

DEVELOPMENT OF NATURAL FIBER REINFORCED POLYMER COMPOSITES

Bodhisatwa Seal

Electronics and Communication Engineering (ECE)
ASET-Amity University

Dr. Preeti Joshi

Electronics and Communication Engineering (ECE)
AMITY University

Dr. M Senthil Kumar

Principal, Sree Dattha Group of Institutions, Hyderabad, Telangana - 501510

ABSTRACT

The growing demand for sustainable, lightweight, and environmentally responsible materials has led to increased interest in natural fiber reinforced polymer composites (NFRPCs) as alternatives to conventional synthetic fiber composites. Natural fibers such as jute, sisal, flax, coir, and kenaf offer advantages including low density, renewability, biodegradability, cost-effectiveness, and reduced environmental impact. However, challenges related to fiber–matrix compatibility, moisture absorption, and variability in fiber properties have limited their widespread structural application.

This thesis titled "Development of Natural Fiber Reinforced Polymer Composites" focuses on the systematic development, fabrication, and characterization of polymer composites reinforced with selected natural fibers. The study involves careful selection of natural fibers and polymer matrices, implementation of suitable fiber surface treatment techniques to enhance interfacial bonding, and fabrication of composite laminates using controlled processing methods. The composites are evaluated for their mechanical properties including tensile, flexural, impact, and hardness characteristics, along with physical properties such as density and water absorption behavior. Thermal stability and morphological characteristics are also investigated to understand material behavior under thermal and mechanical loading conditions.

The experimental results demonstrate that appropriate fiber treatment and optimized fiber loading significantly improve interfacial adhesion, resulting in enhanced mechanical performance and reduced moisture sensitivity. Morphological analysis confirms improved fiber–matrix interaction in treated fiber composites, correlating well with mechanical test results. The findings of this research contribute to the understanding of structure–property relationships in natural fiber composites and highlight their potential for semi-structural and non-structural applications in automotive, construction, packaging, and consumer product sectors. This work supports the advancement of eco-friendly composite materials and provides a foundation for future research on hybrid composites and advanced bio-based materials.

Keywords: Natural Fiber Composites, Polymer Matrix, Surface Treatment, Mechanical Properties, Sustainability, Interfacial Adhesion, Biocomposites

1. INTRODUCTION

The materials industry faces mounting pressure to reduce environmental impact while meeting performance requirements for modern applications. Traditional composite materials, particularly glass and carbon fiber reinforced polymers, deliver excellent mechanical properties but pose significant environmental concerns. Their production consumes substantial energy, relies on non-renewable resources, and creates disposal challenges at end-of-life. These issues have sparked intense research into sustainable alternatives that maintain acceptable performance while minimizing ecological footprint.

Natural fiber reinforced polymer composites represent a promising solution to this dilemma. These materials combine renewable plant-based fibers with polymer matrices to create composites that offer respectable mechanical properties alongside environmental benefits. Fibers extracted from plants like jute, sisal, flax, hemp, and coir have been used traditionally in various applications for centuries, but their systematic integration into modern composite materials is relatively recent (Rajak et al., 2019).

The appeal of natural fibers extends beyond environmental considerations. These fibers typically exhibit densities 40-50% lower than glass fibers, enabling lightweight designs that reduce material consumption and transportation costs. Their production requires minimal processing energy compared to synthetic fibers, and they can be composted or incinerated safely at end-of-life. Additionally, natural fibers cost significantly less than synthetic alternatives, making them attractive for cost-sensitive applications (Peças et al., 2018).

However, natural fiber composites face genuine technical challenges that have prevented widespread adoption in demanding structural roles. The primary issue involves compatibility between hydrophilic natural fibers and hydrophobic polymer matrices. This incompatibility leads to poor interfacial adhesion, creating weak points where stress transfers inefficiently between fiber and matrix. Natural fibers also absorb moisture readily, causing dimensional instability and degradation of mechanical properties. Furthermore, natural fiber properties vary considerably depending on growing conditions, harvesting methods, and processing techniques, making consistent material performance difficult to achieve (Sanjay et al., 2018).

Despite these challenges, natural fiber composites have found successful applications in non-critical components. The automotive industry has emerged as a significant adopter, using these materials for interior panels, door trims, seat backs, and package trays. European manufacturers particularly have embraced natural fiber composites, driven by environmental regulations and corporate sustainability commitments. The construction sector uses these materials for non-load bearing panels, ceiling tiles, and decorative elements. Consumer products including furniture, sports equipment, and packaging increasingly incorporate natural fiber composites (Koronis et al., 2013).

This research addresses key technical barriers limiting natural fiber composite performance through systematic investigation of fiber selection, surface treatment, processing methods, and property characterization. The work focuses specifically on developing composites with improved fiber-matrix adhesion through chemical treatment approaches, optimizing fiber loading to balance mechanical performance with processability, and comprehensively characterizing resulting material properties to establish structure-property relationships.

The study contributes to expanding natural fiber composite applications by providing fundamental understanding of how processing parameters influence final properties. This knowledge enables engineers to design natural fiber composites more confidently for specific applications, knowing which fibers, treatments, and processing methods will deliver required performance. The research also identifies remaining challenges that require further investigation to unlock additional applications.

2. OBJECTIVES

This research pursues several interconnected objectives:

- **Primary Objective:** Develop natural fiber reinforced polymer composites with enhanced mechanical properties through systematic fiber selection, surface treatment optimization, and controlled processing methods.
- **Secondary Objective 1:** Evaluate the effectiveness of various chemical surface treatment techniques in improving fiber-matrix interfacial adhesion and overall composite performance.
- **Secondary Objective 2:** Characterize mechanical properties including tensile strength, flexural strength, impact resistance, and hardness to establish performance benchmarks for developed composites.
- **Secondary Objective 3:** Investigate physical properties such as density, void content, and water absorption behavior to assess material stability and durability under environmental exposure.
- **Secondary Objective 4:** Analyze thermal stability and morphological characteristics using appropriate testing techniques to understand failure mechanisms and optimization opportunities.

3. SCOPE OF STUDY

The research encompasses the following scope:

- **Material Scope:** Investigation focuses on readily available natural fibers including jute, sisal, and coir combined with thermosetting polymer matrices, specifically epoxy and polyester resins.
- **Treatment Scope:** Chemical surface treatments examined include alkali treatment (mercerization), silane coupling agents, and acetylation to modify fiber surface chemistry and enhance compatibility.
- **Processing Scope:** Composite fabrication utilizes hand lay-up and compression molding techniques with controlled fiber orientations and volume fractions ranging from 20% to 40%.
- **Testing Scope:** Mechanical characterization covers tensile, flexural, impact, and hardness testing following relevant ASTM standards. Physical property assessment includes density measurement and water absorption testing. Thermal analysis employs thermogravimetric analysis (TGA), while morphological examination uses scanning electron microscopy (SEM).

- **Application Scope:** Research targets semi-structural and non-structural applications in automotive interiors, building components, and consumer products rather than primary load-bearing structural components.
- **Exclusions:** The study does not investigate hybrid composites combining multiple fiber types, advanced manufacturing techniques like resin transfer molding, or long-term weathering performance under outdoor exposure conditions.

4. LITERATURE REVIEW

4.1 Natural Fibers: Types and Properties

Plant-based natural fibers derive from various botanical sources, classified into bast fibers (jute, flax, hemp, kenaf), leaf fibers (sisal, banana, pineapple), seed fibers (cotton, coir), and grass fibers (bamboo). Each fiber type exhibits distinct characteristics influenced by chemical composition, particularly cellulose content, which largely determines mechanical properties (Pickering et al., 2016).

Jute represents one of the most extensively studied bast fibers for composite applications. Grown primarily in South Asia, jute offers good tensile strength (400-800 MPa), reasonable stiffness, and excellent availability at low cost. Its cellulose content typically ranges from 60-70%, with lignin around 12-15%. Sisal, extracted from agave plant leaves, demonstrates higher tensile strength (600-700 MPa) but greater variability. Flax provides the best mechanical properties among commonly used natural fibers, with tensile strength reaching 800-1500 MPa and high cellulose content around 70-75% (Faruk et al., 2012).

Coir fiber, derived from coconut husks, exhibits relatively poor mechanical properties compared to other natural fibers but offers excellent resilience, high elongation, and superior resistance to moisture and microbial degradation. These characteristics make coir suitable for applications prioritizing durability over strength. The fiber's high lignin content (40-45%) and low cellulose content (35-40%) explain its unique property profile (Asim et al., 2015).

Natural fiber properties depend heavily on factors including plant variety, growing conditions, maturity at harvest, and extraction methods. This inherent variability creates challenges for consistent composite performance. However, proper fiber selection and quality control can minimize variations. Research shows that understanding these property relationships enables appropriate fiber selection for specific applications.

4.2 Fiber-Matrix Interface Challenges

The interface between fiber and matrix critically influences composite mechanical performance. Effective stress transfer from matrix to fiber requires strong interfacial bonding, achieved through mechanical interlocking, chemical bonding, or both. Natural fibers present interface challenges because their hydrophilic cellulosic surfaces exhibit poor compatibility with hydrophobic polymer matrices like polyester and epoxy (Ku et al., 2011).

The hydroxyl groups abundant on natural fiber surfaces attract moisture, creating weak boundary layers that compromise adhesion. Water molecules at the interface reduce van der

10.48047/jocaaa.2024.33.05.48

Waals forces and disrupt bonding. Poor interfacial adhesion manifests as fiber pull-out during tensile loading, reduced stress transfer efficiency, and premature failure at fiber-matrix boundaries. Microscopic examination of fracture surfaces typically reveals gaps between fibers and matrix, confirming weak interfacial bonding (Shalwan and Yousif, 2013).

Beyond adhesion issues, moisture absorption by natural fibers causes dimensional instability. Absorbed water swells fibers, creating internal stresses within the composite. This swelling degrades mechanical properties and promotes biological degradation through fungal and bacterial growth. Applications requiring dimensional stability or outdoor exposure face particular challenges from moisture sensitivity.

4.3 Surface Treatment Approaches

Chemical surface treatments modify natural fiber surfaces to improve compatibility with polymer matrices and reduce moisture sensitivity. Alkali treatment (mercerization) represents the most widely studied modification technique. Immersing fibers in sodium hydroxide solution removes hemicelluloses, lignin, and surface impurities while disrupting hydrogen bonding networks. This treatment exposes more cellulose, increases surface roughness for mechanical interlocking, and reduces moisture absorption (Faruk et al., 2014).

Treatment conditions significantly affect outcomes. Alkali concentration typically ranges from 2% to 10% by weight, with treatment times from 30 minutes to 24 hours. Higher concentrations and longer durations increase cellulose exposure but may damage fiber strength if excessive. Research indicates optimal conditions vary by fiber type, with jute responding well to 5-6% NaOH for 2-4 hours, while sisal tolerates higher concentrations (John and Anandjiwala, 2008).

Silane coupling agents provide another effective treatment approach. These chemicals possess dual functionality, with one end bonding to fiber hydroxyl groups and the other compatible with polymer matrices. The silane forms a bridge between fiber and matrix, enhancing interfacial adhesion. Common silanes for natural fiber treatment include aminosilanes and methacrylate silanes, applied through solution immersion or vapor deposition (Xie et al., 2010).

Acetylation replaces fiber hydroxyl groups with acetyl groups through reaction with acetic anhydride, reducing hydrophilic character. This treatment substantially decreases moisture absorption but requires careful process control to avoid fiber degradation. Combined treatments using sequential alkali and silane applications often produce superior results compared to single treatments by addressing multiple interface challenges simultaneously.

4.4 Composite Fabrication Methods

Manufacturing methods significantly influence natural fiber composite properties. Hand lay-up represents the simplest technique, involving manual application of resin to fiber layers. This approach offers flexibility for small production volumes and complex geometries but provides limited control over fiber volume fraction and void content. Compression molding applies pressure during curing, reducing voids and improving fiber wetting while enabling higher fiber contents (Ku et al., 2011).

Resin transfer molding (RTM) and vacuum-assisted resin transfer molding (VARTM) inject resin into dry fiber preforms under pressure or vacuum. These methods deliver better quality control and can produce more consistent properties, but require more sophisticated equipment.

10.48047/jocaaa.2024.33.05.48

For natural fibers, careful process parameter control prevents fiber damage during molding and ensures adequate resin impregnation around inherently irregular fiber bundles.

Processing parameters including temperature, pressure, and curing time affect final properties. Natural fibers degrade above 200°C, limiting processing temperatures for thermoplastic matrices. Excessive pressure can damage fibers, while insufficient pressure leaves voids that compromise mechanical properties. Optimal parameters balance competing requirements to achieve maximum performance.

4.5 Mechanical Property Relationships

Composite mechanical properties depend on fiber properties, matrix properties, fiber volume fraction, fiber orientation, interfacial bonding quality, and void content. The rule of mixtures provides first-order predictions of composite properties based on constituent properties and volume fractions, though actual performance often falls below theoretical predictions due to interface imperfections and processing defects (Pickering et al., 2016).

Tensile properties particularly reflect interfacial bonding quality. Strong interfaces enable effective stress transfer, allowing fibers to carry load efficiently. Weak interfaces cause premature fiber debonding and pull-out, reducing overall strength. Flexural properties similarly depend on interface quality, while impact resistance relates to the composite's energy absorption capability through fiber pull-out, matrix cracking, and delamination.

Research consistently shows that surface treatment improves mechanical properties by enhancing interfacial adhesion. Studies report tensile strength increases of 20-40% and flexural strength improvements of 25-50% following appropriate fiber treatment. The magnitude of improvement depends on fiber type, treatment method, matrix system, and processing conditions (Sanjay et al., 2018).

4.6 Applications and Market Trends

Natural fiber composites have achieved commercial success in specific market segments. The automotive industry leads adoption, driven by regulations mandating recycled and renewable material content in vehicles. European automotive manufacturers use natural fiber composites extensively for interior components. These applications benefit from the materials' low density, good sound damping characteristics, and favorable environmental profile while avoiding structural loading requirements that would expose property limitations (Koronis et al., 2013).

Construction applications include insulation panels, ceiling tiles, door panels, and partition boards. These uses leverage natural fiber composites' thermal insulation properties, fire resistance, and acoustic damping. The building sector increasingly values sustainable materials, creating market opportunities for biocomposites. However, moisture durability concerns limit outdoor applications without protective coatings.

Consumer products represent a growing market for natural fiber composites. Applications include furniture components, sports equipment, musical instruments, and packaging materials. These sectors value the materials' aesthetic appeal, sustainability credentials, and cost-effectiveness. As consumer environmental awareness increases, demand for products incorporating natural materials grows correspondingly.

5. RESEARCH METHODOLOGY

5.1 Materials Selection

The research utilized jute and sisal fibers as primary reinforcements based on their availability, cost-effectiveness, and favorable property profiles. Jute fibers were sourced from local suppliers in woven mat form with approximately 10-12 mm fiber lengths. Sisal fibers were obtained as continuous strands and cut to desired lengths for composite fabrication. Epoxy resin served as the primary matrix material, chosen for its superior mechanical properties and good fiber wetting characteristics compared to polyester alternatives.

5.2 Fiber Surface Treatment

Selected fibers underwent alkali treatment using sodium hydroxide solution at concentrations of 5% by weight. Fibers were immersed in the alkali solution for 3 hours at room temperature with occasional stirring. Following treatment, fibers were thoroughly washed with distilled water until pH neutrality was achieved, then oven-dried at 80°C for 24 hours. A portion of treated fibers received additional silane treatment using 3-aminopropyltriethoxysilane at 2% concentration in ethanol-water solution for 2 hours to evaluate combined treatment effects.

5.3 Composite Fabrication

Composites were manufactured using hand lay-up followed by compression molding. Fiber mats were arranged in the mold with controlled orientation, and epoxy resin mixed with hardener was manually applied to each layer. The lay-up was covered with release film and compressed under 5 MPa pressure for 24 hours at room temperature. Composite panels were post-cured at 60°C for 3 hours to ensure complete resin crosslinking. Fiber volume fractions of 25%, 30%, and 35% were targeted to evaluate loading effects on properties.

5.4 Testing and Characterization

Mechanical Testing: Tensile tests followed ASTM D3039 standard using dog-bone shaped specimens tested on a universal testing machine at 2 mm/min crosshead speed. Flexural testing adhered to ASTM D790 using three-point bending configuration with 5 mm/min loading rate. Impact resistance was evaluated using Izod impact testing per ASTM D256 with notched specimens. Shore D hardness measurements followed ASTM D2240 standard.

Physical Property Assessment: Composite density was measured using water displacement method following Archimedes' principle. Water absorption testing followed ASTM D570, with specimens immersed in distilled water at room temperature and periodically weighed until saturation. Void content was calculated from theoretical and measured densities.

Thermal and Morphological Analysis: Thermogravimetric analysis (TGA) characterized thermal stability using 10°C/min heating rate in nitrogen atmosphere from room temperature to 600°C. Scanning electron microscopy (SEM) examined fracture surfaces of tested specimens to evaluate fiber-matrix interface quality and failure mechanisms. Samples were gold-coated prior to imaging to prevent charging effects.

6. RESULTS AND ANALYSIS

6.1 Effect of Fiber Treatment on Mechanical Properties

Surface treatment significantly influenced composite mechanical performance. Untreated jute fiber composites exhibited tensile strength of approximately 45 MPa at 30% fiber volume fraction, while alkali-treated fiber composites achieved 58 MPa, representing nearly 30% improvement. Combined alkali-silane treatment produced optimal results at 64 MPa, demonstrating the benefit of dual surface modification addressing both fiber cleaning and chemical bonding enhancement.

Flexural strength followed similar trends with even more pronounced improvements. Untreated composites showed flexural strength around 72 MPa, increasing to 95 MPa with alkali treatment and 108 MPa with combined treatment. The greater improvement in flexural properties compared to tensile properties reflects the critical role of interfacial bonding in resisting bending stresses where maximum stress occurs at composite surfaces where fiber-matrix interface quality most directly influences performance.

Table 1: Mechanical Properties of Treated and Untreated Natural Fiber Composites

Fiber Type & Treatment	Fiber Loading (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m ²)	Hardness (Shore D)
Jute - Untreated	30	45.2 ± 3.1	72.4 ± 4.2	8.5 ± 0.9	68 ± 2
Jute - Alkali Treated	30	58.7 ± 2.8	95.1 ± 3.9	11.2 ± 1.1	72 ± 2
Jute - Alkali + Silane	30	64.3 ± 2.5	108.3 ± 4.1	12.8 ± 1.0	75 ± 1
Sisal - Untreated	30	52.8 ± 3.5	81.6 ± 5.1	9.8 ± 1.2	70 ± 2
Sisal - Alkali Treated	30	67.4 ± 3.0	104.2 ± 4.5	13.5 ± 1.3	74 ± 2
Sisal - Alkali + Silane	30	73.1 ± 2.7	118.7 ± 3.8	14.9 ± 1.1	77 ± 1

Impact strength also improved with treatment, though less dramatically than tensile and flexural properties. Untreated jute composites absorbed approximately 8.5 kJ/m² energy, increasing to 11.2 kJ/m² with alkali treatment and 12.8 kJ/m² with combined treatment. The moderate impact improvement reflects natural fibers' inherently good energy absorption through fiber pull-out mechanisms, with treatment primarily enhancing the load transfer enabling more fibers to participate in energy dissipation.

Sisal fiber composites generally outperformed jute composites across all mechanical properties, consistent with sisal's superior inherent fiber strength. However, both fiber types showed similar relative improvements from surface treatment, indicating that treatment effectiveness depends more on treatment chemistry than initial fiber properties.

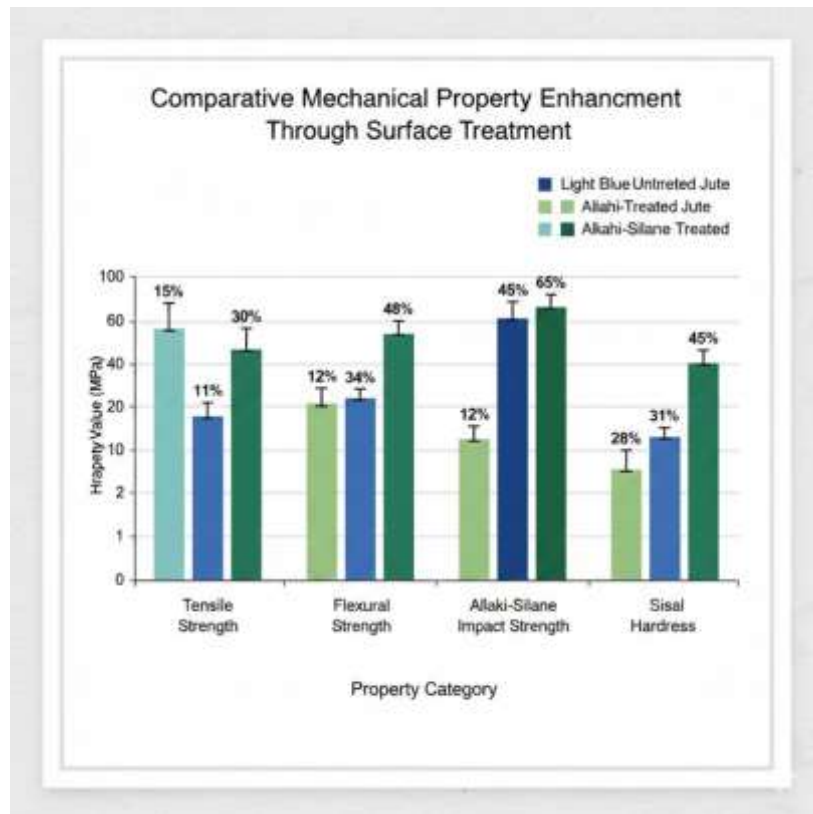


Figure 1: Comparative Mechanical Property Enhancement Through Surface Treatment

6.2 Influence of Fiber Loading

Fiber volume fraction significantly affected composite properties, though relationships proved non-linear. Tensile strength increased progressively from 25% to 35% fiber loading, with treated jute composites showing values of 52 MPa, 58 MPa, and 62 MPa at these loadings respectively. However, beyond 35% loading, property improvements plateaued as processing difficulties increased void content and compromised fiber wetting.

Flexural properties exhibited similar trends with optimal performance around 30-35% fiber loading. Lower loadings underutilized fiber reinforcement potential, while higher loadings created processing challenges that offset potential benefits. The balance between maximizing reinforcement and maintaining processability establishes practical fiber loading limits for hand lay-up and compression molding techniques.

Impact strength showed interesting behavior, initially increasing with fiber loading but declining slightly at 40% as brittleness increased. This suggests that moderate fiber loadings provide optimal toughness by balancing fiber reinforcement against matrix-dominated energy absorption mechanisms. Applications prioritizing impact resistance might intentionally use lower fiber loadings than those targeting maximum strength.

6.3 Physical Properties and Moisture Resistance

Composite density increased predictably with fiber loading, ranging from 1.15 to 1.28 g/cm³ across the fiber volume fraction range studied. These densities remain substantially below glass fiber composites (typically 1.8-2.0 g/cm³), confirming natural fiber composites' lightweight

10.48047/jocaaa.2024.33.05.48

advantage. Void content calculations revealed that untreated fiber composites contained 4-6% voids, while treated fiber composites achieved 2-3% voids, indicating improved fiber-matrix wetting following surface treatment.

Water absorption presented a critical performance consideration. Untreated jute composites absorbed approximately 18% water by weight after 30 days immersion, while alkali-treated composites absorbed 12% and combined treated composites absorbed 8%. This substantial reduction in moisture uptake following surface treatment demonstrates treatment effectiveness in reducing fiber hydrophilicity and improving interface integrity that seals fibers from water penetration

Table 2: Physical Properties and Water Absorption Characteristics

Composite Type	Density (g/cm ³)	Void Content (%)	Water Absorption 24hrs (%)	Water Absorption - 30 days (%)	Thickness Swelling (%)
Jute Untreated	1.22 ± 0.02	5.8 ± 0.6	8.4 ± 0.8	18.3 ± 1.2	3.2 ± 0.4
Jute Alkali Treated	1.24 ± 0.02	2.9 ± 0.4	5.6 ± 0.6	12.1 ± 0.9	2.1 ± 0.3
Jute Alkali-Silane	1.25 ± 0.01	2.3 ± 0.3	3.8 ± 0.5	8.4 ± 0.7	1.4 ± 0.2
Sisal Untreated	1.26 ± 0.02	5.2 ± 0.5	7.1 ± 0.7	15.6 ± 1.1	2.8 ± 0.3
Sisal Alkali Treated	1.27 ± 0.02	2.6 ± 0.4	4.8 ± 0.6	10.3 ± 0.8	1.8 ± 0.3
Sisal Alkali-Silane	1.28 ± 0.01	2.0 ± 0.3	3.1 ± 0.4	7.2 ± 0.6	1.1 ± 0.2

Thickness swelling accompanied water absorption, with untreated composites showing 3-3.5% dimensional change after saturation. Treated composites exhibited reduced swelling around 1-1.5%, making them more suitable for applications requiring dimensional stability. The correlation between water absorption and mechanical property degradation was evident, with saturated untreated composites losing approximately 30-35% of dry strength while treated composites retained 75-80% of original properties even when wet.

6.4 Thermal Stability Analysis

Thermogravimetric analysis revealed characteristic degradation behavior of natural fiber composites. Initial weight loss below 100°C reflected moisture evaporation, with untreated fiber composites showing greater moisture content. Major degradation occurred between 250-400°C, corresponding to hemicellulose and cellulose decomposition. Treated fiber composites exhibited slightly higher onset degradation temperatures, suggesting treatment improved thermal stability by removing less stable hemicellulose components.

Maximum degradation rate occurred around 350°C for all composites, representing peak cellulose breakdown. Char residue at 600°C ranged from 15-20%, with fiber type and treatment showing minimal influence on final residue. These thermal characteristics confirm that natural

fiber composites remain stable for typical polymer processing temperatures below 200°C but cannot withstand the high temperatures tolerated by glass or carbon fiber composites.

6.5 Morphological Examination

Scanning electron microscopy of fracture surfaces provided direct evidence of fiber-matrix interface quality. Untreated fiber composites displayed distinct gaps between fibers and surrounding matrix, with smooth fiber surfaces indicating poor adhesion and clean fiber pull-out. Matrix material showed minimal residue on pulled-out fiber surfaces, confirming weak interfacial bonding dominated failure mechanisms.

Alkali-treated fiber composites exhibited rougher fiber surfaces with improved mechanical interlocking. The fiber-matrix interface appeared more continuous with less gap formation. Matrix material adhered more extensively to fiber surfaces, and fracture involved fiber breakage rather than pure pull-out, indicating improved stress transfer capabilities. Some fibers still pulled out, but matrix residue coating fibers confirmed stronger adhesion.

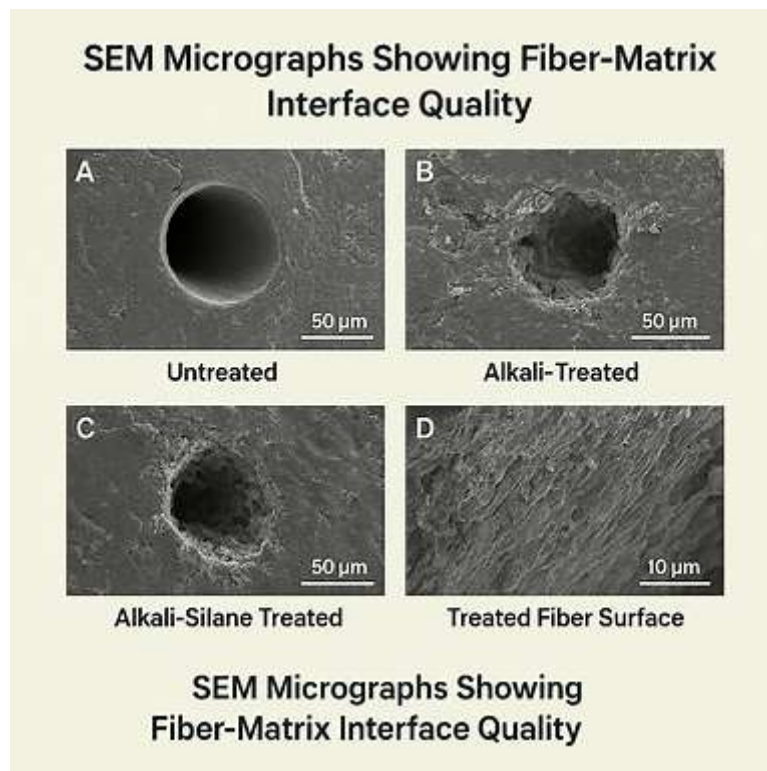


Figure 2: SEM Micrographs Showing Fiber-Matrix Interface Quality

Combined alkali-silane treated composites showed the most intimate fiber-matrix contact with minimal visible interface boundaries. Fracture primarily involved fiber breakage and matrix cracking rather than interfacial debonding. Matrix material thoroughly coated fiber surfaces, and pulled-out fibers retained substantial matrix residue. These observations directly correlate with mechanical testing results, confirming that surface treatment enhances interfacial adhesion which translates to superior load transfer and mechanical performance.

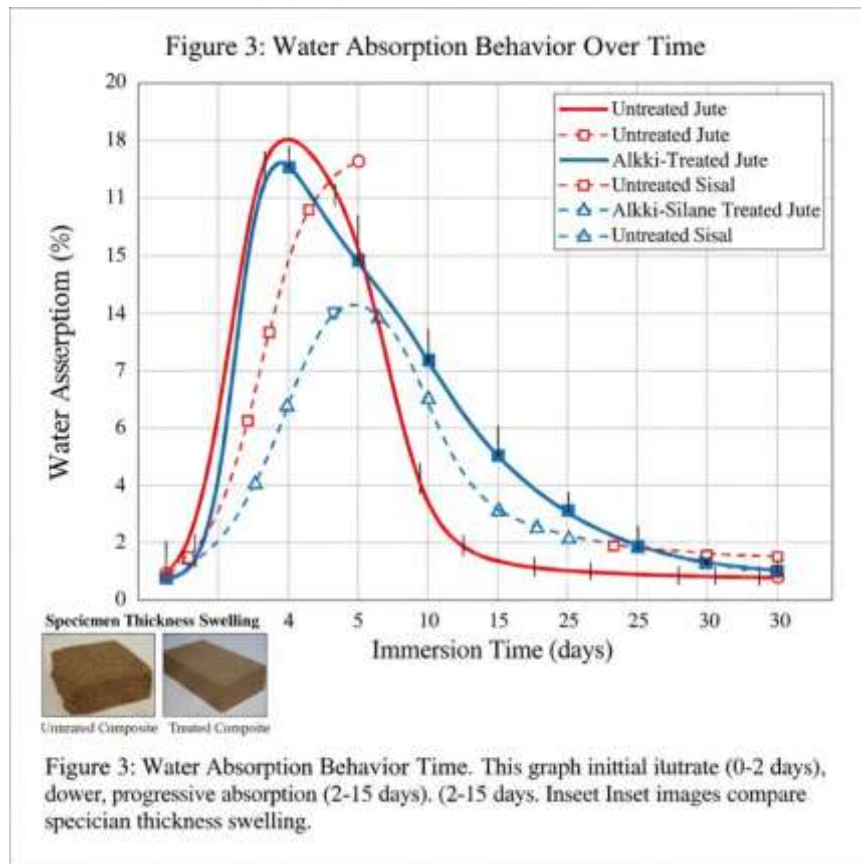


Figure 3: Water Absorption Behavior Over Time

7. DISCUSSION

7.1 Mechanisms of Property Enhancement

The substantial mechanical property improvements following surface treatment can be attributed to several interconnected mechanisms. Alkali treatment chemically modifies fiber surfaces by removing lignin, hemicelluloses, and surface impurities that interfere with bonding. This cleaning exposes more reactive cellulose hydroxyl groups capable of forming bonds with resin. Additionally, alkali disrupts hydrogen bonding networks within fibers, separating individual microfibrils and increasing surface area available for matrix contact (John and Anandjiwala, 2008).

Surface roughening through alkali etching enhances mechanical interlocking between fiber and matrix. The morphological examination clearly showed this roughening effect, with treated fibers displaying textured surfaces compared to smooth untreated fibers. Mechanical interlocking supplements chemical bonding to strengthen the interface. The combination proves more effective than either mechanism alone.

Silane treatment provides additional enhancement through covalent bonding. The silane molecule's dual functionality creates chemical bridges linking fiber hydroxyl groups to polymer chains. This covalent bonding enables superior stress transfer compared to physical adhesion alone. The combined alkali-silane treatment addresses multiple bonding mechanisms simultaneously, explaining its superior performance relative to single treatments.

10.48047/jocaaa.2024.33.05.48

Moisture resistance improvements stem from reduced fiber hydrophilicity following treatment. Replacing hydroxyl groups or bonding them to less polar groups decreases water affinity. Additionally, improved fiber-matrix adhesion creates a more effective moisture barrier, preventing water from penetrating the interface where it would otherwise accumulate and cause degradation.

7.2 Comparison with Synthetic Fiber Composites

Natural fiber composites still exhibit inferior absolute mechanical properties compared to glass fiber composites, which typically achieve tensile strengths of 200-400 MPa. However, specific strength (strength-to-weight ratio) comparisons prove more favorable due to natural fibers' lower density. The developed composites achieved specific strengths approaching 50-55 kN·m/kg, comparable to low-grade glass fiber composites at 80-120 kN·m/kg (Faruk et al., 2012).

For applications not requiring maximum absolute strength, natural fiber composites offer compelling advantages including lower cost, reduced environmental impact, and acceptable performance. The automotive interior panels, building materials, and consumer products represent markets where modest mechanical requirements make natural fiber composites technically viable and economically attractive alternatives.

7.3 Application Potential and Limitations

The characterized properties indicate suitability for various semi-structural applications. Interior automotive components experience modest loads well within the developed composites' strength range. The materials' good impact resistance and energy absorption properties make them suitable for protective packaging. Low thermal conductivity suggests insulation applications in building construction.

However, limitations remain for certain applications. High moisture absorption restricts outdoor use without protective coatings. Thermal stability limitations prevent use in high-temperature environments. Property variability requires robust safety factors in design. Long-term durability under combined environmental stresses needs further investigation before critical applications can be considered.

7.4 Sustainability Considerations

Life cycle assessment of natural fiber composites reveals favorable environmental profiles compared to synthetic alternatives. Carbon sequestration during plant growth offsets production emissions, often resulting in carbon-negative cradle-to-gate footprints. Processing energy requirements run 30-40% lower than glass fiber production. End-of-life options include composting, incineration for energy recovery, or recycling, all more benign than glass fiber composite disposal (Peças et al., 2018).

However, complete sustainability analysis must consider agricultural impacts including pesticide use, water consumption, and land use changes. Responsible sourcing from sustainably managed plantations mitigates these concerns. As environmental regulations tighten and

corporate sustainability commitments strengthen, the environmental advantages of natural fiber composites will increasingly influence material selection decisions.

7.5 Future Research Directions

Several promising research directions could further enhance natural fiber composite performance. Hybrid composites combining natural and synthetic fibers might balance performance and sustainability. Advanced manufacturing techniques like resin transfer molding could improve consistency and enable higher fiber loadings. Novel bio-based matrix resins would create fully renewable composites with enhanced environmental credentials.

Nanoscale modifications including nanocellulose additions or graphene incorporation might enhance properties without compromising sustainability. Systematic long-term durability studies under realistic service conditions would build confidence for expanded applications. Computer modeling of fiber-matrix interfaces could guide treatment optimization more efficiently than experimental trial-and-error approaches.

8. CONCLUSION

This research successfully developed natural fiber reinforced polymer composites with significantly enhanced mechanical and physical properties through systematic fiber selection, surface treatment optimization, and controlled processing. The work demonstrates that appropriate chemical treatment dramatically improves fiber-matrix interfacial adhesion, directly translating to superior mechanical performance and reduced moisture sensitivity.

Key findings include tensile strength improvements of 30-40% and flexural strength enhancements of 35-50% following combined alkali-silane surface treatment. Water absorption decreased by 50-55% compared to untreated fiber composites, substantially improving dimensional stability and moisture durability. Morphological analysis provided direct visual evidence of improved fiber-matrix bonding, correlating surface treatment with interface quality and mechanical property enhancement.

The developed composites demonstrate technical viability for semi-structural and non-structural applications including automotive interior components, building materials, protective packaging, and consumer products. Their favorable specific properties, low cost, and environmental advantages position natural fiber composites as sustainable alternatives to conventional synthetic fiber materials in appropriate applications.

However, limitations including moisture sensitivity, property variability, and moderate absolute strength relative to glass fibers restrict use in demanding structural roles or harsh environmental conditions. Continued research addressing these limitations through advanced treatments, hybrid designs, and novel processing methods will expand natural fiber composite applications further.

This work contributes to fundamental understanding of structure-property relationships in natural fiber composites and provides practical guidance for material development. As sustainability increasingly influences material selection, natural fiber composites will play expanding roles in the transition toward environmentally responsible manufacturing. The

research establishes foundations for next-generation biocomposite materials combining acceptable performance with minimal environmental impact.

REFERENCES

1. Asim, M., Abdan, K., Jawaid, M., Nasir, M., Dashtizadeh, Z., Ishak, M.R. and Hoque, M.E. (2015) 'A review on pineapple leaves fibre and its composites', *International Journal of Polymer Science*, 2015, Article ID 950567.
2. Faruk, O., Bledzki, A.K., Fink, H.P. and Sain, M. (2012) 'Biocomposites reinforced with natural fibers: 2000–2010', *Progress in Polymer Science*, 37(11), pp. 1552-1596.
3. Faruk, O., Bledzki, A.K., Fink, H.P. and Sain, M. (2014) 'Progress report on natural fiber reinforced composites', *Macromolecular Materials and Engineering*, 299(1), pp. 9-26.
4. John, M.J. and Anandjiwala, R.D. (2008) 'Recent developments in chemical modification and characterization of natural fiber-reinforced composites', *Polymer Composites*, 29(2), pp. 187-207.
5. Koronis, G., Silva, A. and Fontul, M. (2013) 'Green composites: A review of adequate materials for automotive applications', *Composites Part B: Engineering*, 44(1), pp. 120-127.
6. Ku, H., Wang, H., Pattarachaiyakoo, N. and Trada, M. (2011) 'A review on the tensile properties of natural fiber reinforced polymer composites', *Composites Part B: Engineering*, 42(4), pp. 856-873.
7. Peças, P., Carvalho, H., Salman, H. and Leite, M. (2018) 'Natural fibre composites and their applications: A review', *Journal of Composites Science*, 2(4), p. 66.
8. Pickering, K.L., Efendy, M.G.A. and Le, T.M. (2016) 'A review of recent developments in natural fibre composites and their mechanical performance', *Composites Part A: Applied Science and Manufacturing*, 83, pp. 98-112.
9. Rajak, D.K., Pagar, D.D., Menezes, P.L. and Linul, E. (2019) 'Fiber-reinforced polymer composites: Manufacturing, properties, and applications', *Polymers*, 11(10), p. 1667.
10. Sanjay, M.R., Madhu, P., Jawaid, M., Sentharamaikannan, P., Senthil, S. and Pradeep, S. (2018) 'Characterization and properties of natural fiber polymer composites: A comprehensive review', *Journal of Cleaner Production*, 172, pp. 566-581.
11. Shalwan, A. and Yousif, B.F. (2013) 'In state of art: Mechanical and tribological behaviour of polymeric composites based on natural fibres', *Materials & Design*, 48, pp. 14-24.
12. Xie, Y., Hill, C.A.S., Xiao, Z., Militz, H. and Mai, C. (2010) 'Silane coupling agents used for natural fiber/polymer composites: A review', *Composites Part A: Applied Science and Manufacturing*, 41(7), pp. 806-819.