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Mechanical Properties of Short Natural Fiber-Reinforced Thermoplastic Composites

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Abstract:

This study investigates the mechanical properties of short natural fiber-reinforced thermoplastic composites (NFCs), emphasizing their potential for enhancing performance while supporting sustainability. By analyzing fibers such as flax, hemp, kenaf, sisal, and abaca, we reveal how their distinct chemical compositions and physical traits impact the mechanical characteristics of NFCs. Key factors including fiber content, length, diameter, and orientation are examined to identify optimal conditions for maximizing strength and stiffness. Our findings underscore the critical role of fiber-matrix interfacial bonding in effective stress transfer, while highlighting techniques like chemical treatments to improve wettability and overcome challenges posed by the inherent differences between natural fibers and polymer matrices. The study also addresses the complexities of fiber dispersion and orientation in composite manufacturing. Despite certain challenges, including moisture absorption and variability in fiber quality, NFCs demonstrate considerable promise in applications across automotive, aerospace, and marine industries, offering lightweight and cost-effective alternatives to traditional materials. This research lays the groundwork for future innovations in sustainable material development, pointing to enhanced performance through refined processing techniques and material selection.

Keywords: *Natural Fiber Composites, Thermoplastic Composites, Mechanical Properties, Sustainable Materials, Fiber-Matrix Bonding.*

1. Introduction:

The increasing demand for sustainable materials in various industries has prompted a renewed interest in natural fiber-reinforced composites, particularly short natural fiber-reinforced thermoplastic composites (NFCs). These composites not only offer enhanced mechanical properties but also align with environmental goals by utilizing renewable resources. Natural fibers, derived from sources such as flax, hemp, kenaf, sisal, and abaca, exhibit unique chemical compositions and physical characteristics that significantly influence the performance of NFCs.This study aims to explore the mechanical properties of these composites, focusing on critical factors such as fiber content, length, diameter, and orientation. Understanding how these parameters affect the strength and stiffness of NFCs is essential for optimizing their use in various applications. The effectiveness of fiber-matrix interfacial bonding is highlighted as a vital component in ensuring efficient stress transfer, which is crucial for maximizing the mechanical performance of the composites.Additionally, the research addresses the inherent challenges posed by the hydrophilic nature of natural fibers and the hydrophobicity of typical polymer matrices. Techniques such as chemical treatments to enhance wettability are examined, providing insights into overcoming these barriers. The complexities of fiber dispersion and orientation during composite manufacturing are also discussed, as they play a critical role in determining the final properties of NFCs.Despite certain challenges, including moisture absorption and variability in fiber quality, the potential applications of NFCs in sectors like automotive, aerospace, and marine industries are promising. This study contributes to the growing body of knowledge on natural fiber composites, paving the way for future innovations in sustainable material development. By refining processing techniques and material selection, this research highlights the opportunity to enhance the performance of NFCs, making them viable alternatives to traditional materials in a variety of applications.

2. Research Objective:

- Evaluate the mechanical properties of fiber-reinforced composites.
- Analyze fiber-matrix bonding effects on composite performance.
- Explore chemical treatments and recommend optimal processing techniques.

3. Problem Statement:

The rising interest in short natural fiber-reinforced thermoplastic composites (NFCs) reflects the demand for sustainable materials. However, challenges such as the complex interactions between natural fibers and polymer matrices, variability in fiber quality, and moisture absorption hinder optimal performance. Understanding these factors is essential to enhance NFCs' mechanical properties and ensure their viability as sustainable alternatives in various industries.

4. Literature Review:

The mechanical properties of short natural fiber-reinforced thermoplastic composites have garnered significant attention in recent years due to their potential for lightweight, sustainable alternatives in various applications. These composites leverage the inherent benefits of natural fibers, such as renewability and biodegradability, while enhancing mechanical performance through thermoplastic matrices. This literature review aims to explore the advancements in understanding the mechanical behavior, fiber-matrix interactions, and the influence of processing techniques, providing insights into their practical applications and future development in engineering materials.

Literature Survey

Author	Work Done	Findings
Elmasry et al. (2024)	Modeling of hybrid biocomposites for automotive structural applications.	Developed models demonstrating improved performance for automotive uses.
Hiremath et al. (2024)	Review of thermal degradation and fire retardant behavior of natural fiber reinforced composites.	Highlighted key properties influencing thermal stability and fire resistance.
Special Chem (2024)	Coefficient of linear thermal expansion for material selection.	Provided essential data for selecting materials based on thermal expansion properties.
Wang et al. (2023)	Comparative study on low-velocity impact properties of flax and carbon fiber reinforced epoxy plates.	Flax fiber composites showed competitive impact resistance compared to carbon fiber.
Singh et al. (2023)	Comprehensive review of natural fiber reinforced composites and their applications.	Identified modern applications and advantages of natural fibers in composites.
Elmasry et al. (2023)	Comparative review of multiscale models for nano- and micro-composites.	Discussed the effectiveness of various modeling approaches for predicting composite behavior.
Chichane et al. (2023)	Review of bio-composites and bio-hybrid composites reinforced with natural fibers.	Emphasized the potential of natural fibers in sustainable composite development.
Doddamani et al. (2023)	Analysis of lightweight natural fiber composites against ballistic impact.	Found that natural fiber composites can offer adequate protection against ballistic threats.
Elmasry et al. (2023)	Modeling of hierarchical fiber-graphene nanoplatelets reinforced composites for energy absorption.	Demonstrated enhanced crashworthiness and energy absorption capabilities.
Baley et al. (2021)	Historical review of composites reinforced by flax fibers over 80 years.	Documented the evolution and advancements in flax fiber composites.
Barteau et al. (2021)	Study on recycling of wood-reinforced poly-propylene composites.	Presented numerical and experimental approaches for effective recycling methods.

6. Methodology:

This study investigates the mechanical properties of short natural fiber-reinforced thermoplastic composites. The research begins with the classification of natural fibers, categorized based on their origin into plant, animal, and mineral fibers. Key fibers like flax, hemp, kenaf, sisal, and abaca are examined for their potential reinforcement in composites.The mechanical properties of the composites are analyzed using experimental methods, focusing on factors like fiber content, length, diameter, and fiber orientation. Fibers are characterized for their cellulose, hemicellulose, and lignin content to understand their chemical composition, which directly influences mechanical performance. The fibers are processed into composites using methods like extrusion and compression molding.Various matrices, such as polypropylene and bio-derived matrices, are incorporated to evaluate interfacial bonding. The study also addresses the effects of porosity, fiber dispersion, and orientation on mechanical strength. Data on tensile strength, Young's modulus, and failure strain are collected, and chemical treatments are applied to enhance fiber/matrix bonding.

8. Result & Discussion:

Classification of Natural Fibres: Fibres are either continuous filaments, resembling hair, or discrete elongated pieces similar to thread. These fibres can be combined to form sheets, such as in the production of paper. Natural fibres are sourced from plants, animals, and minerals. They can be categorized based on their origin as follows:

- Animal Fibres: These fibres are derived from animal sources and include wool, silk, avian fibres, goat hair, horse hair, and feathers.
- Mineral Fibres: These are either naturally occurring or modified fibres obtained from minerals.
- Plant Fibres: Plant fibres primarily consist of cellulose. They can be further classified into various types based on their specific characteristics and sources.

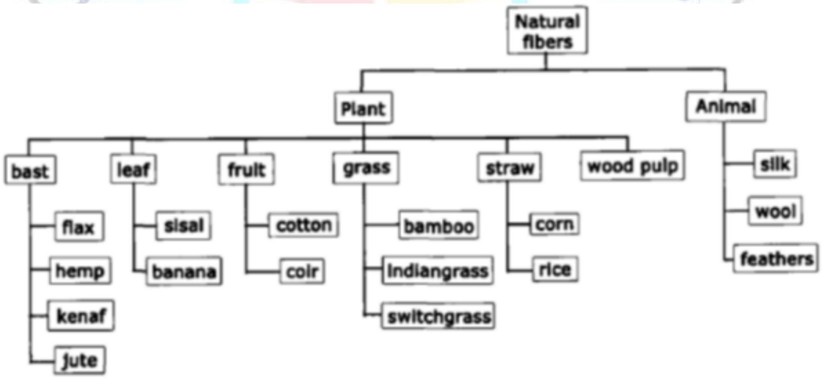

Figure 1 Classification of natural fibres

Flax: Flax is one of the oldest fibres and is cultivated in temperate regions. It falls under the category of bastfibres and is widely utilized in composite materials.

Hemp: Hemp, belonging to the cannabis family and also classified as a bastfibre, is currently the subject of research within the European Union's non-agricultural subsidy programs.

Kenaf: Kenaf, a potential reinforcement material for composite products, belongs to the genus Hibiscus, which comprises about 300 species. It is also explored in innovative decortication processes.

Sisal: Sisal fibre, used primarily for making ropes and matting, is predominantly produced in Brazil and Africa. The fibre comes from the Agave sisalana plant.

Abaca: Extracted from the banana plant, abaca is known for its durability and resistance to seawater, making it one of the strongest commercially available cellulose fibres. Native to the Philippines, abaca's superior properties make it suitable for marine applications.

Properties of Natural Fiber Composites: The physical and mechanical properties of natural fiber composites are influenced by several factors, including the chemical composition of the individual fibers—such as cellulose, lignin, hemicellulose, and moisture content. Other factors include environmental conditions like climate and soil characteristics, aging conditions, and the specific processing methods used. These elements play a crucial role in determining the mechanical properties of short natural fiber-reinforced thermoplastic composites.

Table 1 Chemical Composition of Several Natural Fibres

Type of Fiber	**Cellulose (%)**	**Hemi-cellulose (%)**	**Lignin (%)**
Jute	61-63	13	5-13
Banana	60-65	6-8	5-10
Flax	70-72	14	4-5
Pineapple Leaf	80	-	12
Sisal	60-67	10-15	8-12
Wood	45-50	23	27
Sun Hemp	70-78	18-9	4-5

The mechanical properties of short natural fiber-reinforced thermoplastic composites are influenced by several factors, including the length and diameter of the individual fibers as well as the experimental conditions. Variations in experimental conditions can significantly impact the observed mechanical behavior in many cases.

Table 2 Properties of Natural Fibres

Material	**Density (g/cm²)**	**Tensile Strength (MPa)**	**Young Modulus (GPa)**	**Failure Strain (%)**
Flax	1.45	500-900	50-70	1.5-4.0

Hemp	1.48	350-800	30-60	1.6-4.0
Jute	1.3	300-700	20-50	1.2-3.0
Bamboo	1.4	500-700	30-50	2
Coir	1.2	150-180	4-6	20-40
Sisal	1.5	300-500	10-30	2-5

Factors Affecting Mechanical Performance of Natural Fiber Composites

Fibre Selection: The mechanical performance of short natural fiber-reinforced thermoplastic composites is influenced by the type of fiber, its cellulose content, and microfibril alignment. Plant fibers, primarily composed of cellulose, provide strength, while animal fibers, though strong, may lack stiffness and availability. Geographical availability and fiber properties, such as chemical composition and extraction methods, also play a role. Fiber strength decreases with delayed harvesting and mechanical extraction.Moisture and temperature affect fiber performance: strength increases with moisture but decreases with heat, while Young's modulus decreases with moisture. Higher fiber content generally improves strength and stiffness, but only when fiber/matrix interfacial strength is sufficient. At higher fiber contents, poor wetting and increased porosity can reduce strength, though stiffness may continue to improve. Longer fibers can enhance load-bearing efficiency but may reduce reinforcement efficiency if they cause poor dispersion.

Matrix Selection: The matrix plays a crucial role in natural fiber-reinforced composites, protecting the fibers from mechanical damage, acting as a barrier against environmental factors, and transferring loads to the fibers. Polymeric matrices are most commonly used due to their lightweight nature and low processing temperatures. Both thermoplastic and thermoset polymers serve as matrices, but their selection is constrained by the thermal stability of natural fibers, which degrade above 200°C. Despite this, short-term processing at higher temperatures is sometimes feasible.Thermoplastics like polyethylene, polypropylene, polyvinyl chloride, and polystyrene, as well as thermosets like epoxy resin, polyester, and phenol formaldehyde, are widely used because they soften below 200°C. Thermoplastics are favored for their recyclability, while thermosets offer better realization of fiber properties. Recently, bio-derived matrices such as PLA, which provides higher strength and stiffness compared to polypropylene, have gained popularity as alternatives to petroleum-based matrices.

Interface Strength: The bonding between fiber and matrix is crucial in determining the mechanical properties of natural fiber-reinforced composites. Effective stress transfer between the matrix and fiber requires strong interfacial bonding, though overly strong interfaces can lead to crack propagation, reducing toughness and strength. In plant fiber composites, limited interaction between hydrophilic fibers and hydrophobic matrices often results in poor bonding, which negatively impacts mechanical performance and moisture resistance.Wettability is essential for bonding, as insufficient fiber wetting can cause interfacial defects that act as stress concentrators. Improving wettability enhances strength, toughness, and tensile properties. Chemical and physical treatments, such as plasma or chemical modifications, are commonly used to improve interfacial strength.Mechanical interlocking, electrostatic bonding, chemical bonding, and inter-diffusion bonding are mechanisms that contribute to interface strength. Mechanical interlocking improves shear strength, while chemical bonding relies on reactive groups on the fiber and matrix surfaces. Physical treatments, such as plasma and corona, increase surface roughness and polarity, boosting interfacial adhesion. Chemical treatments, like alkali, silane, and maleated anhydride, are widely used to enhance bonding, while enzyme treatments are gaining popularity for their environmental friendliness.

Fibre Dispersion: Fibre dispersion significantly affects the properties of short natural fiber-reinforced thermoplastic composites (NFCs). The hydrophilic nature of the fibers and hydrophobicity of the matrix make achieving good dispersion challenging. Poor dispersion can lead to fiber agglomeration, especially with longer fibers, while good dispersion promotes better interfacial bonding by minimizing voids and ensuring the fibers are fully surrounded by the matrix. Factors like temperature, pressure, and additives such as stearic acid improve dispersion and interfacial bonding. Intensive mixing processes, such as using twin-screw extruders, enhance fiber dispersion but can damage fibers, reducing their length.

Fibre Orientation: Optimal mechanical properties are achieved when fibers are aligned parallel to the applied load, though aligning natural fibers is more difficult compared to continuous synthetic fibers. Some fiber alignment can occur during processes like injection molding, influenced by matrix viscosity and mold design. Techniques like carding fibers into sheets or using traditional textile processes, such as spinning, can improve alignment. Continuous fiber tapes, produced using natural pectin as an adhesive, also enhance alignment. Fiber orientation greatly influences mechanical performance, with strength and Young's modulus decreasing as fiber orientation angles increase relative to the test direction.

Manufacturing: Natural Fiber Composites (NFCs) are manufactured using methods such as extrusion, compression molding, injection molding, and Resin Transfer Molding (RTM). These processes are influenced by key factors like temperature, pressure, and speed, which affect the final properties of the composite. In extrusion, fibers and thermoplastics are mixed and shaped, with twin-screw systems offering better fiber dispersion. Injection molding produces composites with varying fiber orientation, often resulting in a skin-core structure that affects mechanical performance. Compression molding involves stacking fibers with matrix sheets and applying heat and pressure, requiring careful control to avoid fiber degradation at high temperatures. Film stacking is preferred for reducing thermal damage. RTM injects liquid resin into a fiber preform, offering lower temperature processing and minimizing thermo-mechanical degradation. It's effective for natural fiber composites due to their lower fiber alignment, making them more compactable and suitable for small production runs with strong compact strength.

Porosity: Porosity significantly affects the mechanical properties of composites, and extensive efforts have been made to reduce it in synthetic fiber composites. Porosity arises from air inclusion during processing, limited fiber wettability, lumens, hollow fiber features, and the fibers' low compaction ability. In natural fiber composites (NFCs), porosity increases with fiber content, especially after exceeding the geometric compaction limit. The extent of porosity depends on the type and orientation of the fiber. For instance, in flax/PP composites, porosity increased from 56% to 72%. Incorporating porosity into models improves predictions of strength and stiffness.

Applications: NFCs are rapidly replacing metal or ceramic-based materials in industries such as automotive, aerospace, marine, and electronics. Natural fibers like hemp, flax, and jute are favored for their lightweight and cost-effectiveness. In Germany, automakers like Audi and Mercedes-Benz use NFCs in vehicle interiors. While NFCs offer good specific properties, challenges such as moisture absorption, temperature limitations, and variability in quality affect their performance.

9. Conclusion:

In conclusion, this study underscores the promising potential of short natural fiber-reinforced thermoplastic composites (NFCs) in improving mechanical properties while advancing sustainability in material engineering. By examining various natural fibers such as flax, hemp, kenaf, sisal, and abaca, we have established a clear link between their unique properties and the performance of NFCs. Key factors like fiber content, length, and orientation have been shown to significantly influence mechanical strength and stiffness, emphasizing the critical role of fiber-matrix interfacial bonding for effective stress transfer. Techniques aimed at enhancing wettability, particularly chemical treatments, are essential for addressing the challenges posed by the hydrophilic nature of natural fibers. While obstacles such as moisture absorption and variability in fiber quality persist, the increasing applicability of NFCs in sectors like automotive and aerospace highlights their potential to replace traditional materials. Ultimately, this research lays the groundwork for future innovations in sustainable composites, advocating for optimized processing techniques and strategic material selection.

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