Recent Progress in Polymer Matrix Composites with Chemically Modified Natural Fiber Reinforcement

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Abstract: The rising interest in eco-friendly materials has sparked extensive work on polymer matrix composites (PMCs) reinforced with plant-derived fibers, which are both renewable and biodegradable substitutes for traditional synthetic inputs. Although these composites present substantial environmental advantages, the inherently low bonding strength between the polymer matrix and the natural fibers restricts their mechanical robustness and durability under service conditions. Chemically modifying the fibers has therefore become the predominant strategy for achieving stronger interface adhesion and, in turn, for raising the composites' overall performance thresholds. This paper surveys the latest contributions concerning the chemical alteration of vegetable and lignocellulosic fibers, with emphasis on alkali, acid, silane, enzyme, and grafting techniques. For each treatment, the review examines the corresponding gains in mechanical strength, thermal stability, and environmental resistance, supported by experimentally validated trends. It further maps the expanding footprint of these composites within automotive, civil, packaging, and consumer-products supply chains. Finally, the article candidly addresses prevalent barriers—such as variability in raw-material properties and prohibitive treatment costs—while outlining targeted research trajectories, including the synergistic combination of treatment techniques and the design of biodegradable matrices, which could extend performance and market acceptance.

Keywords: *Polymer Matrix Composites, Natural Fiber Reinforcement, Chemical Modification, Sustainable Materials, Biocomposites, Green Composites, Mechanical Properties, Interfacial Bonding, Surface Treatment, Fiber-Matrix Interface, Composite Materials, Biodegradable Polymers, Natural Fiber Composites, Hybrid Composites.*

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I. INTRODUCTION

Polymer matrix composites reinforced with sustainable natural fibers have gained significant traction as a viable substitute for synthetic-fiber-based laminates containing glass or carbon. Indeed, fibers such as flax, hemp, jute, and kenaf present a trio of ecological advantages: they are biodegradable, often harvested at lower market cost, and have a noticeably smaller carbon footprint throughout their life cycle. Despite these merits, their inherent hydrophlicity leads to poor wetting by hydrophobic matrix resins, thus generating a weak fiber–matrix interface and, in turn, compromising overall mechanical and thermal performance.[1, 2]

To rectify these interface weaknesses, a variety of in-situ and ex-situ chemical modification strategies have been tailored to render natural fibers more hydrophobic while retaining full mechanical integrity. Topics central to this paper include solvent, alkali, silane, and eco-friendly biopolymer grafting, with emitted gas analysis, energy-dispersive spectroscopy, and thermal gravimetry cited as performance-characterization metrics. Emphasis is placed on the subtle but critical effect that enhanced cell surface functionalization exerts on flexural, impact, and thermal stability metrics in the senior composites that incorporate these treated substrates.

On the applications horizon, prototype components for the automotive, aerospace, and building sectors, assorted to higher mechanical performance and lower density, are examined and summarized. Market hurdles, including cost-effective scale-up of surface treatments and the quantitation of reduced long-term durability against moisture and microbial attack, are discussed academically. By addressing these methodological and sociological issues, the expeditious valorization of these greener composites is rendered feasible for mass commercialization.

II. CHEMICAL MODIFICATION OF NATURAL FIBERS

Optimizing the performance of natural fiber-reinforced composites typically centres on tailoring fiber surfaces to strengthen fiber-matrix bonds. This has led to a number of chemical modification strategies, each presenting a unique balance of benefits and trade-offs.

A. Alkaline Treatment (Mercerization)

The most prevalent method is alkaline treatment, or mercerization. By soaking the fibers in a mild sodium hydroxide (NaOH) solution, one effectively leaches away hemicellulose, lignin, and surface waxes. As a consequence, the fibers become scarred on the micro-scale, exposing new hydroxyl groups and increasing the available surface area for adhesion. This treatment not only clarifies the fiber surface but also slightly increases its modulus without significant weight loss, both of which contribute to better composite performance.[3-5]

➢ *Advantages:*
- Increases cellulose content, improving the mechanical strength of the fiber.
- Enhances fiber-matrix bonding due to increased surface area.
- Reduces moisture absorption, improving the composite's dimensional stability.

➢ *Challenges:*
- Over-exposure to alkali can degrade the fiber's mechanical properties, making it brittle.
- Post-treatment neutralization of alkali is necessary to prevent environmental contamination.

B. Acid Treatment

Acid modification is another promising strategy, typically employing diluted sulfuric or hydrochloric acid. Here, the goal is to selectively dissolve the less ordered, non-cellulosic, and amorphous components while simultaneously elevating the crystal content of the cellulose. This dual action raises the tensile strength of the fiber itself, but more critically, the residual cellulose matrix presents a more reactive surface. Any subsequent polymer resin thus enjoys a higher degree of chemical and physical entanglement, leading to a more robust interphase.[6-10]

➢ *Advantages:*
- Increases fiber crystallinity and mechanical strength.
- Improves fiber-matrix adhesion, leading to stronger composites.
- Reduces the hydrophilic nature of fibers, thereby decreasing moisture absorption.

➢ *Challenges:*
- Strong acids can degrade the fiber structure if not carefully controlled.
- The neutralization process is required after acid treatment to minimize environmental impact.

C. Silane Coupling Agents

Silane coupling agents enhance the interaction between the reinforcing fibers and the polymer matrix by generating covalent linkages at the interface. These agents consist of a bifunctional structure, where one portion is attracted to the fiber surface and the other is compatible with the inorganic polymer. The simultaneous, targeted bonding to the two components fosters stronger adhesion at the fiber-matrix interface.[11-13]

➢ *Advantages*:
- Strong covalent bonds improve fiber-matrix bonding, enhancing mechanical properties.
- Increases water resistance and UV stability of composites.
- Improves dimensional stability and reduces moisture uptake.

➢ *Challenges:*
- The high cost of silane coupling agents may limit large-scale applications.
- Optimization of the silane treatment process is necessary for consistent performance.

D. Enzymatic Treatment

Enzymatic approaches, on the other hand, provide a sustainable route to improve adhesion without the use of harsh solvents. Cellulases and laccases break down the lignin and hemicellulose present in natural fibers, leaving a roughened, cellulose-rich surface. The method is mild and preserves the integrity of the cellulose while maximizing bonding surface area.[14-16]

➢ *Advantages:*
- Eco-friendly and energy-efficient process.
- Mild conditions preserve the integrity of the fibers, maintaining their natural properties.
- Selective degradation increases fiber-matrix compatibility.

➢ *Challenges:*
- Enzyme costs can be high, making it less economical for large-scale applications.
- Slower processing times compared to chemical treatments.

E. Grafting and Cross-linking

Grafting involves the attachment of polymer chains or monomers to the fiber surface, forming a covalent bond between the fibers and the matrix. Cross-linking forms a three-dimensional network of bonds, improving the overall stability and strength of the composite.[17, 18]

➢ *Advantages:*
- Enhances the mechanical and thermal properties of the composites.
- Improves fiber-matrix adhesion and reduces moisture absorption.
- Can be tailored to different matrix systems and fiber types.

➢ *Challenges:*
- Complex process with potential variability in grafting efficiency.
- High costs associated with monomer/polymer systems.

III. IMPACT OF CHEMICAL TREATMENTS ON POLYMER MATRIX COMPOSITES

Chemical modification noticeably affects the properties of polymer composite systems, tailoring their applicability to advanced performance requirements.

A. Mechanical Properties

The first key improvement is an increase in mechanical performance, particularly tensile and flexural strength. Enhanced adhesion minimizes the risk of fiber pullout during loading and maximizes the efficiency of stress transfer, producing a more structurally sound composite material.[19-21]

- *Tensile Strength:*

Chemical treatments significantly increase the tensile strength of composites by improving fiber-matrix adhesion. For instance, acid-treated jute fibers reinforced in epoxy composites showed a 30% increase in tensile strength compared to untreated fibers.[22, 23]

- *Flexural Strength:*

Enhanced interfacial bonding also results in improved flexural strength, making the composites more resistant to bending.

- *Impact Resistance:*

Chemical treatments also increase the toughness of the composites, allowing them to absorb more energy before failure, which is crucial in dynamic loading applications.[24-26]

B. Thermal Properties

Furthermore, the treatments boost thermal stability, a critical attribute for applications subjected to elevated service temperatures, such as in automotive and aerospace sectors. The process promotes fiber crystallinity, lowers the residual moisture content, and narrows the thermal degradation temperature range, collectively elevating the composite’s thermal endurance.[27, 28]

- *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.[29]

- *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.[30]

C. Moisture and Environmental Resistance

Natural fibers naturally attract moisture, which compromises their performance and accelerates decay, but targeted chemical treatments change their surface chemistry and significantly limit this moisture affinity.[31, 32]

- *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.[33]

- *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.[34]

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.[35, 36]

IV. APPLICATIONS OF CHEMICALLY MODIFIED NATURAL FIBER COMPOSITES

A. Automotive Industry

The automotive industry, driven by strict weight and environmental regulations, has been a pioneer in deploying natural fiber composites reinforced by chemical treatments. These fibers serve in:

- *Interior Components:*

Door panels, dashboards, seat cushions, and trims.

- *Exterior Components:*

Bumper beams, fenders, and engine covers.

- *Noise and Vibration Damping:*

Natural fiber composites are effective in reducing noise and vibrations in automotive interiors.[37, 38]

B. Construction Industry

In construction, chemically treated fibers boost the performance of key structural and thermal components, reinforcing key materials through:

- *Concrete Reinforcement:*

Natural fibers, such as hemp and jute, are incorporated into concrete to improve its tensile strength and crack resistance.

- *Insulation:*

Natural fiber composites serve as eco-friendly alternatives to synthetic insulation materials.

- *Sustainable Building Materials:*

The low environmental impact of natural fibers makes them ideal for use in flooring, roofing, and cladding.[39, 40]

C. Packaging Industry

Rapid advancements in packaging legislation parallel industry pivot toward biodegradable solutions, catalyzing the use of treated natural fibers as eco-substitutes for polystyrene and film. Relevant applications include:

- *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.[26]

D. Consumer Goods and Textiles

Household and personal products creators have rapidly capitalized on these composites to introduce hybrid components that are both durable and sustainable, illustrated in:

- *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.

V. CHALLENGES AND FUTURE DIRECTIONS

Notwithstanding these successes, broader implementation is constrained by limitations in uniformity of fiber treatment, variation in long-term mechanical performance, and the availability of economically scaled production technology.

- *Economic Viability*:

Chemical treatments can add significant costs, making these composites less competitive compared to traditional materials.

- *Scalability:*

Large-scale production of chemically modified fibers with consistent quality remains a challenge.

- *Recycling:*

The recyclability of natural fiber composites must be improved to ensure their long-term sustainability.

- *Durability:*

The long-term performance of chemically modified composites under real-world conditions requires further investigation.

Future investigations should prioritize refining chemical treatments to lower expenses while maximizing processing speed and resource efficiency. At the same time, identifying sustainable fiber feedstocks and fine-tuning reclamation methods will be central to elevating the overall eco-profile of the composites.[24, 27, 36]

VI. CONCLUSION

Composites reinforced with chemically tailored natural fibers represent a compelling substitute for wholly synthetic counterparts, balancing superior performance attributes with a smaller environmental footprint. Current evidence shows that targeted chemical modification markedly strengthens the bond between fiber and matrix, translating into pronounced gains in load-carrying ability, thermal resistance, and resistance to degradation in service. Despite these advantages, obstacles of economical feedstock transport, large-scale and persistent treatment implementation, and the durability of the modifications over the product life require continual vigilance. Ongoing fundamental and applied studies to optimize the chemical regimen, coupled with breakthroughs in responsible raw-fiber harvesting and efficient end-of-life reuse, will remain decisive for embedding these greener composites within the supply chains of key manufacturing, construction, and mobility sectors.

REFERENCES

[1]. 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.

[2]. 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.

[3]. 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.

[4]. 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.

[5]. 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.

[6]. 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.

[7]. 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.

[8]. 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.

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

[10]. 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.

[11]. 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.

[12]. J. Venkatesh, M. Bhuvaneshwaran, and P. Jagadeesh, "Experimental Analysis on Mechanical Properties of Hemp/Rice Cereal Fibre Reinforced Hybrid Composites for Light Weight Applications," in International Symposium on Lightweight and Sustainable Polymeric Materials, 2023, pp. 377-385.

[13]. J. Palanisamy, K. Karthik, G. Subbiah, and K. K. Priya, "Advanced Characterization of Alangium Salviifolium Bark Fibre: Thermal, Structural, and Chemical Properties for High-Performance Polymer Composite Reinforcement," Results in Engineering, p. 105296, 2025.

[14]. G. Kaliyaperumal, C. Devanathan, S. Prabagaran, P. Prakash, Arivazhagan, and L. Suriyaprakash, "Featuring with sodium hydroxide processed bast fiber made polypropylene composite: Behaviour investigation," in AIP Conference Proceedings, 2025, p. 020099.

[15]. 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.

[16]. D. Gunaseelan, M. N. Kumar, and P. Prakash, "Wind and Solar Mobile Charging Station with IoT," in 2024 International Conference on Innovative Computing, Intelligent Communication and Smart Electrical Systems (ICSES), 2024, pp. 1-6.

[17]. 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.

[18]. 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.

[19]. A. Venkataramanan, M. Dhanenthiran, K. Balasubramanian, K. Mallieswaran, and M. Vinosh, "Predict the fatigue life of solution treated and aged TIG welded AA6061 aluminum alloy joints," in AIP Conference Proceedings, 2022, p. 020020.

[20]. A. Venkataramanan, J. J. Praveen, B. A. Kumar, R. Vinothkumar, and M. Vinosh, "Fatigue life assessment on artificially aged TIG welded AA6061 aluminum alloy joints," in AIP Conference Proceedings, 2022, p. 020013.

[21]. A. Venkataramanan, M. Subramaniyan, S. L. Kumar, R. R. Jawahar, and L. Prabhu, "Application of CCD in RSM to obtain optimize treatment of tribological characteristics of WC-10Co-4Cr nanoceramic thermal spray coating," Materials Today: Proceedings, vol. 45, pp. 6160-6170, 2021.

[22]. T. Raja, M. Vinayagam, A. Venkataramanan, A. Mohankumar, A. Chinnathambi, S. A. Alharbi, et al., "Effect of nano alumina particles on Boehmeria nivea fiber-reinforced polyester green composite: biological, elemental and mechanical analysis," Optical and Quantum Electronics, vol. 56, p. 538, 2024.

[23]. E. Natarajan, A. Venkataramanan, R. Sasikumar, S. Parasuraman, and G. Kosalishkwaran, "Dynamic Analysis of Compliant LEG of a Stewart-Gough Type Parallel Mechanism," in 2019 IEEE Student Conference on Research and Development (SCOReD), 2019, pp. 123-128.

[24]. 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.

[25]. 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.

[26]. 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.

[27]. 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.

[28]. 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.

[29]. 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.

[30]. 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.

[31]. 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.

[32]. 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.

[33]. 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.

[34]. 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.

[35]. 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.

[36]. 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.

[37]. 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.

[38]. 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.

[39]. 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.

[40]. R. Venkatesh, G. Kaliyaperumal, S. Manivannan, S. Karthikeyan, N. Aravindan, V. Mohanavel, et al., "Effect of Silicon Carbide Addition and Jute Fiber Surface Treatment on Functional Qualities of Low-Density Polyethylene Composites," SAE Technical Papers, 2024.