

## REVIEW ARTICLE

# A SHORT REVIEW ON PROCESSING METHODS, MECHANICAL PROPERTIES AND RECENT ADVANCEMENTS IN NATURAL FIBER COMPOSITES

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## ABSTRACT

Natural Fiber Composites (NFCs) have gained significant attention in the past few decades across automotive and aerospace sectors. These fibers have the largescope to dominate the synthetic fibers in view of cost effectiveness, eco – friendly nature and better mechanical properties. However, the performance of these composites rely on fiber type, orientation, matrix material, reinforcement, weight fraction, processing methods etc. Therefore, this paper provides a comprehensive review on the mechanical performance of various natural composites highlighting different matrix – reinforcement combinations. Emphasis was also given w.r.t to challenges associated with the preparation and testing of composites. Effect of chemical treatments in view of improved mechanical properties is also discussed with regards to the durability. This review paper also gives the future directions and potential applications of NFCs in multiple fields for sustainable eco-friendly engineering.

## KEYWORDS

Natural Fiber Composites, flax, hemp, sisal, jute, mechanical properties

## 1. INTRODUCTION

Natural fiber-reinforced composites have garnered considerable interest as a sustainable substitute for conventional synthetic materials. These composites integrate natural fibers derived from renewable resources, including flora and fauna, with a polymer matrix to produce materials with distinctive characteristics. This article aims to enhance the existing knowledge in this domain by exploring recent developments, applications, and emerging trends, thus fostering the creation of new, environmentally sustainable solutions for the future 1 (Bibri et al., 2024). Section 2 provides an overview of natural fibers, including their classification and various types. Section 3 delves into the different types of composites, their processing methods, and properties. Finally, later sections conclude by discussing the mechanical properties, behavior, and applications of

natural fibers in various orientations, along with their future potential.

## 2. NATURAL FIBRES AND THEIR CLASSIFICATION

Natural fibres are sourced from plants, animals, or minerals. Plant-based fibres include cotton, flax, jute, hemp, and bamboo; animal-based fibres include wool, silk, and hair; while mineral fibres include asbestos. Figure 1 shows that fibres are broadly classified into natural and man-made categories. Man-made fibres are created through chemical processes and are further divided into two groups: natural polymer fibres (such as viscose, modal, lyocell, and acetate, which are cellulose-based) and synthetic polymer fibres (including polyesters, polyolefins, polyamides, polyvinyl, and polyurethanes). This classification is vital for selecting the right fibre for various applications, considering attributes like strength, durability, cost, and environmental impact.

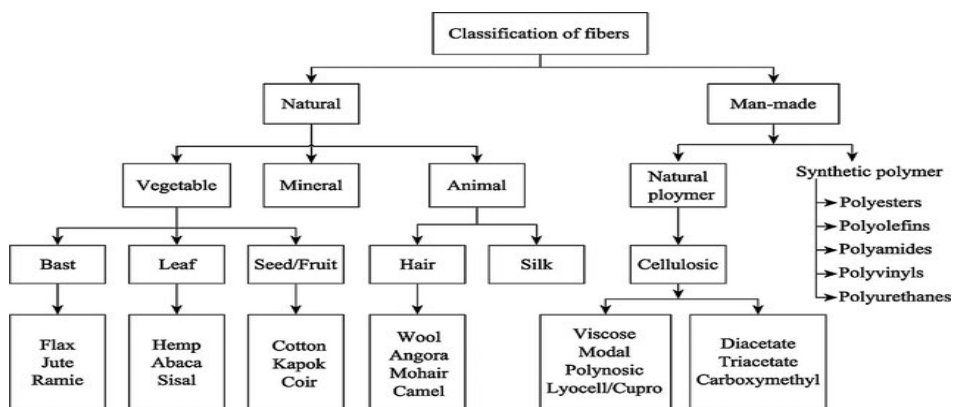


Figure 1: Classifications of Fibers

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Plant-based fibres, sourced from various parts of plants, have been used for centuries in the production of textiles, paper, and other materials (Syduzzaman, et al., 2020; Thakker and Sun, 2021).

## 2.1 BastFibers

### 2.1.1 Flax (*Linum usitatissimum*)



Figure 2: (a) Flax plant

(b) Flax Fiber

Notwithstanding these advancements, the composites fabricated with flax exhibit issues with moisture absorption and impact resistance. Therefore, researchers need to focus on flax-based composites to improve their overall performance and ductility, with the goal of making them more sustainable in a wide range of fields. This is because high ductility in composites makes them better at handling damage, which is important for making sure performance and safety in aerospace and automotive structures.

Fibre extraction encompasses operations illustrated in Figure 2 (a, b), such as retting and scorching, which modify the characteristics of the fibers. Retting employs enzymes to decompose the pectin encasing the flax fibers, facilitating their separation.

### 2.1.2 Jute (*Corchorus capsularis*)

Asia's regions, including India, Bangladesh, China, and Myanmar, cultivate jute, an important natural fiber within four months, the jute plant reaches a height of 15–20 cm, after which the fibers undergo harvesting.

The extraction process involves retting, which can be performed using either chemical methods or biological processes in biological shown in Figure 3 (a,b) retting, harvested stalks are bundled and soaked in water for approximately 20 days. This process breaks down the pectin that binds the bast fibre to the woody core, enabling the fibres to be separated. The extracted fibres are then dried for further use.



Figure 3: (a) Jute

(b) Jute fiber

Jute's durability and versatility make it a valuable material for a variety of applications, including textiles, ropes, and sacks.

### 2.1.3 Ramie (*Boehmerianivea*)

For over a century, the native countries of China, Japan, and Malaysia have abundantly farmed ramie, a herbaceous perennial, for use as a textile

fabric. This rapidly proliferating, non-branching plant may reach heights of 1 to 2 meters.

Fibers derived from the stem of ramie are among the most robust and elongated natural bast fibers. Often used in conjunction with cotton for sweater production, they find applications in upholstery, gas mantles, fishing nets, maritime packings, and other areas.



Figure 4:(a) Ramie Plant

(b) Ramie Fiber

Additionally, industries like automotive, furniture, and construction are exploring ramie fibers for bio-based products. Industries such as textiles, pulp, paper, agrochemicals, and composites extensively use them. Shown in Figure 4 (a, b). The fiber processing techniques for ramie are similar to those used for linen derived from flax.

## 2.2 Leaf Fibers



Figure 5:(a) Hemp Plant



(b) Hemp Fiber

The harvesting process entails the mechanical separation of the woody core from the bast fibers (Figures 5a, b). We purify the core to achieve the required quality and occasionally section it to precise dimensions. We further treat the bastfibres to create yarn or aggregate them for use in diverse applications. The adaptability and sustainability of hemp render it a useful resource across various industries, including textiles, building, and composite manufacture.

### 2.2.2 Abaca fiber (*Musa textilis*)

The *Musa textilis* plant produces abaca fibre, a robust and resilient natural fibre known for its adaptability in numerous applications. Known as "Manila hemp," farmers primarily cultivate it in the Philippines, its original region, and other Southeast Asian nations. Abaca fibers provide remarkable tensile strength, flexibility, and resilience to seawater, making them ideal for maritime and rope applications.



Figure 6: (a) Abaca Plant



(b) Abaca Fiber

The extraction procedure of fiber, as seen in Figures 6(a) and 6(b), entails the removal of the stalks from the abaca plant to procure long, robust fibers. Generally, we subject these fibres to various treatments, such as alkaline processes, to enhance their adhesion to polymer matrices. This enhances the performance of the resultant composites, augmenting their mechanical qualities and durability. Moreover, abaca fibers are biodegradable, making them an eco-friendly material for sustainable composite applications. Due to its exceptional characteristics and increasing demand, abaca is becoming a significant natural fiber for

sophisticated, industrial, and environmentally sustainable composite materials.

### 2.2.3 Sisal (*Agave sisalana*)

Sisal is one of the most widely used natural fibres, with Brazil being one of the largest producers. Native to southern Mexico, sisal plants form rosettes of leaves that grow up to 1.5–2 meters tall. Over its 6–7-year lifespan, a sisal plant produces approximately 200–250 commercially viable leaves.



Figure 7:(a) Sisal Plant



(b) Sisal Fiber

The automotive, nautical, civil construction and agricultural industries extensively use sisal fibers due to their remarkable mechanical properties for anchoring small vessels and handling freight. Examples of these applications include baler twine and agricultural twine. Sisal fibers serve as the fiber core in steel wire cables utilized for elevators.

### 2.3 Seed/Fruit Fiber

#### 2.3.1 Cotton (*Gossypium*)



Figure 8:(a) Cotton seed

(b) Cotton Fiber

After harvesting the cotton plants shown in figure 8(a, b), we remove the leaves and compact the remaining cotton into substantial "modules." Processing facilities, known as cotton gins, receive the modules and extricate seeds, sticks, burrs, and other contaminants from the cotton fibers. The textile sector extensively uses cotton, and current advancements focus on incorporating cotton fibers into composites for industrial purposes.

#### 2.3.2 Kapok (*Ceibapentandra*)

Kapok, a species within the Bombacaceae family, flourishes in tropical areas. Kapok fiber, commonly known as silk cotton, is generally yellowish or light brown and encases the seeds of the kapok tree. Cellulose makes up these fibers, which are lightweight and possess hydrophobic properties.



Figure 9:(a) Kapok Seed

(b) Kapok Fiber

Traditionally, kapok fiber has been utilized in diverse ways, as shown in figures 9(a,b), such as a buoyant material, oil-absorbing agent, reinforcing medium, adsorption material, and even as biofuel.

#### 2.3.3 Coir Fiber (*Cocos nucifera*)

Coir fiber, obtained from the husk of the coconut (*Cocos nucifera*), is a

robust and resilient natural fiber recognized for its adaptability across several uses. It is predominantly cultivated in tropical areas including India, Sri Lanka, Indonesia, the Philippines, and Malaysia. Coir fibers are esteemed for their durability, strength, and water resistance, rendering them suitable for applications in the maritime, automotive, and construction sectors.



Figure 10: (a) Coir

(b) Coir Fiber

Coir fibers are rich in lignin and have a low cellulose content, which gives them excellent durability, particularly in harsh environmental conditions. These fibers are commonly used in the production of ropes, mats, mattresses, brushes, and geotextiles.

Figures 10(a) and 10(b) illustrate the coir extraction procedure, which involves the separation of fibers from the coconut husk, followed by several treatments, such as mechanical or chemical processing, to enhance their strength and adherence with polymer matrices. This enhances the overall efficacy of composites employing coir as reinforcement.

## 2.4 Characteristics of Natural Fibers: Cellulose and Moisture Content

The cellulose composition and moisture levels of natural fibres largely

determine their distinctive characteristics. The characteristics play a crucial role in determining strength, durability, biodegradability, and the appropriateness for diverse applications, such as textiles and environmentally friendly products.

Table 1 outlines the values for cellulose and moisture content of various natural fibres, highlighting their significance in influencing properties and applications. The cellulose content, which ranges from 40% to 90%, plays a crucial role in determining the strength, rigidity, and biodegradability of the fibers. For example, fibers such as cotton and silk have elevated cellulose levels, which enhance their mechanical properties. In contrast, fibers like coir and kapok, which have a lower cellulose content, display diminished strength and flexibility.

**Table 1:** Cellulose and moisture content values for various natural fibers (Syduzzaman et al., 2020)

Fiber	Cellulose (%)	Hemicelluloses (%)	Lignin (%)
Jute	61–71	14–20	12–13
Hemp	68	15	10
Oil Palm	65	—	29
Flax	71–81	16.7–20.6	3
Sisal	65–78	10–12	8–10
Coir	32–43	0.15–0.25	40–45
Silk	70–80	10–15	0.2–0.3
Ramie	70–80	8–12	0.6–0.7
Abaca	60–70	10–12	7–10

Moisture content, generally between 8% and 15%, plays a crucial role in influencing the stability, durability, and processing characteristics of fibers. Increased moisture content can expedite fiber degradation, thereby affecting overall performance. A combination of these attributes plays a crucial role in assessing the appropriateness of natural fibers for use in textiles, composites, and eco-friendly products.

In addition to the aforementioned, Kenaf (*Hibiscus cannabinus*), a bastfiber, is used in paper, rope, and composites due to its strength, stiffness, and insecticide resistance (Thakker and Sun, 2021). Its fibers, derived from the plant's bast and core, undergo chemical or bacterial treatments for purification, making them suitable for textiles, automotive, and construction industries.

Nettle (*Urticadioica*) fibers, extracted through retting or decortication, are valued for textiles and bioenergy, with increasing industrial applications (Faruk et al., 2012). Pineapple leaf fibers (*Ananascomosus*), known for their excellent mechanical properties, are manually extracted and utilized in textiles, composites, and advanced materials like conveyor belts and airbags (Akil et al., 2011).

Date palm (*Phoenix dactylifera*) fibers, rich in cellulose, are used in thermoplastic and thermosetting polymer reinforcements, particularly in automotive applications (Bhusal et al., 2022). Cotton (*Gossypium*), widely cultivated, dominates the textile industry and finds use in industrial composites. Coconut fiber (*Cocos nucifera*) or coir, known for its resilience and high lignin content, is used in mats, ropes, fibers, and agricultural products.

Kapok (*Ceibapentandra*) lightweight and hydrophobic, serve in buoyancy materials, biofuels, and oil absorption. Bamboofibers (*Bambusoideae*) are utilized for their strength in construction and advanced composites, while silk (*Bombyxmori*), renowned for its strength and elasticity, remains a premium material for textiles and specialized applications (Sharma, 1981; Hussain et al., 2020).

## 3. NATURAL FIBER AND COMPOSITES

Composites are engineered materials made by combining two or more distinct components, typically a reinforcing material and a matrix, to achieve superior properties compared to their individual constituents. The principal impetus for utilizing composites is their capacity to provide superior mechanical performance, including elevated strength, stiffness, and toughness, while markedly decreasing weight (Yu et al., 2014). These materials provide design versatility, enabling engineers to customize them for particular purposes by modifying the fiber type and orientation or selecting the matrix material. Moreover, composites demonstrate superior corrosion resistance, durability, and cost-effectiveness, rendering them suitable for diverse applications in sectors such as aerospace, automotive, and construction

### 3.1 Weight Fractions in Natural Fibers

The weight fractions in natural fibers indicate the relative proportions of key components, such as cellulose, hemicellulose, lignin, pectin, and waxes, that constitute the fiber structure. These fractions hold significance due to their ability to alter the chemical, mechanical, and physical properties of fibers. This implies their potential for various applications, particularly in the context of natural fiber composites. Cellulose typically makes up 40–70% of the fiber weight and serves as the main element that provides tensile strength and stiffness, making it essential for structural applications (Ude et al., 2014). Hemicelluloses, which account for 15–35%, contribute to improved flexibility and moisture absorption, possibly necessitating surface treatments to boost durability.

Lignin, comprising 5–20% of the composition, is a hydrophobic polymer that plays a crucial role in binding the fiber structure, thereby enhancing rigidity and providing UV resistance. However, excessive lignin content can reduce the flexibility of fibers, which may limit their use in certain composites. Pectin, though present in smaller quantities (0.5–3%), helps maintain fiber structure and aids in processability (Mallick, 2007). Waxes and other extractives (0.5–3%) influence the surface characteristics of fibers and affect their adhesion to polymer matrices. The balance of these components determines the fiber's overall performance and compatibility in composite materials.

Different natural fibers exhibit varying weight fractions depending on their source. For instance, flax fibers have a high cellulose content (70–72%), making them suitable for high-strength applications, while coir fibers, with a lignin content of 40–45%, are preferred for applications requiring durability and moisture resistance. Jute and hemp fibers, with intermediate weight fractions, offer a balance of strength, stiffness, and flexibility, making them versatile for multiple uses (Reddy and Yang, 2005). These weight fractions also determine the thermal stability and moisture resistance of the fibers, impacting their performance under different environmental conditions.

Adjusting weight fractions via treatments or hybridization can improve the performance of natural fiber composites. For example, treating with alkali can lower the levels of hemicelluloses and lignin, which makes cellulose easier to access so it can bond better with the polymer matrix. These modifications enhance the mechanical properties and decrease the hydrophilicity of natural fibers, thereby expanding their applications in automotive, construction, and consumer goods (Faruk et al., 2012). The increasing focus on these fibers corresponds with worldwide sustainability objectives, highlighting the necessity for further investigation to enhance their characteristics.

### 3.2 Reinforcement

The reinforcement in composite materials is essential for defining the

mechanical, thermal, and chemical characteristics of the final product. The distribution of stresses in composites enhances their load-bearing capacity and stiffness, thereby improving their structural integrity. A matrix material integrates reinforcements, cohesively binding them and

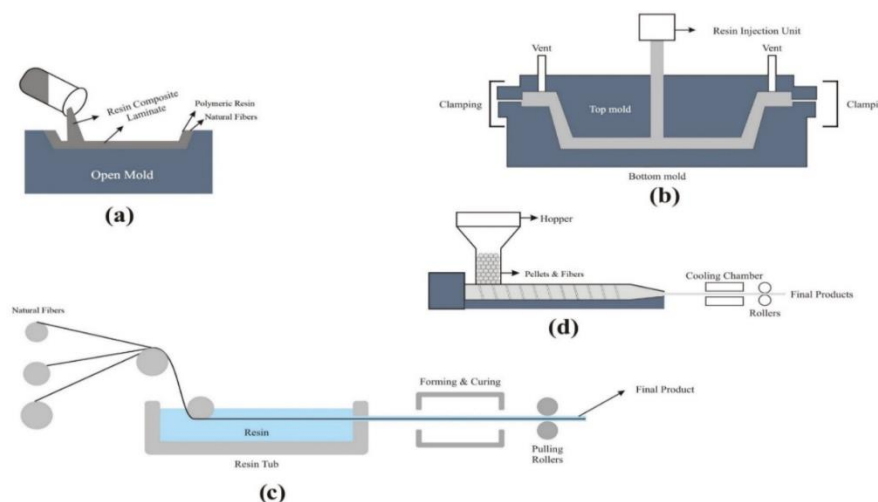
facilitating the transfer of applied loads. The integration of reinforcement and matrix results in enhanced performance attributes, rendering composites appropriate for a variety of applications, including aerospace, automotive, construction, and marine sectors.

**Table 2: Overview of Reinforcements in Composite Fabrication Methods, Their Advantages, Applications, and Relevant References**

Reinforcement Type	Fabrication Method	Advantages	Uses/Applications	References
Natural Fibers	Hand Layup	- Eco-friendly	- Automotive interior panels - Construction materials - Packaging materials - Furniture	Mohanty et al., 2001; Pickering et al., 2016
		- Biodegradable		
		- Lightweight		
		- Cost-effective		
		- Renewable resources		
Synthetic Fibers	Hand Layup	- High tensile strength	- Aerospace components - Sports equipment - High-performance automotive parts	Dhaliwal, 2019
		- Durable		
		- Resistant to moisture and chemicals		
		- Customizable properties		
Powders	Compression Molding	- Excellent filler compatibility	- Electronics casings - Medical implants - High-performance machine components	Sahu and Gupta, 2020
		- Cost reduction in composites		
		- Thermal and electrical properties		
Natural Fibers	Compression Molding	- Improved surface finish	- Roof tiles - Insulation panels - Lightweight furniture components	Petroudy, 2017
		- Good thermal insulation		
		- Reduced weight		
Synthetic Fibers	Injection Molding	- High precision	- Electrical connectors - Consumer electronics - Engine components	Dhaliwal, 2019
		- Complex shapes possible		
		- Consistent quality		
Powders	Injection Molding	- Uniform distribution	- Ceramics - Metal matrix composites - Heat-resistant components	Sahu and Gupta, 2020
		- Excellent surface finish		
		- Precision control		
Natural Fibers	Resin Transfer Molding (RTM)	- Uniform distribution	- Boat hulls - Wind turbine blades - Lightweight structural components	Petroudy, 2017.
		- High-quality surface finish		
		- Low void content		

Extrusion is a widely used technique in the plastics industry due to its ability to provide uniform combination of all components. It is particularly

effective for developed composites where fiber orientation is not a primary concern, as fibers are randomly distributed.



**Figure 11:** Various composite Preparation methodologies (a) Hand layup (b) Resin transfer molding (c) Pultrusion (d) Extrusion (Eze et al., 2022).

The process typically uses single or twin screws that rotate in both clockwise and counterclockwise directions. A single-screw extruder provides minimal mixing, making it suitable for applications where less interaction between fiber and matrix material is needed. In contrast, a twin-screw extruder offers superior mixing and high-thrust forces, ensuring that fibers are evenly distributed throughout the composite.

During extrusion, raw materials are usually fed into a heated chamber, where feed screws process the molten mixture. In the case of jute composites, up to 40% of jute fibers are integrated into a polymeric matrix. Following extrusion, the final product can undergo post-processing to enhance its quality. Shown in figure 11 illustrates various fabrication methods.

## 4. MECHANICAL PROPERTIES

The mechanical properties of natural fiber composites are affected by the type of fiber used, the matrix, and the manufacturing process involved. Although the tensile strength tends to be less than that of synthetic composites, it remains sufficient for numerous applications. The specific strength frequently aligns with that of glass fiber composites, attributed to the low density of natural fibers. The characteristics of fiber type and orientation play a crucial role in determining stiffness, while hybridization techniques have the potential to improve impact resistance, which is generally lower. The characteristics of NFCs position them as a lightweight and sustainable option for a range of applications.

### 4.1 Tensile Testing of Natural Fiber Composites

Tensile testing serves as a prevalent technique for evaluating the mechanical properties of composite materials, particularly those enhanced with natural fibers like hemp, flax, sisal, coir, jute, and others. This assessment yields important information regarding the material's strength, stiffness, and performance when subjected to uniaxial loading conditions. Natural fiber composites generally follow the ASTM D3039 standard, selecting specimen dimensions such as length (250 mm), width (25 mm), and thickness (2-3 mm) based on the fiber type and reinforcement orientation. In tensile testing, we subject the specimen to a pulling force in a designated direction, increasing the load until we observe failure. The material's ductility and tensile strength intrinsically depend on the measurement of elongation and reduction in cross-sectional area (Midani and Elseify, 2022). For example, Hemp fibers generally exhibit high tensile strength (up to 1,000 MPa) and elongation, making them suitable for high-strength applications, while Cotton fibers, although weaker, display good elongation properties, which enhance the ductility of the composite. However, the tensile strength of Bagasse fibers is typically lower, but they contribute to composites with good stiffness and rigidity.

### 4.2 Flexural Testing of Natural Fiber Composites

Flexural testing, often referred to as bending tests, is another critical mechanical test used to assess the performance of composites under bending loads, which are common in structural applications. The ASTM D7264 standard outlines two primary methods for flexural testing: three-point and four-point bending. Flax, Ramie, and Jute fibers are often tested using these methods to determine the flexural modulus and flexural strength of composites.

In three-point bending, the specimen is supported at two points, and a load is applied at the center. This setup is simple, but it can create high shear stresses near the supports, potentially leading to localized damage (Ashraf et al., 2019). In contrast, four-point bending distributes the applied load over a larger area, which results in a more uniform bending moment and reduced shear failure risks.

The flexural properties of composites made from Kenaf or Sisal fibers show that the bending stiffness can be increased with proper alignment of the fibers, although the failure strain can be lower for fibers like Cotton compared to tougher materials like Flax or Hemp. These tests are crucial in applications such as automotive and construction materials, where bending stresses are significant, and the composite needs to maintain both strength and flexibility.

### 4.3 Impact and Ductility Testing of Natural Fiber Composites

Tests that measure impacts are necessary to find out how well composite materials can handle damage and absorb energy, especially when they are loaded quickly or heavily. Natural fibers, including sisal, jute, and banana, have undergone testing for impact resistance to evaluate their capacity to endure fractures during high-energy impacts.

The Charpy and Izod impact tests are commonly utilized to evaluate the energy received during fracture. A pendulum impacts a notched specimen in the Charpy test, and the difference in the pendulum's height before and

after the impact calculates the absorbed energy (Joseph et al., 2003). Banana fibers, noted for their remarkable durability, exhibit superior energy absorption in Charpy tests, rendering them ideal for impact-resistant applications like automotive components.

Specimen geometry, fiber orientation, and notch configuration may influence the outcomes of these tests. Although coir and bagasse exhibit lower impact resistance than fibers such as flax or sisal, they remain suitable for non-structural applications where impact resistance is not paramount. Tensile tests, bend tests, and impact tests assess ductility, an essential feature that measures a material's capacity for plastic deformation prior to failure. Natural fiber composites frequently demonstrate a combination of strength and ductility, with fibers like jute, hemp, and ramie generally providing favorable elongation and plastic deformation characteristics, but sisal and flax are characterized by more stiffness and reduced ductility.

Ductility testing is essential for assessing materials in applications necessitating energy absorption, such as automobiles and sporting equipment. In the tensile test, elongation and reduction in cross-sectional area during deformation are direct markers of ductility (Alotaibi et al., 2019). Jute and banana fibers exhibit more elongation at breaks compared to cotton fibers, rendering them superior for material deformation prior to failure. Despite their inferior tensile strength, the flexibility and elongation of cotton fibers enhance the ductility of the composite. Coir fibers exhibit greater deformation prior to failure than hemp due to their lower stiffness, whereas they possess inferior strength. The interactions and alignments between the fiber and matrix significantly influence the ductility of natural fiber composites.

Chemical treatments and hybridization with alternative materials can enhance this Tensile, flexural, impact, and ductility tests clarify the mechanical properties of natural fiber-reinforced composites. Hemp, flax, jute, sisal, and other fibers possess distinct advantages for specific uses, as evidenced by their performances in these studies. Hemp and ramie are robust and durable, whereas cotton and coir are pliable and elongated. The incorporation of these fibers with various matrixes and suitable testing facilitates the production of composites for construction, automotive parts, packaging, and consumer products. Manufacturers can ascertain the ideal fiber-matrix combinations for specific applications by employing mechanical studies to understand the performance of these fibers (Jayamol et al., 1997; Li et al., 2000; Joseph et al., 2003; Alotaibi et al., 2019).

## 5. HYBRID COMPOSITE

Hybrid composites represent a sophisticated class of materials that combine natural fibers with synthetic fibres or other natural fibres to enhance the overall properties of composite materials. This combination seeks to utilize the benefits of both types of fibers. Natural fibers, including jute, flax, hemp, and sisal, offer significant environmental benefits, including biodegradability, cost-effectiveness, and sustainability. Synthetic fibers, including glass and carbon fibers, offer improved mechanical properties, such as greater strength, stiffness, and durability (Jayamol et al., 1997). Through the integration of these fibers, hybrid composites achieve an optimal equilibrium between performance and ecological advantages. This renders them highly advantageous in sectors that prioritize robust material performance along with sustainability.

In sectors like automotive and construction, which widely employ composite materials, this benefit is particularly significant. Investigations are underway into hybrid composites within the automotive sector as a sustainable alternative for the production of lightweight components, including door panels, dashboards, and sections of the car body (Li et al., 2000). The combination of natural fibers and synthetic materials in these composites reduces the overall weight of automobile components, thereby enhancing fuel efficiency and lowering CO<sub>2</sub> emissions, which supports vehicle environmental sustainability.

**Table 3: Natural Fiber Hybrid Composite Properties and Applications**

Natural Fiber	Hybrid Material (Fiber/Matrix)	Advantages	Applications	References
Jute	Jute + Glass Fiber	- Enhanced mechanical properties (e.g., tensile and flexural strength)	Automotive panels, construction, marine components	Prusty et al., 2017.
		- Reduced weight		
		- Cost-effective		

**Table 3 (cont):** Natural Fiber Hybrid Composite Properties and Applications

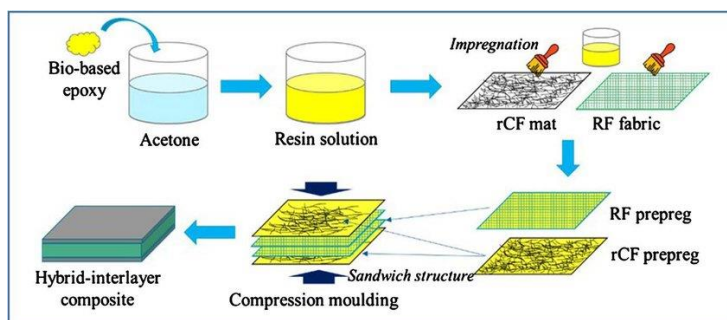
<b>Hemp</b>	Hemp + Carbon Fiber	- Improved stiffness and strength	Aerospace components, sports goods	Pan et al., 2016
		- Lightweight		
		- Excellent thermal properties		
<b>Coir</b>	Coir + Polypropylene (PP) + Glass Fiber	- High impact strength	Automotive interiors, furniture	Jawaid et al., 2011
		- Damping properties		
		- Suitable for semi-structural applications		
<b>Flax</b>	Flax + PLA Matrix + Hemp Fiber	- Fully biodegradable	Biomedical devices, packaging, consumer products	Pickering et al., 2016
		- Good tensile and flexural properties		
		- Low environmental impact		
<b>Kenaf</b>	Kenaf + Epoxy + Basalt Fiber	- High thermal stability	Industrial components, structural reinforcements	Rana et al., 2003
		- Improved flexural strength		
		- Suitable for high-load applications		
<b>Sisal</b>	Sisal + Polyester + Glass Fiber	- Good toughness	Construction, decking, marine applications	Islam, 2008
		- Resistance to moisture		
		- High tensile strength		
<b>Bamboo</b>	Bamboo + Carbon Fiber + Epoxy	- Excellent compressive strength	Construction, furniture, sports equipment	Sathish et al., 2024
		- Sustainable option for high-performance applications		
<b>Abaca</b>	Abaca + Polypropylene + Kevlar	- High impact resistance	Helmet shells, automotive underbodies, safety equipment	Rana and Purohit, 2017
		- Lightweight		
		- Resistance to fatigue		
<b>Ramie</b>	Ramie + Polycaprolactone (PCL) + Carbon Fiber	- Superior tensile strength	Medical implants, lightweight aerospace and automotive components	Praveenkumara et al., 2018
		- Suitable for biomedical and structural applications		

This table presents a comparative analysis of various hybrid composite materials sourced from natural fibers. We categorize the composites into groups based on the natural fibres they contain, such as jute, hemp, coir, flax, kenaf, sisal, bamboo, abaca, and ramie. The document provides a detailed account of the specific combination of fibers and matrix materials used in their production. The "Hybrid Material (Fiber/Matrix)" column shows what the composition is. It usually means a mix of natural fibers and man-made materials like carbon fiber, glass fiber, or polymers like polypropylene, epoxy, and PLA. This hybridization seeks to improve the composite's overall performance by integrating the advantageous characteristics of each component.

## 6. CHEMICAL TREATMENTS

Recent advancements in natural fiber composites (NFCs) have markedly improved their mechanical, thermal, and environmental characteristics; hence, they are expanding their use across diverse industries. Nonetheless, obstacles such as inadequate fiber-matrix interfacial adhesion, suboptimal wettability, and elevated water and

moisture absorption continue to exist. The hydrophilic characteristics of natural fibers lead to inadequate contact with the polymer matrix, adversely affecting the composite's overall performance. Chemical and surface treatments are essential for optimizing the fibers to resolve these difficulties (Raj et al., 2022; Du et al., 2015; Gassan and Bledzki, 1999; George et al., 2001; Rangappa, and Siengchin, 2018). Recent advancements in material development have resulted in the substitution of glass and carbon-reinforced composites with natural fiber-reinforced composites in applications including automobile interiors, pedestrian bridges, shipping pallets, composite roof tiles, furniture, and toys (Sanjay et al., 2018; Yashas et al., 2018; Sepe et al., 2018). Natural fibers are not compatible with thermoplastics because they are hydrophilic, which means they don't interact well with the matrix. This is a major drawback of using natural fibers as reinforcement. This results in diminished mechanical characteristics of the composites. To enhance the performance of these composites, it is essential to change natural fibers to diminish their hydrophilicity. Figure 12 presents an overview of diverse chemical treatments applied to natural fibers (Senthamaraikannan and Kathiresan, 2018).



**Figure 12:** Overview of various chemical treatments applied to natural fibers (Madhu et al., 2019a)

### 6.1 Alkaline Treatment

Alkaline treatment is essential for improving the characteristics of natural fibers by altering their structure, particularly the cellulose content. Natural fibers are made up of lignin, pectin, waxes, and natural oils that cover the outside of the fiber cell walls and might make it hard for the fiber to interact with the polymer matrix (Madhu et al., 2019b). Using sodium hydroxide (NaOH) as a chemical reagent in an alkaline treatment changes these parts and cleans the fiber surfaces.

This improves the adhesion between the fibers and the matrix and the

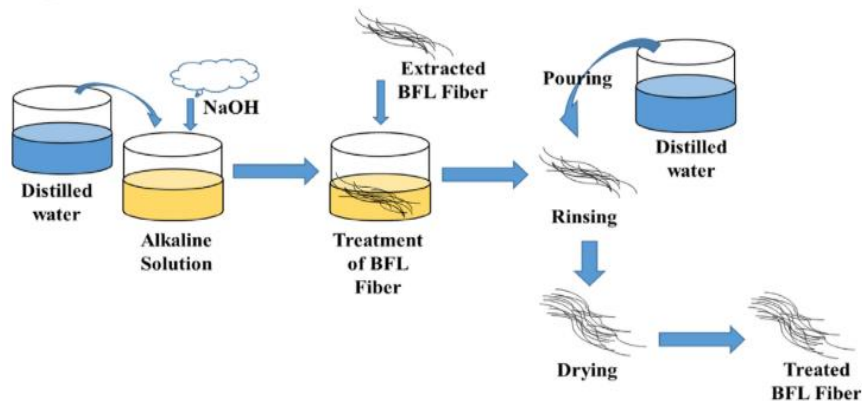


Figure 13: Various types of NaOH Treatment Methods

In a unique experiment, we treated kenaf fibre mats with NaOH for 24 hours at 45°C. After the treatment, we rinsed the mats with tap water, immersed them in distilled water with 1% acetic acid to neutralise any excess NaOH, and then dried them at 45°C for 12 hours as shown in fig 13. After the treatment, we removed the excess NaOH using distilled water and dried the fibers for 56 hours. A 60-minute treatment successfully eliminated hemicelluloses and lignin, resulting in enhanced fiber properties (Atiqah et al., 2018).

### 6.2 Silane Treatment

Sugar palm fibers undergo treatment with a 2% silane solution and 6% NaOH for a duration of 3 hours. The treatment enhanced the interfacial contact between the fibers and thermoplastic polyurethane. Kabir et al. looked at what happens when you treat natural fiber surfaces with silane. They found that silane groups act as a glue between the fiber and the matrix, which makes the mechanical properties better (Kabir et al., 2012). Bodur et al. did a study that looked at how the tensile strength and Young's modulus changed when silane-treated composites were soaked for different amounts of time. They observed significant enhancements in strength compared to untreated fiber composites. The production of silanol (Si-OH) groups, which exhibit strong bonding with the -OH groups of the fibers, is responsible for the strength boost. The leftover Si-OH groups stick together with nearby Si-OH groups, making a polymerized silane that doesn't like water. This polymerized silane can then adhere to the polymer matrix via van der Waals forces, establishing a robust contact between the fiber and polymer. The tensile strength of low-density polyethylene composites is increased by the good contact between the fiber and the polymer matrix (Bodur et al., 2016).

### 6.3 Acetylation Treatment

Acetylation is a chemical technique that adds acetyl groups to the surface of natural fibers, enhancing their hydrophobicity and improving the stability of the resultant composites. This treatment makes it easier for fibers and matrix to stick together, which makes the bond stronger and gives natural fiber-based composites better overall properties (Sreekala and Thomas, 2003).

During acetylation, the hydroxyl groups in the fibers interact with the acetyl groups, making them more hydrophobic. Because lignin and hemicellulose have hydroxyl groups, they usually react with acetyl groups to make the fibers less water-repellent. The fibers often undergo an alkali solution treatment prior to acetylation. Subsequent to alkali treatment, the fibers are submerged in glacial acetic acid for one hour and then soaked in acetic anhydride (with two drops of concentrated for two to five minutes). We subsequently clean and dry the fibers in an oven at 80°C for six hours (Mishra et al., 2003). This acetylation treatment markedly enhances the fiber's hydrophobicity, increasing its compatibility with polymer matrices and hence improving the performance of the composites.

### 6.4 NaOH Treatment

overall performance of the composite. In a study, Mwaikambo and Ansell subjected hemp, jute, sisal, and kapok fibers to NaOH treatment at 20°C for approximately 48 hours. Madhu et al. subsequently rinsed the fibers with distilled water and acetic acid to neutralize the surplus NaOH. We examined the modified fibers for their thermal characteristics, surface morphology, and crystallinity. The results showed that the fibers that had been treated stuck to the resin better, which led to more interfacial energy and better thermal and mechanical properties in the composites that were made (Saravanakumaar et al., 2018).

Alkaline treatment, typically utilizing sodium hydroxide (NaOH), is a prevalent method for altering the surface properties of natural fibers for use in composites. The process, referred to as mercerization, entails the immersion of fibers in sodium hydroxide (NaOH) solutions with differing concentrations and exposure times, thereby facilitating the removal of impurities including lignin, hemicellulose, waxes, and pectin. The removal results in heightened surface roughness, better fiber-matrix adhesion, and improved mechanical interlocking within the composite structure. The reaction with NaOH modifies the cellulose structure, enhancing crystallinity and fiber strength. Mwaikambo and Ansell investigated the effects of 5% NaOH treatment on hemp, jute, sisal, and kapok fibers. The study demonstrated that the mechanical properties of the fibers improved significantly due to enhanced connectivity between the matrix and the fibers. Asumani et al. observed that NaOH treatment of kenaf fiber mats led to significant improvements in the mechanical performance of composite materials (Asumani et al., 2012). The enhancements can be attributed to the greater surface area for bonding and the enhanced compatibility between the hydrophilic fiber surface and the hydrophobic polymer matrix.

Optimizing NaOH treatment parameters, including concentration, temperature, and treatment duration, is essential for attaining desired outcomes while minimizing fiber damage. Higher concentrations and extended durations may improve impurity removal; however, they can also result in fiber degradation and a reduction in mechanical strength if not meticulously regulated. Research has investigated various treatment conditions to enhance the equilibrium between surface modification and fiber integrity. A group of researchers looked at what happened to flax fiber properties when NaOH concentrations were changed (Li et al., 2007). This study shows how important it is to find the best treatment conditions for better reinforcement in composite materials. NaOH treatment has proven effective for various natural fibers, such as flax, hemp, and kenaf, establishing it as a versatile method for improving the performance of natural fiber composites (Mwaikambo and Ansell, 2002).

## 7. CONCLUSION AND FUTURE SCOPE

This research analyzes the composition of natural fibers, highlighting the weight proportions of cellulose, hemicelluloses, lignin, pectin, and waxes and their influence on the qualities and utility of the fibers in composite materials. We delineate various composite manufacturing techniques, including hand layup, compression molding, injection molding, and resin transfer molding, emphasizing their distinct advantages and applications. The study focuses on the mechanical properties of NFCs, including their tensile, flexural, and impact characteristics. The study cites standard testing procedures like ASTM D3039 for tensile, ASTM D7264 for flexural, and Charpy/Izod for impact, and analyzes the impact of fibre type, orientation, and matrix material on these properties. The report reiterates the promise of NFCs as sustainable and versatile materials, emphasizing the need for continued research to improve their properties, optimize processing techniques, and expand their applications across various

industries. To make NFCs work best for a sustainable future, we need to look at advanced processing methods, surface modifications, hybrid composites, life cycle assessment, cost-effectiveness, and standardisation.

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