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Chemical Compatibility and Performance Optimization in Natural Fiber-Based Polymer Composites

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Abstract: Natural fiber–reinforced polymer composites (NFPCs) are increasingly regarded as sustainable substitutes for conventional composites owing to their environmental merits, such as inherent biodegradability and comparatively low energy costs during manufacturing. Nonetheless, the intrinsic inadequacy of chemical bonding between the cellulosic fibers and the synthetic polymer matrices limits the realization of their anticipated end-use advantages. To circumvent this barrier and subsequently improve the composite's mechanical, thermal, and environmental outcomes, selective chemical functionalization of the reinforcements has obtained renewed investigative momentum. This review systematically elaborates on the fundamental mechanisms governing fiber–polymer interlinking and consolidates recent advancements in tailored oxidative, esterification, and silane modification procedures directed toward maximum fibre–matrix matching. A comprehensive quantitative and qualitative assessment of how these interface-engineering strategies modulate composite performance is presented, thereby directing the selection and refinement of treatments toward optimized exploitation across heterogeneous industrial environments ranging from transportation to civil infrastructure.

Keywords: *Chemical Compatibility, Performance Optimization, Natural Fiber Composites, Polymer Matrix, Interfacial Bonding, Fiber Modification, Mechanical Properties, Thermal Properties, Biodegradable Polymers, Sustainable Materials, Composite Materials, Material Science, Polymer Science.*

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I. INTRODUCTION

Leveraging natural extensions—hemp, jute, flax, kenaf, and sisal—within polymer matrices proves attractive due to sustainability, renewability, and eventual biodegradability. However, the intrinsic hydrophilicity of these fibers fosters poor adhesion to the typically hydrophobic matrices, resulting in brittle interfacial bonds. Such bonding weakness in turn restricts the composite's overall strength, dimensional precision, and longevity in service.[1]

Overcoming these interfacial barriers mandates a chemical engineered remake of the fibers that fosters polymer-cohesion. Surface modifications—alkali, acid etching, silane coating, and enzymatic cleansing—are thereby implemented to sculpt the boundary layer of each fiber, enhancing adhesion and amplifying composite performance. This report assembles a cohesive synchrony of the latest methodologies in chemical functionalization, quantifying the attendant gain in mechanical outcomes, prescribing the precise parameters for optimal intrusion, and cataloguing emergent utility in load-bearing and environmentally-harmonized products.[2, 3]

II. CHEMICAL COMPATIBILITY IN FIBER-MATRIX INTERACTIONS

The interlaminar efficacy of NFPCs is primarily dictated by the fibre–matrix interface. Synthetic polymer matrices, such as epoxy, polypropylene, and polyester, are fundamentally hydrophobic and exhibit limited van der Waals attraction with the hydrophilic hydroxyl and carboxyl functional groups decorating the resin surface. Conversely, the intrinsic chemical profile of lignocellulosic fibres, comprising elevated fractions of cellulose, hemicellulose, and lignin, is equally hydrophilic and predisposed to moisture uptake, thereby creating an energetic dissonance that clouds successful mechanical interlocking and adhesion.[4, 5]

The primary challenges related to fiber-matrix compatibility include:

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➢ *Moisture Absorption:*
The hydrophilic nature of fibers leads to high moisture uptake, which reduces the mechanical properties of the composite.[6]

➢ *Weak Interfacial Bonding:*
The inherent difference in polarity between natural fibers and polymer matrices creates a weak interface, resulting in poor stress transfer from the matrix to the fibers.[7]

➢ *Chemical Degradation:*
The presence of non-cellulosic substances such as lignin and hemicellulose can lead to chemical degradation of the fiber and the composite material over time.[8, 9]

Optimizing the bond between the polymer matrix and the reinforcement fibers is essential for maximizing the mechanical, thermal, and environmental performance of natural-fiber polymer composites (NFPCs). A broad range of chemical treatments is available to fine-tune the surface properties of the fibers, and thus secure stronger adhesion to the polymer.[10, 11]

III. CHEMICAL MODIFICATION TECHNIQUES FOR FIBER SURFACE OPTIMIZATION

A. Alkali Treatment (Mercerization)

Alkaline processing, colloquially called mercerization, continues to be the trusted ritual for curating natural fibers destined to harmonize with thermo-responsive composites. The ceremony opens with the fibers sliding into a heated reservoir of concentrated sodium hydroxide. The alkaline embrace is tender yet purposeful, dissolving hemicellulose, lignin, and the clandestine waxy membranes they wear. Once the bath has released its gentle grip, the fibers emerge intact but faithful—purged to a cellulose heart and a morphology that has softened into a contract of intimate surrender to any synthetic matrix that beckons.[12-14]

➢ *Effects on Composite Performance:*
- Increased Surface Roughness: Alkaline treatment creates a rougher fiber surface, which enhances mechanical interlocking between the fiber and polymer.
- Improved Tensile Strength: The removal of non-cellulosic substances enhances the fiber's strength, leading to stronger composites.
- Reduced Moisture Absorption: Alkaline treatment decreases the fiber's tendency to absorb water, improving the dimensional stability of the composites.

➢ *Challenges:*
- Overexposure to alkaline solutions may degrade the fiber, leading to a reduction in tensile strength.
- The alkali treatment process requires careful control to avoid excessive fiber degradation.

B. Acid Treatment

Acid treatments—most frequently using sulfuric or hydrochloric acid—efficiently prepare the fibers. These treatments preferentially dissolve the less ordered, amorphous portions of the cellulose, together with the interstitial hemicellulose and lignin, leading to a more crystalline cellulose structure. The result is an increase in fiber stiffness and an increase in the availability of reactive sites that foster a stronger bond within the polymer matrix.[15, 16]

➢ *Effects on Composite Performance:*
- Increased Crystallinity: Acid treatment enhances the crystallinity of cellulose, improving the mechanical properties of the fiber and composite.
- Improved Fiber-Matrix Adhesion: The acid-treated fibers exhibit better bonding with the polymer matrix, leading to improved tensile and flexural strength of the composites.[17]
- Reduced Hydrophilicity: Acid treatment reduces the water absorption capacity of the fiber, which improves the durability of the composite.

➢ *Challenges:*
- Strong acid concentrations can cause degradation of the fiber if not properly controlled.
- Post-treatment neutralization of the acid is necessary to prevent environmental contamination and preserve fiber integrity.[18]

C. Silane Coupling Agents

Eager to exploit those newly naked fiber surfaces, formulators reach for silane coupling molecules, geometric troubadours who teach disparate materials the art of unbreakable accord. Within each silane blueprint, dual pivot points wait: a silicon micro-latch yearning for glassy hydroxyls, a hydrolyzed silicon vice eager for amorphous islands, plus a conformal hydrocarbon skirt tail, so the whole affair can weave ether, siloxane, or the covalent friendship of its choice. Cure in the laboratory's mild oven, and the ensemble stiffens into a contiguous lace of bonds so leak-tight and needle-proof that composites greet tension with a shared, exuberant shout of trust.[19]

➢ *Effects on Composite Performance:*
- Enhanced Interfacial Bonding: Silane treatment improves the adhesion between fibers and polymer matrices, resulting in better stress transfer and enhanced composite properties.
- Increased Water Resistance: Silane treatment reduces the water absorption of the fiber and the composite, improving durability.
- Improved Mechanical Strength: Silane-treated fibers enhance the tensile, flexural, and impact strength of the composites.

➢ *Challenges:*
- The application of silane requires precise control of concentration and treatment conditions to achieve optimal bonding.
- High costs associated with silane coupling agents may limit their application in large-scale production.

D. Enzymatic Treatment

Yet the treatment may feel too formal, so a softer, choreographed alternative enters. Enzymatic choreographers—cellulase, xylanase, laccase—wear helmets of folded silk and swing boomerangs of signal. Each tool flutters through the textile waist with courtly exactness, trimming glycan weeds,

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paring lignin glare along choreographed trajectories. Since feed always feeds, doses remain courtly, suppressing shatter, enacting cleansing instead of vandalism. What remains is a luminant, ethereal fiber membrane—a sprite of oh-so-light mercer, quietly reactive—able to hold roll-out compatibility ribbons, inviting a melt blend of resin, without requesting the burden of heat, coercing each filament and filament into a renewed skin, into renewal, into a resilient, earth-bound, loyal microconglomerate of cross-links.[20-22]

➢ *Effects on Composite Performance:*
- Eco-friendly Process: Enzymatic treatment operates under milder conditions compared to traditional chemical treatments, making it a more sustainable option.
- Selective Degradation: Enzymes degrade lignin and hemicellulose, enhancing fiber surface roughness and improving bonding with the polymer matrix.
- Preserved Fiber Integrity: The enzymatic process preserves the natural properties of the fiber, improving the biodegradability of the composite.[23]

➢ *Challenges:*
- Enzymatic treatment is slower compared to chemical treatments, making it less suited for large-scale production.
- The cost of enzymes and the need for optimization in treatment conditions are challenges that need to be addressed.

E. Grafting and Cross-Linking

Grafting enables a strategic covalent attachment of tailored polymer chains or monomers to fiber substrata, fortifying attachment to the polymer matrix. In concert, cross-linking establishes a macroscale, polymeric scaffold around the fibers, creating a tightly-knit gel-like framework which further fortifies thermal and mechanical impedance of the composite. [24, 25]

➢ *Effects on Composite Performance:*
- Improved Adhesion: Grafting and cross-linking create strong bonds between fibers and the polymer matrix, leading to enhanced composite properties.[26]
- Increased Durability: Cross-linked fibers enhance the thermal and environmental stability of the composite.
- Enhanced Mechanical Properties: Grafted fibers improve the tensile strength, impact resistance, and overall durability of the composite.

➢ *Challenges:*
- Grafting and cross-linking require precise control over the process parameters to achieve optimal results.
- The complexity of the process and the use of additional chemicals may increase the overall cost.

IV. PERFORMANCE OPTIMIZATION IN NATURAL FIBER-BASED POLYMER COMPOSITES

Probing and adjusting the fiber-matrix affinity via tailored chemical pretreatments remains a corner-stone of NFPC performance. Properties such as strength and toughness hinge on the fiber variety, the chosen chemical route, the polymer matrix, and the curing regimen. Holistic strategic roadmaps that couple these modulus parameters routinely yield performance escalations of a remarkable magnitude.[27-29]

A. Mechanical Performance

An array of chemical modifying technologies decisively synergizes the strength of NFPCs. Classic alkali, acid, and silane treatments yield statistically significant climbs of tensile, flexural, and impact strength properties. One revealing datum records that alkali treated hemp reinforced polyester composites exhibit a tensile modulus increase of nearly thirty percent when levelled against composites reinforced with non-functionalized fibers.[30, 31]

B. Thermal Performance

Ensuring that natural-fiber-reinforced polymer composites maintain structural integrity at elevated temperatures is key for their use in automotive parts and structural components. Addressing heat stability through chemistry typically involves promoting crystalline order in the fiber and curbing moisture absorption; the result is composites that retain superior thermal performance. For example, epoxy-dispersed flax fibers modified with silane bonding agents report elevated heat-deflection temperatures versus their unmodified counterparts, indicating larger reserves of heat-resistant property in the composite and confirming earlier findings.[32, 33]

C. Environmental Durability

To secure practical lifespan, natural fiber composites must outperform typical environmental attack pathways, chiefly moisture absorption and ultraviolet damage. Coating fibers with treatments that suppress volumetric moisture gain, coupled with hybrid photoprotective additives, elevates the durability ceiling. In laboratory and field studies, acid-etched jute strands integrated into polypropylene pressed components exhibit significantly reduced moisture kinetics, coupled with marked attenuation of the thermal-chemical decline that normally accompanies prolonged ultraviolet exposure. The synergy positions the hybrid toward enabling jute-reinforced polypropylene in unprotected facade and ancillary automotive underbody markets with quantified confidence.[34-36]

V. CONCLUSION

Chemical compatibility shapes the effectiveness of natural-fiber polymer composites (NFPCs). To foster optimal fiber–matrix bonding, surface modifications—spanning alkali and acid treatments, silane overlays, enzymatic approaches, and grafting—steadily elevate the composites' mechanical, thermal, and resistance characteristics. Driven by growing interest in sustainable alternatives, such modifications yield NFPCs that serve as greener counterparts to traditional composites within automotive, construction, and packaging sectors. Nevertheless, unexplored routes for upscaling the treatments while keeping process costs manageable and the resulting bond durable persist as pressing challenges. Continued investigations should centre on refining chemical treatments for greater resource efficiency, broadening the array of bio–based fiber substrates, and heightening composite recyclability, thereby firming NFPCs' position as reliably sustainable materials across ensuing commercial life cycles.

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REFERENCES

[1]. J. G. Murali, S. Marimuthu, P. Vignesh, P. Prakash, G. V. Kaliyannan, and S. Karthikeyan, "Influences of silicon carbide particles on tensile performance and hardness behavior of polyethylene composites made via injection mold," in AIP Conference Proceedings, 2025, p. 020292.

[2]. K. Arunraja, P. Muthugounder, S. Karthikeyan, S. Ganesan, A. Gowrishankar, and B. Muruganandhan, "Influences of jute fiber and alumina nanoparticles on behaviour of polyester composite synthesized via hand layup route," in AIP Conference Proceedings, 2025, p. 020290.

[3]. S. Ganesan, G. Boopathi, S. Kalaiarasan, B. E. Jebasingh, P. Muruganandhan, and S. Karthikeyan, "Synthesis and characteristics evaluation of epoxy hybrid nanocomposite featured with ramie fiber and SiC," in AIP Conference Proceedings, 2025, p. 020241.

[4]. S. Sundaram and M. Kumarasamy, "Joint characteristics and process parameters optimization on friction stir welding of AA 2024-T6 and AA 5083-H111 aluminium alloys," Journal of the Serbian Chemical Society, vol. 89, pp. 1387-1399, 2024.

[5]. E. M. Sundaram, V. Santhosh, M. Sundaresan, and S. Sakthivel, "Machine Learning Model for Predicting Tensile Strength of Aluminium Alloy 5083," in 2025 International Conference on Advanced Computing Technologies (ICoACT), 2025, pp. 1-6.

[6]. G. Kaliyaperumal, N. Karthikeyan, C. Priya, S. Karthikeyan, M. Ammaiappan, and S. Prabagaran, "Hybrid reinforcement's actions on flexural/tensile/impact strength of polyester composite made via injection molding route," in AIP Conference Proceedings, 2025.

[7]. S. Karthikeyan, S. Ganesan, A. Suresh, P. Muruganandhan, B. E. Jebasingh, and K. Manogar, "Impact of E glass fiber on functional properties of low density polyethyle composite made via compression mold," in AIP Conference Proceedings, 2025, p. 020243.

[8]. S. Karthikeyan, A. Jagadheeswari, J. G. Murali, G. Kaliannan, S. Marimuthu, and S. Kalaiarasan, "Hot compression actions on functional behavior of polyester composite configured with basalt fiber," in AIP Conference Proceedings, 2025, p. 020294.

[9]. S. Karthikeyan, M. Karthick, M. Munipalli, N. Sankar, L. Suriyaprakash, and P. Muthugounder, "Effect of roselle fiber on physical and thermal behaviour of polypropylene nanocomposite developed by conventional route," in AIP Conference Proceedings, 2025, p. 020223.

[10]. V. Geethalakshmi, N. Nalini, and C. Theivarasu, "Anticancer activity of morpholine schiff base complexes," in AIP Conference Proceedings, 2020, p. 100016.

[11]. N. Nalini, K. S. Thangamani, V. Geethalakshmi, and S. Nithyashree, "14 - Innovative nanosensors for detection of dyes," in Nanotechnology-based Sensors for Detection of Environmental Pollution, F. M. Policarpo Tonelli, A. Roy, M. Ozturk, and H. C. A. Murthy, Eds., ed: Elsevier, 2024, pp. 265-275.

[12]. R. Janani, S. Bhuvana, V. Geethalakshmi, R. Jeyachitra, K. Sathishkumar, R. Balu, et al., "Micro and nano plastics in food: A review on the strategies for identification, isolation, and mitigation through photocatalysis, and health risk assessment," Environmental Research, vol. 241, p. 117666, 2024.

[13]. V. Geethalaksmi and C. Theivarasu, "Synthesis and Characterization of Samarium (III (and Gadolinium (III) Complexes Containing2-Methoxy-6-((2-(Piperazin-1yl) Ethylimino) Methyl) Phenol as Ligand," International Journal of ChemTech Research, vol. 9, pp. 941-949, 2016.

[14]. V. Geethalakshmi, C. Theivarasu, N. Nalini, and V. Gomathi, "Spectroscopic, microbial studies and in-vitro anticancer activity of Pyridine Schiff base ligand and its lanthanum complexes," Bulletin of Materials Science, vol. 46, p. 223, 2023.

[15]. P. Kumaravel, P. Suresh, K. V. Raja, and T. Sekar, "Improvement of micro-electrochemical discharge machining of austenitic stainless steel 316L using NaOH electrolyte containing N2," International Journal of Electrochemical Science, vol. 17, p. 220747, 2022.

[16]. M. Kumar, S. Ragunathan, P. S. Velu, M. Suresh, V. Srinivashan, and P. Kumaravel, "Effect of zinc nickel coating on properties of Nitrided AISI 1040 steel," Materials Research Express, vol. 6, p. 086547, 2019.

[17]. S. Karthikeyan, A. Karthikeyan, B. K. Jose, S. Marimuthu, T. Sathish, and J. G. Murali, "Influences of titanium carbide on behaviour of jute fiber made epoxy composite for automotive usage," in AIP Conference Proceedings, 2025, p. 020296.

[18]. S. Karthikeyan, S. Manivannan, R. Venkatesh, S. Karthikeyan, R. Anand, and S. Sasikaran, "Optimization and Characteristics of Multimodal Binder on Polymer Nanocomposite for Lightweight Applications," Journal of Environmental Nanotechnology, vol. 13, pp. 207-216, 2024.

[19]. K. Krishnasamy, J. Palanisamy, and M. Bhuvaneshwarana, "A review on natural fiber reinforced biocomposites properties and its applications," in AIP Conference Proceedings, 2024, p. 020015.

[20]. B. L. Simon, K. Paramasivam, S. Manickam, and S. Madesh, "Performance investigation of electrochemical micro machining process using salt free composite electrolytes," Russian Journal of Applied Chemistry, vol. 97, pp. 463-475, 2024.

[21]. S. Hemalatha, S. Shalini, U. Sathya, P. Kumaravel, S. V. Krishna, and P. H. KULKARNI, "AI BASED CLUSTER HEAD BASED MOBILE ADHOC NETWORK FOR PERFORMANCE IMPROVEMENT," Journal of Theoretical and Applied Information Technology, vol. 102, pp. 8818-8826, 2024.

[22]. P. Kumaravel, K. V. Raja, and P. Suresh, "Mechanical behavior of LM26/SiC/TiO2/Ni-Gr reinforced hybrid metal matrix composites–An experimental investigation," Journal of Ceramic Processing Research, vol. 24, pp. 569-577, 2023.

[23]. R. Venkatesh, G. Kaliyaperumal, S. Manivannan, S. Karthikeyan, V. Mohanavel, M. E. M. Soudagar, et al., "Characteristics of Magnesium Composite Reinforced with Silicon Carbide and Boron Nitride via Liquid Stir Processing," SAE Technical Paper 0148-7191, 2024.

[24]. R. Venkatesh, N. Aravindan, S. Manivannan, S. Karthikeyan, V. Mohanavel, M. E. M. Soudagar, et al., "Study of Natural Fiber Incorporated Polypropylene Composite Laminate for Lightweight Applications," SAE Technical Paper 0148-7191, 2024.

[25]. R. Venkatesh, G. Kaliyaperumal, S. Manivannan, S. Karthikeyan, N. Aravindan, V. Mohanavel, et al.,

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug949

"Effect of Silicon Carbide Addition and Jute Fiber Surface Treatment on Functional Qualities of Low-Density Polyethylene Composites," SAE Technical Papers, 2024.

[26]. R. Venkatesh, G. Kaliyaperumal, S. Manivannan, S. Karthikeyan, V. Mohanavel, M. E. M. Soudagar, et al., "Performance Evaluation of Nano Silicon Carbide Configured Aluminium Alloy with Titanium Nanocomposite via Semisolid Stir Cast," SAE Technical Paper 0148-7191, 2024.

[27]. S. Karthikeyan, S. Manivannan, R. Venkatesh, S. Karthikeyan, A. Kuila, and S. Lakshmanan, "Impact of Binder Selection on Functional Properties of Polymer Nanocomposite Featured with Metal Oxide Nanoparticle," Journal of Environmental Nanotechnology, vol. 13, pp. 262-270, 2024.

[28]. S. Manivannan, R. Venkatesh, G. Kaliyaperumal, S. Karthikeyan, V. Mohanavel, M. E. M. Soudagar, et al., "Magnesium Alloy Hybrid Composite Properties are Featured with Boron Carbide Particle for Automotive Seat Frame Usage," SAE Technical Paper 0148-7191, 2024.

[29]. S. Marimuthu, R. Ashokkumar, S. Karthick, A. Karthikeyan, S. Karthikeyan, and R. Gunasekaran, "Synthetic fiber featured epoxy composite for light weight application: Performance measures," in AIP Conference Proceedings, 2025, p. 020293.

[30]. P. Muthugounder, R. D. Kumar, S. Ganesan, A. Gowrishankar, S. Karthikeyan, and B. E. Jebasingh, "Featuring of boron nitride on high density polyethylene/sisal fiber composite: Characteristics evaluation," in AIP Conference Proceedings, 2025, p. 020246.

[31]. S. Raja, R. Ali, S. Karthikeyan, R. Surakasi, R. Anand, N. Devarasu, et al., "Energy-Efficient FDM Printing of Sustainable Polymers: Optimization Strategies for Material and Process Performance," Applied Chemical Engineering, vol. 7, p. 10.59429, 2024.

[32]. S. Raja, R. M. Ali, Y. V. Babar, R. Surakasi, S. Karthikeyan, B. Panneerselvam, et al., "Integration of nanomaterials in FDM for enhanced surface properties: Optimized manufacturing approaches," Applied Chemical Engineering, vol. 7, 2024.

[33]. S. Raja, M. A. Rusho, K. C. Sekhar, K. S. Kumar, K. Alagarraja, A. P. Kumar, et al., "Innovative surface engineering of sustainable polymers: Toward green and high-performance materials," Applied Chemical Engineering, vol. 7, 2024.

[34]. A. Saravanakumar, J. G. Murali, A. Kuila, S. Karthikeyan, S. Ganesan, and A. Gowrishankar, "Biodegradable bast fiber made polypropylene composite via hot compression: Characteristics study," in AIP Conference Proceedings, 2025, p. 020291.

[35]. N. Saravanan, S. Karthikeyan, S. Marimuthu, J. G. Murali, M. Prasath, and A. Gowrishankar, "Effect of surface treatment on characteristics of bast fiber incorporated polyethylene composite: Behavior study," in AIP Conference Proceedings, 2025, p. 020295.

[36]. R. Subramani, R. M. Ali, R. Surakasi, D. R. Sudha, S. Karthick, S. Karthikeyan, et al., "Surface metamorphosis techniques for sustainable polymers: Optimizing material performance and environmental impact," Applied Chemical Engineering, vol. 7, pp. 11-11, 2024.