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**Research Paper**

# Natural Fiber Reinforced Polymer Composites: A Comprehensive Review with Special Emphasis on Hemp Fiber Reinforced Polyethylene Composites

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***Abstract***
*Natural fiber reinforced polymer composites (NFRPCs) have attracted significant attention in recent years due to increasing environmental awareness, depletion of petroleum resources, and demand for sustainable engineering materials. Natural fibers such as hemp, flax, jute, sisal, kenaf, bamboo, banana, and coir have emerged as suitable alternatives to synthetic fibers because of their low density, biodegradability, renewability, and acceptable mechanical properties. Among various natural fibers, hemp fiber has gained considerable industrial and research interest owing to its excellent tensile strength, high stiffness, low moisture requirement, and eco-friendly nature. This paper presents a detailed review of natural fiber reinforced polymer composites with special emphasis on hemp fiber reinforced polyethylene composites. The paper discusses the classification of composites, matrix materials, natural fiber characteristics, polyethylene as a matrix, fiber-matrix interaction, advantages of hemp fiber, and applications of natural fiber composites. A comprehensive literature review based exclusively on previous studies provided in the source document is presented to analyze the effects of chemical treatments, fiber loading, moisture absorption, interfacial bonding, and processing techniques on composite performance. The review concludes that chemical modification of fibers significantly improves mechanical properties, thermal stability, and water resistance of composites. Natural fiber composites possess enormous potential for automotive, transportation, construction, packaging, and bioengineering applications because of their lightweight nature and environmental sustainability.*

***Keywords:*** *Natural fiber composites, Hemp fiber, Polyethylene composites, Mechanical properties*

## I. INTRODUCTION

In recent years, increasing environmental concerns, depletion of non-renewable resources, and the growing demand for sustainable engineering materials have accelerated research on natural fiber reinforced polymer composites (NFRPCs). These composites are considered promising alternatives to conventional synthetic fiber composites because of their low density, biodegradability, renewability, low cost, and satisfactory mechanical properties. Natural fibers such as hemp, flax, jute, sisal, kenaf, bamboo, banana, and coir are abundantly available and require significantly less energy for production compared to synthetic fibers like glass and carbon fibers. Their utilization contributes to reduced environmental pollution and lower carbon emissions. Composite materials generally consist of two major constituents: the matrix phase and the reinforcement phase. The matrix binds the reinforcing fibers together, transfers applied loads, and protects the fibers from environmental damage, while the reinforcing fibers provide strength and stiffness to the composite. The combination of these constituents results in materials possessing superior mechanical and physical properties compared to the individual components. Among various polymer matrices, polyethylene (PE) is widely used because of its low cost, lightweight nature, chemical resistance, recyclability, and ease of processing.

Among natural fibers, hemp fiber has attracted considerable attention due to its excellent tensile strength, high stiffness, low density, and eco-friendly characteristics. Hemp fibers possess good mechanical properties and are increasingly used as reinforcement in polymer composites for automotive, packaging, construction, transportation, and bioengineering applications. However, natural fiber composites also exhibit certain limitations such as poor interfacial adhesion between hydrophilic fibers and hydrophobic polymer matrices, moisture absorption, and relatively lower thermal stability. These issues adversely affect the mechanical performance and durability of composites. To overcome these limitations, various chemical treatments and surface modification techniques such as alkali treatment, silane treatment, acetylation, and maleic anhydride treatment have been widely employed to improve fiber–matrix compatibility and enhance composite properties. Several researchers have reported significant improvements in tensile strength, flexural strength, thermal stability, and moisture resistance after chemical treatment of natural fibers.

The present paper provides a comprehensive review of natural fiber reinforced polymer composites with special emphasis on hemp fiber reinforced polyethylene composites. The study discusses the classification of composites, characteristics of natural fibers, polyethylene as matrix material, fiber–matrix interaction, and recent developments in chemical treatments and processing techniques affecting the mechanical, thermal, and physical properties of composites.

## II. CLASSIFICATION OF COMPOSITES

Composites are generally classified according to the type of matrix material used. These include Polymer Matrix Composites (PMCs), Metal Matrix Composites (MMCs), Ceramic Matrix Composites (CMCs), and Carbon Matrix Composites. Polymer Matrix Composites are the most widely used because polymers are lightweight, inexpensive, easy to process, and possess good chemical resistance. Thermoplastic and thermosetting polymers are commonly used matrices in natural fiber composites.

- **Metal Matrix Composites** consist of metal matrices such as aluminum and magnesium reinforced with fibers or particles to improve strength and stiffness.
- **Ceramic Matrix Composites** are suitable for high-temperature applications because of their superior thermal resistance.
- **Carbon Matrix Composites** use carbon fibers in carbon matrices and are employed in extremely high-temperature engineering applications.

## III. CONSTITUENTS OF COMPOSITES

Composite materials consist mainly of matrix and reinforcing phases. The matrix phase binds fibers together and transfers load uniformly throughout the structure. Thermoplastics such as polyethylene and polypropylene and thermosetting polymers such as epoxy and polyester are commonly used matrices. The reinforcing phase consists of fibers that provide strength and stiffness to composites. Natural fibers mainly contain cellulose, hemicellulose, and lignin. Cellulose is responsible for the strength and rigidity of fibers, whereas lignin acts as a binding material.

## IV. NATURAL FIBERS

Natural fibers are renewable materials obtained from plants, animals, and minerals. Plant fibers are the most commonly used natural fibers in composite manufacturing. These fibers are categorized into bast fibers, leaf fibers, fruit fibers, wood fibers, and grass fibers. Hemp fiber is one of the most important bast fibers due to its superior mechanical properties. It contains approximately 70% cellulose, 20% hemicellulose, and 5% lignin. Hemp fibers exhibit tensile strength in the range of 550–900 MPa and possess good stiffness and durability. Despite these advantages, natural fibers absorb moisture because of their hydrophilic nature, which reduces dimensional stability and interfacial adhesion with hydrophobic polymer matrices.

## V. POLYETHYLENE AS MATRIX MATERIAL

Polyethylene (PE) is one of the most widely used thermoplastic polymers in natural fiber composites. It possesses good chemical resistance, flexibility, durability, and low density. PE can easily be melted and remolded, making it highly suitable for composite manufacturing. However, polyethylene is non-biodegradable and may cause environmental pollution if improperly disposed.

## VI. FIBER-MATRIX INTERFACE

The fiber-matrix interface plays an important role in determining the mechanical performance of composites. Strong interfacial adhesion improves stress transfer between fibers and matrix, thereby increasing tensile strength, flexural strength, and impact resistance. Poor interfacial bonding leads to Fiber pull-out, Crack propagation, Reduced strength, Increased moisture absorption

To overcome these issues, chemical treatments such as alkali treatment, silane treatment, acetylation, maleic anhydride treatment, and benzoylation are commonly applied to modify fiber surfaces and improve compatibility with polymer matrices.

## VII. STRUCTURE AND MECHANICAL PROPERTIES OF NATURAL FIBER

The fiber consists of number of walls, namely primary and secondary wall, which in turn, consists of two walls (W1 and W2). The fiber walls are made of three major constituents (cellulose, lignin and hemicellulose) is represented by Fig. 1. The cellulose content varies from primary to secondary walls. But hemicellulose and lignin content remain same in all of the fiber walls.

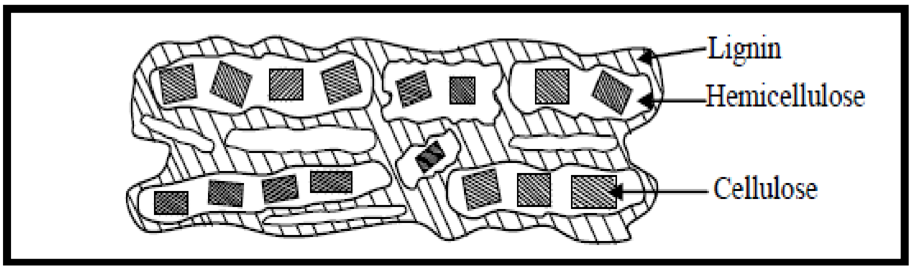


**Fig. 1: Constituents of natural fiber (Kabir 2012)**

The cellulose content is the major part of fiber structure. It is responsible to provide strength to the fiber. Each cellulose molecule is connected with each other by a hydrogen bond. The lignin content binds the cellulose and hemicellulose together and in turn holds the micro fibrils together to form a fiber unit. The hemicellulose molecules are hydrogen bonded with cellulose micro fibrils **(Kabir 2012)**.

**Table 1: Mechanical properties of different fibers (Li et al. 2007)**

| Fiber | Density (g/cm$^3$) | Elongation (%) | Tensile Strength (MPa) | Young's Modulus (GPa) |
|---|---|---|---|---|
| **Cotton** | 1.5-1.6 | 3.0-10.0 | 287-597 | 5.5-12.6 |
| **Jute** | 1.3-1.46 | 1.5-1.8 | 393-800 | 10-30 |
| **Flax** | 1.4-1.5 | 1.2-3.2 | 345-1500 | 27.6-80 |
| **Hemp** | 1.48 | 1.6 | 550-900 | 70 |
| **Ramie** | 1.5 | 2.0-3.8 | 220-938 | 44-128 |
| **Sisal** | 1.33-1.5 | 2.0-1.4 | 400-700 | 9.0-38.0 |
| **Coir** | 1.2 | 15.0-30.0 | 175-220 | 4.0-6.0 |
| **Softwood** | 1.5 | - | 1000 | 40.0 |
| **E-glass** | 2.5 | 2.5-3.0 | 2000-3500 | 70.0 |
| **S-glass** | 2.5 | 2.8 | 4570 | 86.0 |
| **Aramide (normal)** | 1.4 | 3.3-3.7 | 3000-3150 | 63.0-67.0 |
| **Carbon (standard)** | 1.4 | 1.4-1.8 | 4000 | 230.0-240.0 |

## VIII. HEMP AS A NATURAL FIBER

Hemp fiber belongs to the Cannabis family. It is an annual plant that grows in temperate climates. Hemp is known to provide an excellent mechanical strength and Young's modulus, consists of cellulose (55–72%), hemicelluloses (8–19%), lignin (2–5%), wax (<1%) and minerals (4%). It is estimated that in recent years, China has become the world leader in hemp fiber production, (nearly one third of total production. However, the application of hemp fiber is still mainly limited to the textile industry. The tensile strength, elastic modulus, and flexural strength of the composite prepared with alkali treated hemp fiber are much higher than those of poly lactic acid (PLA) alone (Hassan et al. 2012). Hemp fiber (Cannabis sativa) is one of the plant-based bast fibers and is recently gaining the attention as diversified reinforcing applications in engineering composites industry. One of the limitations of using this fiber in high strength composite applications is its poor adhesion properties with the polymeric matrix and also poor dimensional stability because fibers are normally hydrophilic while the matrices are hydrophobic. It results in degrading the mechanical properties of composites during the service. Additionally, hemp fiber cannot resist high temperature, which limits the curing or extrusion during composite manufacturing. Celluloses in hemp fiber are identified as a main structural component of the fiber. While lignin and hemicelluloses also play an important role in controlling its properties (Kabir et al. 2011).

**Table 2 Tensile properties of hemp fibers (Shahzad, 2011)**

| Tensile Strength (MPa) | Tensile modulus (GPa) | Elongation At break (%) |
|---|---|---|
| 690 | – | 1.6 |
| 1235 | – | 4.2 |
| 310–750 | 30–60 | 2–4 |
| 550–900 | 70 | 1.6 |
| 895 | 25 | – |
| 500–1040 | 32–70 | 1.6 |
| 690–1000 | 70 | 1.0–1.6 |
| 920 | 50 | – |
| 270–900 | 20–70 | 1.6 |

In hemp plant, fibers are contained within the tissues of the stems which help to hold the plant erect, in doing so these fibers impart strength and stiffness to the tree. This high strength and stiffness of hemp fibers makes them a useful material to be used as reinforcement in composite materials **(Shahzad, 2011).**

## IX. DETAILED LITERATURE REVIEW

A large number of researchers have investigated the mechanical, physical, thermal, and morphological properties of natural fiber reinforced polymer composites. Anuar et al. (2011) investigated the tensile and flexural properties of thermoplastic elastomer composites reinforced with 20% kenaf fiber. The researchers observed that maleic anhydride treatment significantly improved tensile strength by nearly 81%. Scanning Electron Microscopy (SEM) revealed better fiber-matrix adhesion after treatment, resulting in enhanced mechanical performance.

Cheung et al. (2009) discussed the applications of natural fiber composites in bioengineering and environmental engineering. They concluded that natural fibers possess sufficient ductility and elastic modulus for applications such as orthopedic joints and bone fixation systems. The study highlighted the environmental advantages of plant fiber composites.

**Behzad and Sain (2007)** studied thermal conductivity of hemp fiber composites and found that fiber orientation significantly affects thermal behavior. **Naik and Mishra (2007)** observed that maleic anhydride treatment reduced water and steam absorption in natural fiber composites. **Li et al. (2007)** reviewed various chemical treatments and concluded that they improve fiber–matrix adhesion, mechanical properties, and moisture resistance. **Panthapulakkal and Sain (2007)** showed that hybridization of hemp with glass fibers enhanced flexural, impact, and water resistance properties. John and **Anandjiwala (2008)** reviewed chemical modifications of natural fibers and highlighted their importance in improving composite performance. **Favaro et al. (2010)** and **Rahman et al. (2010)** demonstrated that chemical treatment of fibers improved adhesion and mechanical properties of HDPE-based composites. **Kabir et al. (2011), Oza et al. (2011),** and **Santos et al. (2011)** reported enhanced thermal and mechanical behavior of hemp and sisal fiber composites after alkali and silane treatments. **Ku et al. (2011) and Kumar et al. (2011)** reviewed tensile and mechanical properties of natural fiber composites and emphasized their lightweight, eco-friendly, and high-strength characteristics. **Michel and Billington (2012)**, **Hassan et al. (2012), and Faruk et al. (2012)** discussed the environmental benefits, weathering behavior, processing methods, and mechanical performance of bio-composites reinforced with natural fibers. **Lu and Oza (2013), Fang et al. (2013), and Robertson et al. (2013)** investigated hemp fiber composites and found that fiber treatment, coupling agents, and optimized fiber loading significantly improve thermal stability, moisture resistance, and mechanical properties. **Cao et al. (2013)** studied flax/hemp-HDPE composites prepared through screw extrusion techniques. Fourier Transform Infrared Radiation (FTIR) analysis revealed that sodium hydroxide and maleic anhydride treatments effectively removed non-cellulosic materials from fibers, resulting in improved tensile strength and flexural modulus. Water absorption was also reduced after chemical treatment. **Chandramohan et al. (2011)** reviewed the importance and future potential of natural fiber composites. The researchers emphasized that natural fibers can provide cost-effective and lightweight materials suitable for advanced engineering applications. Their study also highlighted the lack of sufficient research on composites reinforced with sisal, banana, and roselle fibers. **Chen et al. (2013)** analyzed the mechanical properties and water absorption behavior of hemp fiber reinforced unsaturated polyester composites. Hemp fibers were chemically treated using Isocyanate Ethyl Methacrylate. The study reported improved tensile strength, flexural strength, flexural modulus, and water resistance due to enhanced interfacial adhesion. **Dhakal et al. (2007)** investigated the effect of water absorption on hemp-polyester composites. Composite specimens were immersed in water at different temperatures and durations. The results demonstrated that tensile and flexural properties decreased with increasing moisture absorption, indicating the hydrophilic nature of hemp fibers. **Duval et al. (2011)** studied the influence of stem sampling area on the mechanical properties of hemp fibers. Tensile testing showed that fibers extracted from the middle portion of the stem exhibited higher tensile strength compared to fibers obtained from the top and bottom sections. **Guduri et al. (2009)** investigated flax fiber reinforced copolyester composites prepared using compression molding techniques. Alkali-treated fibers exhibited superior tensile and flexural properties due to improved fiber-matrix adhesion. FTIR and SEM analyses confirmed surface modification after chemical treatment. **Ho et al. (2011)** discussed critical factors affecting the manufacturing processes of natural fiber composites. The study emphasized the significance of fiber wettability, processing techniques, and interfacial bonding on composite performance. Poor bonding and poor wettability were identified as major limitations in natural fiber composites. **John et al. (2009)** evaluated chemically modified flax fiber reinforced polypropylene composites. Zein-treated fibers showed improved interfacial adhesion and better flexural properties compared to untreated composites. SEM analysis confirmed enhanced bonding between fibers and matrix. **Joshi et al. (2004)** concluded that natural fiber composites are environmentally superior to glass fiber composites due to their lower environmental impact, lower energy consumption, and reduced pollution during manufacturing.

**Kabir et al. (2011)** reported that chemical modification of hemp fibers significantly improved fiber-matrix adhesion and mechanical properties. The study also observed that untreated hemp fibers absorbed more moisture, which reduced composite performance. **Kaczmar et al. (2011)** investigated alkali and maleic anhydride treatment of hemp fibers reinforced in polypropylene composites. SEM and FTIR analyses confirmed improved interfacial bonding and enhanced thermal and mechanical properties. **Kord et al. (2011)** studied sawdust flour reinforced polypropylene composites using maleic anhydride as a coupling agent. The results indicated improvements in tensile, flexural, and impact properties because of stronger interfacial bonding. **Kumar et al. (2011)** reviewed various chemical modification techniques for natural fibers and concluded that alkali treatment is one of the most effective methods for improving mechanical properties and reducing moisture absorption. **Troedec et al. (2009)** studied the physico-chemical interactions between hemp fibers and lime mineral matrices using SEM, FTIR, and X-ray diffraction techniques. The researchers observed improved rigidity after lime water treatment. **Li et al. (2007)** extensively reviewed chemical treatments for natural fibers including alkali, silane, acetylation, benzoylation, acrylation, isocyanate, and permanganate treatments. These treatments improved fiber-matrix adhesion and reduced moisture absorption. **Liu et al. (2009)** studied banana fiber reinforced HDPE/nylon-6 composites. Maleic anhydride grafted polyethylene improved flexural properties and interfacial bonding. However, water absorption increased with nylon addition.

**Madsen et al. (2009)** developed analytical models to study stiffness and porosity in plant fiber composites. The study emphasized the influence of fiber orientation, fiber length, and porosity on mechanical behavior. **Prasad et al. (2011)** investigated jowar fiber reinforced polyester composites and compared their performance with sisal and bamboo composites. Jowar composites exhibited higher tensile and flexural strength under similar processing conditions. **Singhal et al. (2014)** evaluated the effects of alkali, silane, benzyl chloride, and maleic anhydride treatments on jute fiber composites. Chemically treated composites showed significantly better damping and strength properties than untreated composites. **Souza et al. (2011)** analyzed HDPE/textile fiber composites produced through injection molding. Sulphuric acid treatment improved fiber dispersion and interfacial bonding, resulting in enhanced tensile properties. **Tayeb et al. (2009)** studied sugarcane/polyester composites at different fiber lengths. SEM analysis indicated that 5 mm fiber length provided the best mechanical properties due to optimum stress transfer. **Thygesen et al. (2006)** compared hemp fiber composites with glass fiber composites for wind turbine applications. Hemp composites showed good stiffness but lower tensile strength compared to glass fiber composites. **Rahman et al. (2010)** manufactured rice husk reinforced polyethylene composites and observed that alkaline treatment significantly improved mechanical properties and interfacial bonding compared to untreated fibers.

## X. CONCLUSIONS

a) Natural fiber reinforced polymer composites are increasingly becoming important engineering materials due to their environmental sustainability, low density, biodegradability, and satisfactory mechanical properties. Hemp fiber reinforced polyethylene composites have demonstrated considerable potential for industrial applications because of their lightweight nature, good stiffness, and cost-effectiveness.
b) The literature review clearly indicates that chemical treatments play a vital role in improving interfacial adhesion between natural fibers and polymer matrices. Alkali treatment, maleic anhydride treatment, silane treatment, and other surface modification techniques significantly enhance tensile strength, flexural strength, thermal stability, and moisture resistance.
c) Although natural fiber composites still face challenges such as moisture absorption and lower thermal stability, continuous advancements in fiber treatment methods and processing technologies are expanding

their industrial applicability. Future research should focus on hybrid composites, improved surface modification techniques, moisture resistance, and large-scale industrial processing methods.

d) Natural fiber composites represent a promising pathway toward sustainable engineering materials and environmentally friendly manufacturing technologies.

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