ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug817

Developments in Eco-friendly Composite Materials: Applications of Chemically Treated Natural Fibers in Polymers

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Publication Date: 2025/08/22

Abstract: Addressing the growing concerns on environmental damage because of plastic waste and the increasing depletion of fossil resources has changed the focus of material science towards greener alternatives. The concern of Natural Fiber Reinforced Polymer Composites is their availability, as they are renewed and biodegradable and easy to compost. Natural fibers are intrinsically low in efficiency for composite usage because of their compatibility to hydrophobic polymer matrices. Nevertheless, the perimeter of natural fibers is enhanced by chemical treatment, improving their mechanical, thermal and environmental properties, which in turn makes them more useful for industrial purposes. This report explores various chemical treatments to natural fibers, the impact of the fibers on the resultant composite, along with their application in the automotive, construction and packaging industries.

Keywords: *Natural Fibers, Polymer Composites, Hybrid Composites, Plant Fibers, Eco-Friendly Materials, Sustainable Composites.*

How to Cite: J. Sethubathi (2025) Developments in Eco-friendly Composite Materials: Applications of Chemically Treated Natural Fibers in Polymers. *International Journal of Innovative Science and Research Technology*, 10(8), 823-827. https://doi.org/10.38124/ijisrt/25aug817

I. INTRODUCTION

The last few decades have seen increased attention towards natural fibers as reinforcements in composite materials because of the focus on sustainable materials. Composed of renewable resources, natural fibers jute, hemp, flax, sisal, and kenaf have a low density and offer a high strength-to-weight ratio, in addition to being more environmentally friendly than synthetic alternatives. Nonetheless, issues with polymer composite durability, high moisture absorption, and low polymer adhesion have limited the application of natural fibers reinforced polymer composites.[1]

To enhance durability and adhesion, chemical treatments are often applied to natural fibers. These treatments are designed to alter the natural fiber's surface chemistry, improving adhesion, mechanical strength, and environmental resilience of the polymer matrix composite. This report discusses the different chemical modification methods and focuses on the modifications and their effects on the properties and applications of natural fiber composites.[2, 3]

II. CHEMICAL TREATMENTS FOR NATURAL FIBERS

A. *Types of Chemical Treatments*

To make natural fibers work better with polymers, various chemical treatments are done:

➢ *Alkaline Treatment (Mercerization)*

Fibers are immersed in sodium hydroxide (NaOH) solution, which clears the fibers of pollutants like lignin, hemicellulose, and waxes. In addition to alkaline treatment, sodium hydroxide also changes the composition of the fiber and makes it rough and more crystalline in which the fibers and polymers are to be bonded.

➢ *Acid Treatment*

Using weak solutions of sulfuric and hydrochloric acids will aid in removing lignin and other non-cellulosic components from the fiber surface. Removal of non-cellulosic components from fiber surfaces with weak acids will increase the cellulose and will help in enhancing compatibility with polymers.

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➢ *Silane Treatment*

Fibers made of polymers have surfaces which are bonded with chemical groups acrylonitrile, glycidyl methacrylate and silane. These chemical groups possess reactive sites which help bond with fibers and polymers and therefore increase the interfacial adhesion and the mechanical properties of the fiber reinforced composite materials.

➢ *Enzymatic Treatment*

An example of this is the use of the non-cellulosic compounds with enzymes. Compared to harsher chemicals, enzymes are milder alternatives, and they can be used to aid the environment.

➢ *Grafting and Cross-linking:*

To make fibers more durable, cross-linking is used to increase the structural integrity and this is done through addition of monomers which is called grafting. Both techniques are used to improve the mechanical and thermal properties of the composites.

B. Mechanisms of Chemical Modification

The assessed treatments applied to natural fibers had more to do with their surface chemistry linings and shape structures. Decellularization processes increases the number of reactive hydroxyl groups on the fibers surface which enhances the adhesion of the fiber to a polymer matrix. Moreover, the chemical treatments boost the fibers burns and stiffness which is helpful to their mechanical properties and yields a better performance of the composite materials.[4-6]

III. PROPERTIES OF CHEMICALLY MODIFIED NATURAL FIBER COMPOSITES

A. Mechanical Properties

Natural fibers are preferred to be composite because of their strength to yield better mechanical properties to polymer and the endurance of the polymer matrix that is within the fibers. The composite that undergoes chemical treatment processes portrays the following changes:

➢ *Tensile Strength*

The composite improves adhesion due to the treatment which reduces fiber brittleness and improves the bond between fiber and polymer matrix.[3, 7]

➢ *Flexural Strength*

Since the composite is reinforced with chemically treated fibers, it shows improved flexural strength which is suitable to be used in applications that are commonly subjected to flexural stresses.[8, 9]

➢ *Impact Resistance*

The bonded chemically treated fibers and polymer proven to exhibit greater weak zone toughness compared to traditional polymers leading to a greater resistance to impact and crack propagation.

B. Thermal Properties

For many uses of fiber-reinforced composites, thermal stability is a key design goal. By applying appropriate chemical treatments, natural fibers gain properties that translate directly into better thermal performance.

➢ *Decomposition Temperature*

When fibers receive chemical modification, their decomposition temperature rises noticeably. By pushing that thermal threshold upward, the composites can steadily hold their mechanical properties in elevated temperature environments.[10-12]

➢ *Heat Deflection Temperature*

Composites built with treated fibers show a marked increase in heat deflection temperature. Such gains translate into design margins that suit hot under-the-hood automotive parts, ventilation ducts, and even heated area panels in construction.

C. Moisture and Environmental Resistance

Another challenge with natural fibers is their propensity to pick up moisture. Chemistry that modifies the surface can combat this design vulnerability quite effectively.

➢ *Moisture Absorption:*

Both alkaline and silane treatments are well-documented to lower moisture adsorption. By directly repairing the fiber surface and improving fiber-matrix interlock, the composites retain tensile properties under the dimensional-shift stress of humid exposure.

➢ *UV and Weathering Resistance*

Co-bonding with UV stabilizers and antioxidants is becoming a routine step. When integrated during fiber modification, these additives absorb and dissipate harmful UV photons and oxidizing radicals, which curbs performance shifts in outdoor, long-life applications like bus shelters and building reinforcements.[13-15]

D. Biodegradability

One of the most compelling advantages of incorporating natural fibers into composite materials is their promise of biodegradability. Even after undergoing chemical modification, these composites preserve their ability to break down naturally, carving out a pathway to sustainability that fossil-fuel-based, synthetic fibers cannot match. This lower lifecycle environmental footprint renders them especially appealing for packaging systems and other applications that are intended to be single-use and, ultimately, discarded.[16-18]

IV. APPLICATIONS OF CHEMICALLY TREATED NATURAL FIBER COMPOSITES

Novel characteristics arising from controlled chemical treatments enhance the performance of natural fiber composites and extend their potential to numerous industry sectors. By fine-tuning the fiber-matrix interface, manufacturers are unlocking just the right stiffness, strength, and thermal resistance needed for precise applications, across sectors as diverse as automotive manufacturing and civil engineering, where maintaining performance with the lightest possible weight is a strategic advantage.[19-21]

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A. Automotive Industry

In the automobile industry, for example, the relentless drive to trim overall vehicle mass translates directly into lower fuel consumption, reduced operational CO_2 emissions, and lower operational costs. Treated plant fibers are already seeing use in headliners, door panels, and other non-load-bearing, yet structurally significant, interior components, where the composites deliver a startling combination of rigidity, thermal properties, and acoustic absorption. This multifunctional combination both trims parts weight and moderates cabin noise, delivering performance that drivers appreciate while simultaneously contributing to regulatory compliance.[22, 23]

- *Interior Components:*
  Door panels, dashboards, seat backs, and headliners.

- *Structural Components*
  Bumpers and reinforcement parts.

The superior mechanical properties, sound insulation, and reduced weight make them ideal for the automotive sector.

B. Construction Industry

The construction sector is not far behind. Design teams are evaluating natural fiber composites for components ranging from interior panelling and finishing materials to strictly load-bearing structural assemblies. When resins of carefully calibrated stiffness and strength are infused into mats of treated flax, hemp, and jute, the resulting panels and beams boast competitive bending properties, thermal insulation, and a much lower environmental footprint than comparably performing traditional composites. By substituting a portion of their concrete, steel, or synthetics with these bio-based alternatives, builders can both lighten structural loads and lower the embodied carbon of their designs, a respectable double win for the planet and the bottom line.[24-26]

- *Reinforced Concrete*
  The incorporation of chemically treated natural fibers into concrete improves its mechanical strength and resistance to cracking.

- *Insulation Materials*
  Natural fiber composites are being used for thermal and sound insulation in buildings.

- *Sustainable Building Materials*
  Natural fibers contribute to more eco-friendly construction materials, reducing the overall carbon footprint of buildings.[27-29]

C. Packaging Industry

Booming interest in brand-lift sustainable packaging grocery to e-commerce has already seeded pilot-blessed pilot lots of these composites in:

- *Biodegradable Packaging*
  Natural fibers are used in producing eco-friendly, biodegradable packaging materials as an alternative to petroleum-based plastics.

- *Food Packaging*
  Composites made from chemically treated fibers can be used for food packaging, ensuring safety, durability, and environmental sustainability.

D. Consumer Goods and Textiles

In the consumer goods industry, chemically treated natural fibers are used in various products:

- *Textile Products*
  Eco-friendly clothing, bags, and footwear made from fiber-reinforced polymers.

- *Durable Goods*
  Bicycles, furniture, and sporting goods.

These applications take advantage of the high strength, low weight, and environmentally friendly nature of the composites.[30, 31]

V. FUTURE DIRECTIONS AND CHALLENGES

A. Scaling Production and Cost-Efficiency

While small-scale lab work has yielded encouraging data, moving the production of chemically modified natural-fiber composites beyond the pilot plant is still tricky. Affordable treatment and fabrication routes that stand up under megaton-scale scrutiny have to be hammered out if these materials are ever to give traditional synthetics a run for their money.[32, 33]

B. Recycling and End-of-Life Management

Funding concerns keep recyclability a hot research topic. Attunements at every stage—from production via tailored geometry to decommissioning via mild, solvent-aided depolymerization—are compulsory for the composites to hold their self-proclaimed sustainable tyre.[34, 35]

C. Scaling Production and Cost-Efficiency

Laser-focus continues to be laser-focus-kitchen. Juggling natural fibers with tailored, or waste-heavy, bio-degradable or, bio-derivable geeks expands the frontier of high-performance composites. The brackets of the current investigations still hinge on perfecting cohesion, stacking and architecture so that, for instance, tensile load and water curtain lose to handle with a clear conscience.[36-39]

VI. CONCLUSION

Modern composites based on chemically treated natural fibers are gaining traction as sustainable substitutes for synthetic counterparts, combining ecological advantages and high performance. Targeted chemical modifications selectively strengthen and functionalize fibers, raise mechanical strength, reduce moisture absorption, and improve adhesion to polymers. These gains open pathways to diverse sectors, including lightweight automotive parts, durable bio-based coatings, high-performance insulating panels, and fully biodegradable packaging. Growing legislative and consumer commitments to carbon-neutral sourcing are multiplying adoption pathways, while laboratories and pilot plants perfect scalable surface grafts, cost-effective bioresins, and closed-loop recycling. The horizon for chemically prescribed natural composites is

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug817

therefore expanding, with innovations that integrate multi functionality, digitally tuned fiber networks, and thermoplastic/thermoset hybrids poised to accelerate commercialization at a planetary scale.

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