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Hemp fibers as sustainable reinforcement in natural fiber composites: A comprehensive review

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Authors' Contribution **Huzaifa, M.** & **N. Akhtar** compile the literature, **S. Zahoor** critically review the literature, **M. H. Abdullah**, **M. Arslan** & **A. K. Niazi** collected the references.

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ABSTRACT

Review Process: Peer review

Cannabis sativa, sometimes known as industrial hemp, is frequently used for manufacturing of high-cellulose bast (highly fibrous) fibers. The need for environmental conservation, combined with the beneficial characteristics of these fibers like their low thickness, high definite forte, and toughness prompts a strong interest in their utilization. Additionally, a great deal of effort has been put into developing novel materials thus improves the mechanical performance through surface modifications. Hemp fibers' most promising uses involve hybridization or as reinforcement in polymeric composites. However, more research is required to enhance their properties and broaden the scope of their uses. In the context of long-lasting applications and the ability to consistently reproduce the desired qualities of these composites, one significant concern is the biodegradability aspect, which requires careful consideration. This review offers a comprehensive examination of the existing body of research on hemp fibers, encompassing aspects such as the mechanical as well as chemical properties of hemp fibers, surface enhancements, hybrid composite materials, and both current and prospective applications.

Keywords: Biodegradable, composites, ecofriendly, fiber, natural.

INTRODUCTION: One of the primary issue is environmental conservation (Rashid *et al.*, 2017) and the ongoing efforts are to improve these composites through various physical and chemical surface treatments. This increase in research activity is driven by the growing concern for environmental protection. Furthermore, natural fibers are attaining prominence as feasible alternatives to artificial fibers, like glass fibers, as they provide several eco-friendly benefits. Natural fibers are gentle on processing equipment, cost-effective, sourced from renewable materials, possess low density, and exhibit commendable specific strength and stiffness. Natural fibers stand out for their sustainability and positive environmental impact (Mwaikambo and Ansell, 2006), The making of natural fibers necessitates approximately 60% lesser energy compared to the manufacturing of glass fibers, leading to a reduction in Air borne pollutants. Moreover, the waste generated from natural fiber production is predominantly organic and entirely biodegradable (Gurunathan *et al.*, 2015; Mochane *et al.*, 2019).

A life-cycle assessment compared components manufactured from natural fiber-reinforced amalgams and glass fiber (Joshi *et al.*, 2004). Their findings highlighted these superior environmental friendliness of naturally occurring fiber-reinforced amalgams for several reasons. These fibers (Natural fiber composites) offered increased content of fiber for similar performance. This, in turn, led to reduced emissions and fuel consumption throughout the product's life cycle. Additionally, the overall production of natural fibers had fewer negative environmental consequences. In light of these benefits, it was concluded that the life-cycle of hemp in glass fiber-reinforced thermoset amalgams is ecologically sound choice than the traditional practice with glass fiber exclusively (La Rosa *et al.*, 2013). Adopting natural fibers has many advantages, but there are some drawbacks as well. According to Challenges associated with natural fibers include their inherited hydrophilicity, extreme anisotropy, and susceptibility to microorganisms, thermal stability, variations in properties that are mechanical, and inferior characteristics when compared to synthetic fibers (Khan *et al.*, 2018). Additionally, various factors, such as growth conditions, harvesting methods, and maturity, consistently impact the properties of natural fibers (Mochane *et al.*, 2019). The innate hydrophilic quality of these fibers presents challenges like insufficient dispersion, restricted interaction with the matrix, and considerable moisture absorption. These aspects can lead to fiber swelling and a potential decline in the strength of the matrix-fiber interface (Azwa *et al.*, 2013). These processes encompass water diffusion within polymer microcapsules, capillary movement into imperfections and flaws at the matrix-fiber junction (Shalwan and Yousif, 2013), and the conveyance of moisture through micro-cracks formed during the fiber's swelling (Safri *et al.*, 2018).

OBJECTIVES: The purpose to compile this review article is to summarize current research initiatives concerning hemp fibers and their application in composite reinforcing.

Hemp fibers: Hemp fibers, derived from the stalks of the Cannabis sativa plant (figure 1), primarily reside in the upper stem layer. These robust, lengthy, and flexible fibers have a rich history in various industrial and commercial applications owing to their exceptional strength, durability, and adaptability. They find widespread use in textile manufacturing, paper production, construction materials, cordage, and as reinforcement in composite materials. Notably eco-friendly due to their biodegradability and low environmental impact during cultivation, hemp fibers have earned a reputation for their environmental friendliness.

Figure: 1 Hemp fibres extraction (Fathordoobady *et al.*, 2019)

Hemp is an easily available and economically rated naturally occurring fiber. Canada and Europe may grow the specific hemp strains but they contain less than 0.2% (in Europe) or 0.3% (in Canada) tetra hydro cannabinol (THC) (Panthapulakkal and Sain, 2007). Hemp has a rich historical legacy, spanning millennia, as a versatile fiber used in the manufacturing of various products. These include textiles, paper (with notable historical instances such as the Bible's first copies printed on hemp paper), ropes, and sails (Crini *et al.*, 2020). Although it has been grown in practically all temperate and tropical nations, hemp is a native of India and Persia (Salisu *et al.*, 2019). With nearly 33% of the yearly global production, Russia is the leading producer of hemp fiber. Significant amounts of hemp fiber are also produced in other nations, including Japan, France, China, Italy, Chile, Yugoslavia and Peru and Germany (Pappu *et al.*, 2019). Hemp fiber stands out as a highly promising candidate for reinforcing composite materials, thanks to its remarkable strength and stiffness, ranking it among the most robust natural fibers available today. Hemp is an annual plant that typically reaches maturity within two to three months of planting (Sature and Mache, 2015). The hemp plant's base hosts fibers that exhibit an impressive level of rigidity, comparable to the stiffness of glass fibers (Chen *et al.*, 2013). These fibers, which are situated in the bottom of the hemp plant, have a particular rigidity that is comparable to glass fibers (Chen *et al.*, 2013). The phloem contains the primary bast fibers (figure 1), which are a roll of fibers that goes through the entire size of the plant stem and is composed of roughly 70-7% cellulose, 15-2% hemicellulose, 3.5-5.7% lignin, 0.8% pectin, and 1.2-6.2% wax (Dhakal and Zhang, 2015). Secondary bast fibers of the phloem

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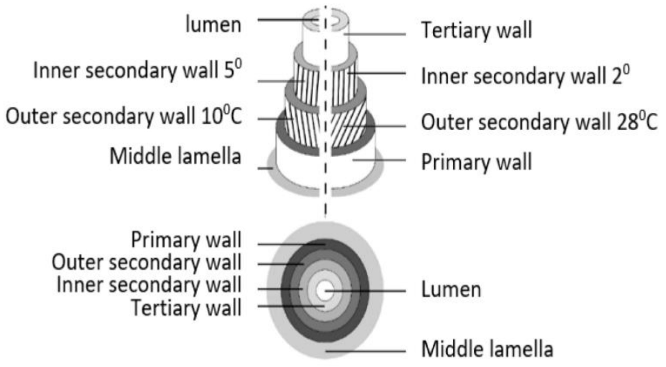
develop from cambium (Kiruthika, 2017).

Structure and composition: The cell wall structure of hemp fibers presents a complex arrangement comprising multiple layers, including the primary cell wall developed during initial cell growth and the secondary wall consisting of three distinct layers referred to as S1, S2, and S3. This structural makeup resembles a composite material with multiple lumens running parallel (fig 2)(Dhakal and Zhang, 2015). Lignin, constituting about 90% of the middle lamella and responsible for binding the elementary fibers, is a prominent component. Notably, the S2 layer boasts the highest cellulose content, around 50%, making it the thickest layer and influencing the fiber's characteristics (Kabir *et al.*, 2013; Dhakal and Zhang, 2015; Chegdani *et al.*, 2018). Retting, a microbiological process, loosens the fiber linkages (Väisänen *et al.*, 2018). Post-retting, fibers are extracted from the hemp stem either mechanically or manually (Hepworth *et al.*, 2000). In a research study investigating various factors such as retting conditions and duration, sodium hydroxide mercerization, and hydrothermal treatment, researchers explored their influence on hemp thread tensile properties. Alterations in surface morphology due to mercerization and hydrothermal treatment enhanced mechanical characteristics, potentially linked to changes in the mini-structure configuration. Interestingly, a 22-day retting process showed no impact on the tensile strength of the hemp yarns.



Figre: 2 structure of hemp fibres at micro level (Dhakal and Zhang, 2015)

The impact of temperature on hemp yarn properties was investigated. Exposure to 100°C for 24 hours led to an approximately 18% increase in the tensile strength of hemp fibers but caused a decrease in their Young's modulus (Manaia *et al.*, 2019). However, subjecting hemp yarns to 200°C for the same duration resulted in a loss of mechanical rigidity, rendering them fragile and weak. A comprehensive examination of the mechanical and physical attributes of hemp fibers was conducted (Shahzad, 2013). It was observed that hemp began to break down around 150°C, while hemicelluloses and pectin degraded at approximately 260°C, and cellulose degradation commenced at about 360°C. Additionally, the study revealed that hemp fibers exhibited polygonal cross-sections, possessed a tensile strength of 277± 191 MPa per fiber (with a mean fiber width of 67 ±26 μm), and showcased tensile moduli of 2.3± 0.8 GPa with a corresponding failure strain of 9.5± 5.8%.

Fiber Processing: The impressive mechanical properties of Natural Fiber Polymer Composites (NFPCs) in structural applications are primarily due to the strong interactions of polymer matrix and fibers, which occur within a region known as the interphase. However, the interphase's thickness and characteristics are influenced by the choice of matrix-fiber combinations, and these factors can negatively impact the adhesion of the fibers to the polymer (Pereira *et al.*, 2015; Cruz and Fangueiro, 2016). A significant challenge associated with natural fibers pertains to their hydrophilic characteristics. This nature restricts their suitability with hydrophobic matrices of polymer, leading to amalgams with elevated H_2O absorption capabilities. This issue has been highlighted in research work (Zhang *et al.*, 2014; Zheng, 2014; Pereira *et al.*, 2015). The high susceptibility to water leads to fiber swelling and a plasticizing effect, causing dimensional instability and a decline in mechanical properties (Bismarck *et al.*, 2002). Moreover, the existence of natural waxes on the fiber surface creates a substantial barrier to the bonding between fibers and the polymer. This obstacle impedes the polymer's ability to adequately wet the fibers. The presence of free H_2O and OH groups, particularly within the powdered segment of fibers, also presents challenges for fiber grip to many manmade matrices. In cases where intramolecular hydrogen bonding is particularly robust, as observed in superior fibers along with a enhanced concentration of crystal-like cellulose, the penetration of polymer chains into the fibers is limited, resulting in a less effective interphase. To overcome these challenges, it is possible to enhance fiber adhesion and achieve an appropriate level of cellulose crystallinity by replacing some of the hydroxyl groups with other responsive moieties. While such modifications of cellulose can be expensive and involve the use of hazardous chemicals, they can impart moisture repellency, flame-retardant properties, bio-durability, and weather resistance (Bismarck *et al.*, 2002). Various compatibilizing procedures are employed to achieve optimal fiber-matrix adhesion. These approaches include matrix-oriented methods, modification of fiber techniques (chemical, biological, physical, physicochemical, or combinations thereof), the use of additives like compatibilizing agents, and suitable combinations of these methods. It is challenging to formulate a single hypothesis that describes the bonding mechanism in composites utilizing compatibilizing technology, as these processes are complex. Factors such as the interphase and its properties, wetting phenomena, surface energy, interface reactions and more, all need to be considered to understand these intricate processes.

Chemical methods: Treatments of hemp fibers with various reagents aim to improve the performance of composite materials by lowering the hydrophilic structure of the yarns and the crystalline index of the cellulose, as well as improving the compatibility of the fibers with polymers, the mechanical properties of the fibers, and their dimensional stability (Kabir *et al.*, 2013; Zhang *et al.*, 2014; George *et al.*, 2015; George *et al.*, 2016; Pickering *et al.*, 2016). A range of reagents has been proposed in the literature to modify natural fibers. These include acids such as sulfuric acid, formic acid, sulfonic acid, inorganic salts with acidic properties, ammonium salts, Lewis acids, organic acid anhydrides, n-butylamine, n-propylamine, along with alcohols like methanol, ethanol, or butanol, often used in the presence of acids or alkalis (George *et al.*, 2015). Additional techniques involve treatments with Acetylation, Acrylation, Acrylonitrile grafting, Fatty acid derivatives, Isocyanate, Peroxide, Reactions with permanganate, Silanes, Sodium chloride, Stearic acid, Triazine (like oleoyl chloride) among others (Zhang *et al.*, 2014). Some of the most significant and often utilized chemical treatments are provided in table1.

Chemical treatment	Reagent employed
Mercerization / Alkali treatment	Sodium hydroxide
Acetylation	Acetic anhydride
Benzoylation	Benzoyl peroxide
Acrylation	Acrylic acid
Acrylonitrile grafting	Acrylonitrile
Peroxide treatment	Benzoyl peroxide
Permanganate treatment	Potassium permanganate
Isocyanate treatment	Toluene diisocyanate
Silane coupling	alkoxy / amino silanes
Maleated coupling agents	PP PE)-graft-maleic anhydride

Table 1: Chemical method for natural fiber modification

The choice of treatment method depends on the desired level of enhancement, such as significant improvements in fineness achieved by treating hemp fibers with ethylene diamine tetra acetic acid (EDTA). Salinization, on the other hand, results in a smoother surface (Sawpan *et al.*, 2011). The selection of the treatment method also considers the intended applications, production costs, and environmental impact (Sonar *et al.*, 2015).

Silane treatment: Utilizing joining agents which make reaction with hydroxyl and functional groups in matrix structure is a key approach to greatly enhance the compatibility among natural fibers and polymer matrices (figure 3).

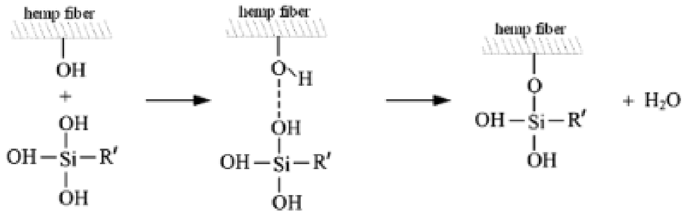


Figure: 3: Hemp fibers as treated with silane (Kabir *et al.*, 2013).

This method leads to the formation of an improved interphase with boosted properties and better linkage at the fiber-matrix edges (Kabir *et al.*, 2013; Sonar *et al.*, 2015; Pickering *et al.*, 2016). One such group of coupling agents considered in this context is organosilanes, (Xia *et al.*, 2016). Examples of these agents include triazine, maleic anhydride, zirconates, and titanates, which generally follow the formula R-[CH2]-X-[OR']m, where m ranges from 0 to 3, X represents Ti or Zr, and OR' stands for a hydrolysable alkoxyl group, with R and R' representing organic functional groups (Sawpan *et al.*, 2011). It has been observed that a judiciously chosen fiber treatment can substantially enhance the performance of resultant amalgams. A fundamental silane treatment involves immersing natural fibers in a diluted silane solution. Typically the process results in the hydrolysis of silane to produce silanol, which further interacts with hydroxyl groups in the fibers. As established by several sources, including the silane treatment is a complex process with intermediate stages (Rachini *et al.*, 2012; Kalia *et al.*, 2013). The choice of silane agents is crucial, with the most commonly used including alkyl silanes, methacryl-, trialkoxysilanes, glycidoxy- and amino-. Considering the kind of polymer matrix, the remaining radicals in the silane agents can symbolize various functional groups, such as glycidoxy, amino, methacryloxy, vinyl, or mercapto which also influence the compatibilization. This fosters molecule is preventing fibers from swelling within the matrix. The characteristics of the fiber surface are further influenced by various processing parameters, irrespective of silane employed in fiber treatment. For instance, concentration of silane solution, pH, reaction duration, and temperature play essential roles. While silanes like vinyl- and acryl-silanes, when combined with peroxides as initiators, are used for covalently linking fibers and the matrix, amino silanes, such as -amino propyl-triethoxy silane (APS), can lead to increased hydrophilic characteristics at the interface. This, however, can result to greater water and moisture absorption, adversely affecting fiber-matrix adherence. Therefore, strategies such as utilizing mixtures of hydrophilic and hydrophobic silanes, like phenyltrimethoxysilane, have been found to be effective. Studies comparing methacryloxypropyl-trimethoxysilane and aminopropyl-trimethoxy silane for the alteration of hemp yarns that had not undergone prior NaOH treatments exhibited that degree of grafting increased with starting thickness of silane solutions. This process entailed the establishment of bridges among the terminal functional group of silane and untouched OH groups present in hemp fibers. This also resulted in the formation of shared bonds between hydrolyzed silane and the OH groups in yarns of hemp. Furthermore, investigations into thermal breakdown to hemp fibers before and after chemical treatment revealed that these treatments enhanced the thermal stability of hemp.

Another study used APS, glycidoxypropyl trimethoxy silane (GPS), MPS, and potassium permanganate on raw hemp fibers. The chemical processes resulted in smaller and the separation of fibers bundles, with silane treatment prove the most effective and free from unfavorable effects, unlike potassium permanganate, where moderate oxidation occurred. The mechanical properties of associated composites, such as tensile modulus of elasticity, were also improved, particularly at the highest fiber loading (20%). A comparative analysis of hemp fibers-polyester composites was conducted, which used fibers subjected to various chemical treatments, including salinization, Various treatments were applied to the fibers, including silane treatment, alkali treatment, and reactions involving reagents commonly used for paper sizing, such as alkyl-ketene dimer, SMA, and ASA. These treatments all had a pronounced effect on enhancing the hydrophobic characteristics of the fibers. However, it was observed that when paper sizing chemicals were used, there was a reduction in the flexural and tensile properties of the composites. This is likely because these chemicals led to weaker fiber-matrix interfacial connections. On the other hand, treatments like silane, SMA, and alkali had a modest positive impact on the mechanical properties. This suggests that while alternative techniques like fiber hybridization (such as employing hybrid glass/hemp fibers) are being explored to enhance composite performance, there are limitations to how effectively they can improve the adhesion between fibers and polymer matrix.

Fiber Scattering, its volume, length and orientation: The arrangement, volume percentage, length, and orientation of fibers within the matrix play a substantial role in determining the mechanical properties of composites (Sgriccia *et al.*, 2008; Shalwan and Yousif, 2013). Manipulating the length of hemp fibers positively impacts the mechanical characteristics of polymer composites by optimizing the fiber aspect ratio (length: diameter). Maintaining fibers above a critical length ensures effective stress transfer between the matrix and fibers, enhancing the fibers' hydrophilic nature within the matrix, reducing pore content through proper yarn embedding, and reinforcing the interface between matrix and fibers through optimal fiber dispersion (Shalwan and Yousif, 2013). However, it's important to consider that the use of twin-screw extruders with thermoplastic matrices might inadvertently cause fiber breakage and reduce fiber length. In injection molding processes, fiber alignment with the flow direction depends on several factors, including matrix viscosity, mold design, fiber volume percentage, and fiber length (Pickering *et al.*, 2016).

Composite materials demonstrate peak mechanical properties when fibers align precisely with the applied force direction (Islam *et al.*, 2011). Any deviation from this alignment, indicated by the angle of fibers concerning the primary loading direction, results in a notable decrease in tensile strength and elastic modulus.. A study on aligned hemp fiber-reinforced PLA composites with various off-axial orientations and found that off-axis composites revealed diminished tensile, flexural, and influence values than to the primary fiber path. It was noted that off-axis composite characteristics are more influenced by the properties of matrix, while on-axis properties of composite are powerfully affected by both properties of both. This aligns with findings from other studies on natural fiber-reinforced polymeric amalgams (Brahim and Cheikh, 2007).

Increasing the fiber volume percentage generally guides to improved mechanical properties of compound materials. Conversely, beyond the certain threshold, mechanical qualities of the composite begin to deteriorate due to issues like delicate yarn dispersion & inadequate hydrophilic characters in matrix, Furthermore, the absorption of water, which causes puffiness of natural yarns and the deboning of the matrix-fiber edges, negatively impacts the characteristics of the composite (Dhakal *et al.*, 2007; Hargitai *et al.*, 2008). Researchers have investigated the optimal relationship of mechanical properties and volume fraction, with the typical maximum fiber content involving injection-molded thermoplastic matrix amalgams reinforced with natural yarns falling within range of 40% to 55% by weight of fiber content (Al-Oqla and Sapuan, 2014).

Reinforcement of hemp fibers: Composite materials are created when 2 or more than 2 dissimilar ingredients are joined to create a different designed material. Composite materials typically involve a matrix material that has been strengthened by the inclusion of fibers (Mohammed *et al.*, 2015). The mechanical characteristics of these composite materials were influenced due to various factors, such as the uniformity and arrangement of reinforcements, quality of bond between the matrix and reinforcements, the physical characteristics of the fibers, such as their surface modifications, dimensions, and alignment, as well as considerations such as the volume proportions of components and the specific testing conditions. These aspects collectively impact the overall mechanical enactment of the composite material (Ku *et al.*, 2011; Khan *et al.*, 2018).

For more than a millennium, hemp fibers have been utilized to fortify products (Rashid *et al.*, 2017). Hemp fibers are once again gaining popularity as a result of their low cost and the consistently improving performance of technical and conventional plastics. Hemp fiber composites are gaining increased attention due to their potential to serve as more cost-effective and environmentally friendly alternatives to synthetic fibers in reinforcement materials. This surge in interest spans across industrial applications and fundamental research (Sarikaya *et al.*, 2019). It was evaluated and compared all properties of amalgams form from coir fibers, glass fiber-reinforced polypropylene, hemp, sisal, jute, kenaf (Wambua *et al.*, 2003). The research found that hemp fiber-reinforced composites showed the highest tensile strength, reaching 52 MPa, although it's worth noting that the coir composites excelled in terms of impact strength. Certain characteristics of composites made of hemp fiber were discovered to be than those of glass fiber.

Natural fiber-reinforced composite: Fiber-reinforced composites consist of two essential components: the matrix and the reinforcement. Polymer plastic matrices, including Polypropylene (PP), low-density polyethylene (LDPE), polyether ether ketone (PEEK), and high-density polyethylene (HDPE), have been identified in various studies as common materials (Van de Velde and Kiekens, 2001; Wielage *et al.*, 2003; Rouison *et al.*, 2004; Paul *et al.*, 2008) often paired with synthetic fibers such as glass and carbon fibers (Maqsood and Rimašauskas, 2021). Improving the mechanical properties of plastics is achievable by incorporating high-strength materials, such as fibers, as reinforcing agents (Zahid *et al.*, 2019; Reis *et al.*, 2020). Generally, plastics exhibit subpar mechanical

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qualities. Composite materials have historically served vital roles in practical applications. Ancient civilizations, like the Egyptians circa 1500 BCE, utilized composite materials in constructing mud walls and laminated wood incorporating bamboo particles (Chawla, 2012). In 1800 AD, sword-making involved metal lamination techniques (Zaaba and Ismail, 2019). The continuous demand for composite materials, driven by their strength and eco-friendly features, has spurred advancements in design, manufacturing techniques, and technology (Mohanty *et al.*, 2004).

Researchers and engineers increasingly favor natural fiber-reinforced polymeric materials over conventional fibers due to the numerous advantages of natural fibers, such as easy decomposability, eco-friendliness, cost-effectiveness, and lightweight properties (Khalid *et al.*, 2021). Plants yielding natural fibers are categorized as primary or secondary based on their intended use. Primary plants like jute, sisal, and kenaf are grown primarily for their fiber content (Singleton *et al.*, 2003; Salisu *et al.*, 2019). In contrast, secondary plants like coir, oil palm, and pineapple are cultivated specifically for their fibers or strands(Pervaiz and Sain, 2003). Some of the important qualities of NFs reported in the literature are described in Table 2.

Fiber	**Density (g / cmÂ^3)**	**Tensile strength (MPa)**	**Tensile modulus (GPa)**	**Specific modulus**	**Elongation to break (%)**	**Moisture absorption (%)**	**World production (10Â^3 t)**
Sisal	1.33	600-700	38	29	3-Feb	11	378
Hemp	1.48	550-900	70	47	1.6	8	214
Flax	1.4	800-1500	60-80	26-46	1.2-1.6	7	830
Jute	1.46	400-800	30-Oct	21-Apr	1.8	12	2300
Kenaf	1.4	292	22	15	2	-	970
Banana		54-754	20-Jul	-	-	-	-
Coir	1.25	220	6	5	15-25	5 10	100
Bamboo	0.8	391-1000	48-89	-	-	-	10000
Pineapple leaf fiber		413-1627	34.5-82.5	-	EF	-	-
Abaca	1.5	980	-	-	-	-	70
Ramie	1.5	500	44	29	2	17-Dec	100
E - glass	2.55	2400	73	29	3.0 3	-	

Table 2: Characteristics of different natural fibers

Natural fiber-reinforced composites possess a multitude of favorable attributes and serve crucial roles across industries including plastics, electronics, packaging, and automotive applications (Ho *et al.*, 2012; Huda and Widiastuti, 2021). They not only reduce material expenses and weight but also offer sustainable solutions. These hybrid composites, reinforced with natural fibers, are employed in various consumer products like interior paneling, furniture, window panels, and chairs (Sarki *et al.*, 2011; Ho *et al.*, 2012). Furthermore, they stand as eco-friendly alternatives for interior paneling in automobiles and aircraft. Literature presents numerous studies showcasing the commendable mechanical qualities of these materials alongside their usage limitations. Natural fibers notably reduce composite weight (Venkateshwaran *et al.*, 2011). Studies investigating fiber length variations revealed that composites featuring 15 mm lengths exhibited superior flexural and tensile properties (Bisaria *et al.*, 2015). When utilized as reinforcement, these fibers mitigate tool wear during machining processes (Khalid *et al.*, 2021). Additionally, introducing components like wood flour and shells into the polymer enhances composite properties, reducing shrinkage and enhancing material resistance. These components play a role in imparting beneficial effects in the composites, such as minimizing shrinkage and enhancing creep resistance post-molding.

Benefits: Hemp is a quick-growing, highly renewable plant that offers an environmentally beneficial substitute for composite materials. Comparatively speaking to many other crops used for fiber reinforcement, it requires less water and pesticides. Because hemp fibers are often lightweight, composite items may weigh less overall. This is especially helpful in sectors like automotive and aviation where weight savings are essential. Hemp fibers are biodegradable, as opposed to synthetic fibers like fiberglass or carbon fiber. This indicates that hemp composites have the potential to degrade naturally at the end of their valuable lives, dropping their impact on the environment. Hemp fibers are suitable for applications requiring structural integrity, such as automotive parts, building supplies, and sporting goods, because they have a reasonable tensile strength and stiffness. As compare with other natural yarns like flax or jute, hemp yarns are frequently less expensive. Because of its affordability, hemp composites are a desirable option for many industries. When compared to the production of synthetic fibers, the manufacturing of hemp fibers frequently uses less energy, reducing the environmental impact.

Disadvantages: Because hemp fibers have a propensity to soak moisture, the composite material may eventually degrade as a result. Due to this restriction, they are less suitable for conditions where moisture exposure poses a threat without further mitigation. Hemp fibers' properties can change depending on things like the environment in which they are grown, how they are harvested, and how they are processed. It may be difficult to guarantee consistent material performance due to this variability. Because hemp fiber production may not be as common as that of other natural fibers, some businesses may worry about having a reliable and accessible supply chain. At high temperatures, hemp fibers could not perform as well as synthetic fibers. When exposed to high temperatures, they may soften or crumble, which limits their use in applications requiring high-temperature tolerance. Processing hemp fibers can be more difficult than processing synthetic fibers, requiring specialized tools and knowledge. This may raise manufacturing costs and prevent the use of hemp composites in some sectors. Compared to more established materials like fiberglass or carbon fiber, long-term performance data for hemp fiber-reinforced composites may be limited. When considering the application of hemp fiber-reinforced composites in outdoor settings, long-term performance and durability emerge as critical considerations. Various environmental factors, including humidity, temperature fluctuations, and UV radiation, can have detrimental effects on the service life of these composites. Notably, when subjected to continuous loads, composites reinforced with hemp fibers exhibit a higher susceptibility to creep compared to those reinforced with glass fibers. These challenges pose limitations on the widespread industrial adoption of hemp composite products. To mitigate these issues and enhance the characteristics of hemp fiber composites, manufacturers often employ strategies such as the incorporation of coupling agents and UV absorbers during the production process. These measures are aimed at bolstering the composite's resistance to the deteriorating influences of weathering conditions

Polymeric matrices: The matrix's responsibilities include transporting the loads to the fibers, protecting them from the outside environment, and controlling the composite form and surface appearance (Mohammed *et al.*, 2015). The properties of the matrix, such as its maximum service temperature, resistance to chemicals and moisture, and thermal stability, play a significant role in determining these aspects. As they have low mass and able to be treated at low degree of temperatures, polymers, both thermoplastic and thermoset, are now the most widely utilized matrix in hemp fiber composites (Koronis *et al.*, 2013; Pickering *et al.*, 2016). Table 3 summarizes the parameters of thermoplastic and thermoset polymeric matrices utilized for hemp fibers.

Thermoplastic resin: Due to their thermoplastic nature, both branched and linear polymers undergo reversible toughening and melting in response to temperature changes (Manaia *et al.*, 2019). When natural fibers are combined with thermoplastics, there's a potential for increased modulus as these fibers often possess higher moduli compared to the thermoplastic materials (Sgriccia *et al.*, 2008). Two primary processing methods utilized for hemp fiber composites are compounding and pressing through melting. The melt compounding process involves single- or twin-screw extruders and interior melt mixers used individually or in combination. Typically, either small or long yarns or loosely chopped fibers are employed in melt pressing. This method involves alternating the thermoplastic matrix with the fibers before applying heat and pressure. By meticulously controlling parameters like viscosity, pressure, temperature, and dwell time, and considering the fiber type and matrix, high-quality composites can be achieved (Mochane et al., 2019). Commonly discussed thermoplastic matrices include Polyethylene, polylactic acid (PLA), polystyrene, and polypropylene (PP)(Sain *et al.*, 2005; Mochane *et al.*, 2019).

Polymer	Price (kg) (USD)	Density (g / cmÂ^3)	Failure Strain (%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Glass Trans. Temp . (Tg Â° C)	Melting Temp. (Tm Â° C)
Thermoplastics							
PP	1.65	0.89-0.92	20-400	30-40	1.1-1.6	-10 to -23	161-170
HDPE	1.76	0.94-0.96	2-130	14.5-38	0.4-1.5	-100 to -60	120-140
PS	2.14	1.04-1.06	1-2.5	25-69	5-Apr	100	110-135
PLA	2.42	1.21-1.25	2.5-6	21-60	0.35-3.5	45 to 60	150-162
Thermosets							
Epoxy	-	1.1-1.4	6-Jan	35-100	6-Mar	60 to 170	-
Polyester	-	1.2-1.5	7-Apr	40-90	2-4.5	-47 to 120	-

Table 3: Characteristics of thermoplastic and thermoset polymer matrices.

Polypropylene is often favored due to its comparison to other thermoplastic matrices. However, the lack of strong interfacial attraction between hydrophilic hemp fibers and PP can hinder stress transmission between them. To enhance this adhesion, coupling agents like maleated polypropylene (MAPP) have been employed (Li and Sain, 2003; Pickering *et al.*, 2007; Al-Oqla and Sapuan, 2014; Sullins *et al.*, 2017) primarily for their cost-effective production and efficient interaction with the fibers' hydroxyl groups (Keener *et al.*, 2004). The influence of maleated polypropylene on the mechanical properties of PP composites reinforced with hemp fibers was investigated. Compared to composites without a coupling agent, the formulation with 40% hemp fibers exhibited a 49% increase in tensile strength and a 38% increase in flexural strength after adding 4% w/w maleated polypropylene (Mutjé *et al.*, 2006).

Critical considerations include the melting point of the polymeric matrix and the temperature at which natural fibers start to thermally degrade. The thermal breakdown of hemp fibers, likely occurring around 260°C for hemicelluloses and 360°C for cellulose (Shahzad, 2013), may be triggered by the higher melting temperature of certain thermoplastics. This thermal exposure can lead to physical and/or chemical structural changes in fibers, including de-carboxylation, dehydration, oxidation, de-polymerization, re crystallization, and hydrolysis (Gassan and Bledzki, 2001). For using polyethylene and polypropylene as matrices for hemp fibers, their melting points must be below 200 degrees Celsius (Pickering *et al.*, 2016; Mochane *et al.*, 2019). Green or 100% bio-based composites are gaining popularity, and one such thermoplastic biopolymer matrix is poly lactic acid (PLA). PLA offers unique features such as high impact resistance, excellent transparency, and a glossy appearance. However, it has inherent brittleness, low toughness, low melt viscosity, high cost and a tendency to decompose. For long-life applications, these drawbacks need to be considered (Ray and Bousmina, 2005; Siakeng *et al.*, 2019). PLA is relatively expensive, making it cost-prohibitive for large-scale production, even when its strength surpasses that of PP. As an example, PLA is at least 1.5 times more costly than PP (Siakeng *et al.*, 2019).

Thermoset matrix: Thermoset matrices consist of cross-linked polymers that undergo a chemical reaction with a hardener or curing agent to achieve permanent hardening. These materials, including vinyl esters, epoxies, polyimides, and phenolics, are valued for their exceptional mechanical properties, dimensional stability, and chemical resistance, making them essential in advanced composite applications within industries like construction, aerospace, and insulation (Mochane *et al.*, 2019). Hardeners commonly used include multifunctional amines, anhydrides, and acids (Mashouf Roudsari *et al.*, 2017).

Among natural fibers, polyester and epoxy are the most effective in reinforcing thermosets. The processing temperatures for these materials generally exceed the breakdown temperature of hemp fibers, which initiates at 150°C and could lead to thermomechanical degradation. Thermosets offer the advantage of lower processing temperatures, preventing deterioration, and facilitating the incorporation of a higher quantity of natural fibers into the composite matrix compared to thermoplastics. In contrast, thermoplastics provide more design flexibility but still face challenges in efficient recycling (Mochane *et al.*, 2019; Pappu *et al.*, 2019). Various processing techniques are employed to thermoset composites, manual layup, vacuum-aided resin transferal casting, sheet casting complex, resin transfer molding, pultrusion. For high-end applications, such as those in the aerospace industry, vacuum-assisted methods are typically employed. The following are some benefits of vacuum-assisted procedures: (1) laminates with a higher fiber content; (2) laminates with fewer voids; and (3) laminates with improved fiber wet-out as a result of pr. Hemp fiber-reinforced polyester amalgams were created via resin transfer molding. They were able to source pieces of excellent flexural quality. However, it was discovered that these materials' impact strength was rather poor to rival glass fiber in structural applications.

Repurposing thermoset polymer matrices and thermoplastic: Biodegradability is gaining increased importance, with thermoplastics offering distinct advantages over thermosets due to their capability to reshape when heated beyond their melt point. Recycling thermoset composites encompasses three main approaches:

Chemical recycling: This method involves procedures like pyrolysis, where the matter is melted in an oxygen-free environment to produce one or more recoverable substances.

Particle recycling: Here, the thermoset composite is mechanically milled into particles, serving as fillers in new plastic or composite applications.

Energy recycling: This involves incinerating the material to extract energy from its chemical composition.

Similarly, thermoplastic composites can be recycled using energy or chemical processes akin to thermoset composites. Additionally, they can undergo recycling through initial grinding, followed by reprocessing using methods like injection molding (Pickering *et al.*, 2007). At the end of their useful life, hemp fibers, being renewable, can be incinerated. Regarding natural fiber-reinforced composites, mechanical recycling takes precedence over thermal recycling from an eco-performance perspective. However, issues surrounding thermal breakdown during recycling and reprocessing can significantly affect the eco-performance of natural fiber composites. Life-cycle assessments highlight that natural fibers, owing to their lower weight, possess an advantage over glass fibers rather than their recyclability (Peijs, 2000).

Reinforcement of hemp fiber with hybrid composites: Hybridization in polymeric materials involves combining one or more polymers with various fiber types to reinforce them. Particularly in high-end applications, hybridization broadens versatility and enhances composite qualities (Gurunathan *et al.*, 2015; Safri *et al.*, 2018). These composites offer increased stiffness and strength, improved impact and fatigue resistance, enhanced fracture toughness, and reduced weight and overall cost (Panthapulakkal and Sain, 2007; Dong *et al.*, 2016). Advancements in textile engineering enable the creation of cost-effective hybrid fabrics with controlled fiber composition, orientation, and texture, such as plain, satin, and twill fabrics. In a study focusing on PLA composites reinforced with hemp fibers, twill fabric, characterized by closer fiber packing, showed superior impact strength and improved thermal and viscoelastic properties compared to plain-woven fabric (Song *et al.*, 2012).

Reinforcement of synthetic and hemp fiber composites: Employing a combination of synthetic and hemp fiber-reinforced composites enhances resulting composite materials' performance and attributes while mitigating moisture absorption and maintaining cost-effectiveness (Hajiha and Sain, 2015). For instance, a comparative study highlighted strengths in different stress scenarios between hemp/glass and bamboo/glass fiber hybrid-reinforced epoxy composites (Sature and Mache, 2015). Water absorption significantly influenced the mechanical properties of hemp fiber-reinforced polypropylene (PP) composites, leading to debonding at the matrix-fiber interface. However, hybrid composites, incorporating glass fibers, notably reduced water absorption without significantly impacting strength properties (Panthapulakkal and Sain, 2007). In pultruded polyester composites, the inclusion of glass fibers decreased water absorption, and hybrid composites exhibited better strength retention over time (Akil *et al.*, 2014).

Reinforcement of natural and hemp fiber composites: Hybridizing natural fibers like jute, hemp, and flax within epoxy composites resulted in improved mechanical properties when compared and studied (Swolfs *et al.*, 2014; Sarasini *et al.*, 2017; Mochane *et al.*, 2019). These hybrid composites showcased remarkable mechanical properties, especially those combining hemp and flax fiber reinforcement with epoxy resin, exhibiting enhanced tensile strength, elastic modulus, and impact strength. Interwoven hybrid composites of kenaf/jute and kenaf/hemp yarns within an epoxy matrix displayed superior mechanical properties and improved resistance to water compared to their individual woven counterparts (Maslinda *et al.*, 2017; Chaudhary *et al.*, 2018).

Industrial uses: Industrial hemp has diverse applications in numerous industries, spanning composites, textiles, automotive components, heat-insulating materials, fiberboard, and building construction (Holbery and Houston, 2006). Hemp concrete, for instance, demonstrates significant benefits, consuming 45% less energy compared to cellular concrete and stabilizing indoor humidity levels. Recent research also highlights the suitability of hemp fibers for sound insulation and absorption. Additionally, these fibers excel in vibration damping, prompting exploration into their use in brake pads, sporting goods, and musical instruments. Notably, in the automotive sector, hemp-reinforced composites offer advantages like increased strength (25% to 30% stronger at the same weight) and non-brittle fracture characteristics, crucial for interior plastic components (table 4).

Country	Manufacturer	Model	Applications
	Saturn	L300	Package trays and door panel
		Trucks	Internal engine cover , engine insulation , sun visor , interior insulation , bumper , wheel box , and roof cover
France	Peugeot	406	Front and rear door panels , seat backs , and parcel shelf
France	Citroen	C3 Picasso , C5	Parcel shelves , boot linings , door panels, interior door panelling , and mud guards
Germany	Opel	Vectra , Astra , Zafira	Door panels , pillar cover panel , head – liner panel , and instrumental panel
Germany	Volkswagen	Passat Variant , Golf , A4 , Bora	Seat back , door panel , boot - lid finish panel , and boot - liner
Germany	Audi	A2 , A3 , A4 , A4, Avant , A6 , A8 , Roadstar , Coupe	Boot - liner , spare tire - lining , side and back door panel , seat back , and hat rack
Germany	Daimler Chrysler	A , C , E , and S class , EvoBus (exterior)	Pillar cover panel , door panels , car windshield / car dashboard , and business table
Germany	BMW	3 , 5 and 7 series and other Pilot	Seat back , headliner panel , boot - lining , door panels , noise insulation panels , and moulded foot well linings
Germany	Mercedes Benz	C , S , E , and A classes	Door panels (flax / sisal / wood fibers with epoxy resin / UP matrix) , glove box (cotton fibers / wood molded , flax / sisal) , instrument panel support , insulation (cotton fiber) , molding rod / apertures , seat backrest panel

Table 4: Automotive applications of natural fiber-reinforced polymers composite

CONCLUSION: Currently, there has been significant research and rising curiosity in Cannabis sativa, commonly referred to as industrial hemp, as a source for innovative materials. This interest is well-founded, primarily owing to the exceptional characteristics of hemp fibers, including their low density, high specific strength, and stiffness. Additionally, hemp fibers are entirely biodegradable, cost-effective, and sourced from renewable resources. As a result, hemp is being increasingly explored as a potential alternative to synthetic fibers. The main drawbacks of hemp fibers, however, include their inherent hydrophilicity, low microbial resistance, low heat stability, and fluctuating characteristics due to growth and maturity. Through advanced research and development, hemp fibers have seen improvements in their wettability, dimensional stability, and the bonding interface between the matrix and fibers, all aimed at enhancing their mechanical performance. The most promising applications for hemp fibers involve their utilization in hybridization or as reinforcement in polymeric composites. Hybridization offers a means to overcome limitations and creates new possibilities for expanding the use of hemp fibers. It's important to highlight that hemp fiber hybrid composites provide a competitive edge in various industrial sectors. These industries cover a wide range of applications, including automotive, sporting goods, sound insulation, musical instruments, brake pad applications, fiberboard, composites, heat-insulating materials, fiber-reinforced concrete, and textiles, in which industrial hemp is utilized. To further broaden their applications and enhance their properties, additional research is essential. When investigating the potential uses of hemp fiber composites, particular attention needs to be given to addressing challenges related to biodegradability.

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