it is commercialised all over India, then it will open a huge scope for the Indian textiles and fashion industry in domestic as well as global fashion markets [65-67]. In addition to the fashion industry, pharmaceutical, construction etc industries too will be benefitted as the hemp plant has no wastes [65-67]. The whole plant is useful for making different products from cosmetics and medicines to geotextiles [65-67]. Rural communities in India will also benefit as it will create new job opportunities and generate income for farmers, weavers and artisans [65-67].
- Hemp has a great cultural and historical value in India because it has been grown and used here for thousands of years [65-67]. This cultural history can be conserved and honoured by using hemp in the fashion and textile business [65-67].

8. Disadvantages of Hemp fibres in textile Industries

The processing of cotton fibres is easier than the processing of hemp fibres. Concerning energy use and efficiency, cotton is taking the lead [10-52]. Since the invention of the cotton gin and the spinning jenny in the 18th, the machinery for cotton production and processing could be more and more refined in the past 250 years [10-52]. Most processing technology for natural fibres being developed in the textile industry focuses on the use of cotton as raw material [20-52]. This is deduced from the fact that cotton still is the most used natural fibre [30-52]. Comparing the processing technology of hemp and cotton fibres, it is visible that the majority of the machinery used for hemp was not directly developed for operating with hemp crops and fibres [20-52]. Moreover, these machines derive either from the cotton or linen harvesting and processing, even if sometimes slightly adjusted for hemp [30-52]. Due to the prohibition of cultivating industrial hemp in many countries in the past for many decades, little research and progress was made, in terms of optimizing the crop, cultivation, processing and machinery [10-52]. The spinning process being applied to spin long bast fibres for instance, is slower than existing cotton spinning processes [25-52].

The production of cotton fibres nowadays, is cheaper and more efficient by comparison with hemp fibres [20-52]. Consequently, the hemp fibres become more expensive on the global fibre market, making them less attractive for the sourcing managers [10-52]. The cellulose content per hemp plant is lower compared to cotton plants, leading to a lower fibre yield, whereas on the other hand, the fibre yield per cultivated hectare is two times higher, as more hemp than cotton plants can be cultivated on the same area [20-52].

The possibility to obtain long aligned fibre bundles from hemp is limited by the lack of dedicated harvesting machines that can mow hemp stems, lay them on the field in aligned swaths and cut them in 1 m long portions, so that they can be fed in flax scutching lines [64]. Further bottlenecks, that wet spinning, are the retting process and the availability of processing machines suitable for hemp [64]. **Retting** is a biochemical process, in which enzymes produced by microorganisms attack the pectins that glue together fibre cells, aiding the separation of fibre bundles within the bast fibre and of shives from bast fibre [64]. Microbiological retting can be carried out in water (water retting) or on the soil (dew retting) [64]. In the past, the retting process was carried out in open water basins. Nowadays water-retting is considered to have a high environmental impact, due to high water use and high oxygen demand (BOD) of the waste waters [64]. The impact of water retting is reduced in the case of controlled warm water retting, where the retting process is optimized with target bacterial inoculum and performing retting on un-retted scutched hemp [64]. The influence of uncontrollable microclimatic conditions on the dew retting process is extremely high: over-retting and under-retting can occur frequently, affecting hemp fiber quality [64]. In order to avoid degradation of cellulose, a mixture of selected enzymes or fungi can be spread on the stems resulting in a reduced dew retting duration characterized by a low cellulosic activity. Harvesting technique, retting method, as well as agronomic practice, and genotype are important determinant of fibre quality, that affect the possibility to use hemp fibre for high-added value application as textile and high performance bio-based composites [64].

9. Conclusion

Over the last several decades, *Cannabis sativa* L. has become one of the most fashionable plants. As a textile fibre, hemp possesses a range of excellent properties such as, high tensile strength, low strain, high elasticity and breathability with quick drying. Hemp fibre also has got a good antimicrobial property, better moisture, thermal control, biodegradability and resistance to UV radiation. However, there are also some drawbacks of hemp fabrics such as higher stiffness and rough handle. The rigidity of cell wall is lignin which is located in the middle of lamellae and secondary wall. The amorphous and unoriented constituent are hemicellulose, which occupy spaces between the fibrils in both primary and

secondary walls. Raw hemp fibre consists of about 67-78% cellulose, approximately 5.5-16.1% hemicelluloses, 3.7-8% lignin, 0.9-4.3% pectin and some fats and waxes. Hemp is a high yielding, sustainable, and environmental friendly crop that can provide valuable raw materials to a large number of applications. Traditionally harvested at full flowering to optimize long fibre bundle extraction, nowadays hemp is mainly harvested at seed maturity for dual-purpose applications and has a great potential as multipurpose crop.

The cultivation of hemp has significantly less environmental impact compared to cotton. Regarding climate change, acidification, eutrophication and several toxicity categories the impact of hemp is far lower than that of cotton. Hemp also uses only half of the land. This only applies to fibres used in technical applications like biocomposites. The hemp textiles used in textiles are further processed, called degumming. Adding this process to the cultivation scenario makes that degummed fibre have a higher impact in every relevant impact category except for marine eutrophication and terrestrial ecotoxicity. Much of the impact is related to the energy use in the degumming process. Therefore, this is the absolute environmental hotspot for hemp fibres. Comparing the fabric scenarios shows that there is no considerable technical difference when adding hemp to cotton fabrics except for the degumming process. Again marine eutrophication is the only impact category with a higher impact for cotton fabrics. This is partly because the contribution of fibre production to the total impact is fairly limited.

Some additional advantages of hemp over cotton are further to be stated. As the hemp crops are able to absorb high amounts of CO_2, the carbon footprint is positively affected, and very low compared to other natural fibres. Therefore, it is stated that using hemp as a raw material for a variety of products can make a major contribution on creating a more sustainable and eco-friendly economy. Additionally, it was found that hemp fibres showed high absorbability of other toxic gases. The nearly non-existent use of agrochemicals in the processing, leads to fibres not being charged with any of these. Furthermore, hemp is barely affected by mites or insects, the fibres showed anti-bacterial characteristics and have an outstanding resistance to UV-rays, making them highly suitable for home textiles. Rural communities in India will also benefit as it will create new job opportunities and generate income for farmers, weavers and artisans. Hemp has a great cultural and historical value in India because it has been grown and used here for thousands of years. This cultural history can be conserved and honoured by using hemp in the fashion and textile business.

Compliance with ethical standards

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