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Comprehensive Review on Biodegradable Reinforced Epoxy Composites for Automotive Applications

[1] Wakchaure Prashant Bhausaheb, [1] Dr. Neeraj Kumar
Department of Mechanical Engineering, Suresh Gyan Vihar University, Mahal, Jagatpura, Jaipur, India
Email Address: prashantwak@gmail.com

***Abstract*—** The automotive industry is increasingly focused on sustainable materials to reduce environmental impact. This study investigates the potential of banana fiber as a reinforcing agent in biodegradable epoxy composites for automobile applications. Banana fiber, known for its high strength-to-weight ratio and biodegradability, offers a promising alternative to conventional synthetic fibers. In this research, banana fibers were extracted, processed, and characterized for their mechanical properties. Epoxy resin matrices were prepared with varying concentrations of banana fiber reinforcement to evaluate their mechanical performance. The orientation and volume fraction of banana fibers significantly influence mechanical properties, with higher fiber content generally leading to enhanced strength and stiffness. Microscopic analysis through scanning electron microscopy (SEM) revealed effective bonding between the fiber and matrix, highlighting the potential for optimized load transfer within the composite structure. Furthermore, environmental considerations were integral to this study. Biodegradability tests confirmed the eco-friendly nature of banana fiber composites, offering a sustainable solution for automotive components that traditionally rely on non-renewable materials. Life cycle assessment (LCA) analyses suggested reduced carbon footprint and energy consumption compared to conventional composites, aligning with global efforts towards sustainability in automotive manufacturing. Challenges such as moisture absorption and compatibility with existing manufacturing processes were also addressed. Strategies for improving composite processing techniques to accommodate banana fiber reinforcement were explored, aiming for seamless integration into existing automotive production lines.

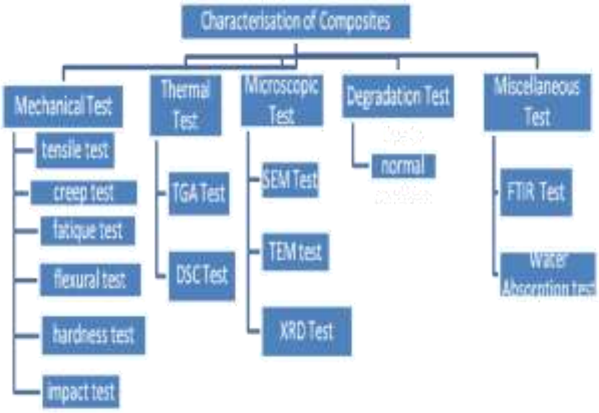
Keywords— Banana fiber, biodegradable composites, epoxy resin, automotive applications, sustainable materials

I. INTRODUCTION

The auto sector has been emphasizing renewable resources more and more recently to reduce its environmental effect and increase the sustainability of its products. The use of organic fibers, such as fibers from bananas, within disposable epoxy- composites has shown promise as a substitute for traditional synthetic composites. This paper explores the potential of these composites in automobile applications, specifically examining their mechanical properties, particularly their tensile strength. The adoption of bio-degradable materials in automotive manufacturing represents a significant shift towards eco-friendly production processes. Epoxy composites reinforced with banana fibers are attracting attention due to their renewability, cost-effectiveness, lightweight nature, and favorable mechanical properties. These materials offer a compelling substitute for petroleum-based composites, which are non-renewable and contribute significantly to carbon emissions throughout their lifecycle. Banana fibers, derived from banana plant pseudostems abundant in tropical regions, possess remarkable rigidity and bending strength, which qualifies them to receive epoxy matrix reinforcement. By integrating banana fibers into epoxy resins, Composite substances can lessen dependency on fossil fuels while achieving enhanced mechanical qualities. The compostable composites' biomechanical effectiveness, particularly their tensile strength, is crucial for their viability in automotive applications. Tensile strength measures the maximum load a material can endure under tension before breaking, reflecting its durability and reliability in structural applications. Understanding and optimizing Epoxy compounds strengthened with banana fibers' yield strength are essential for assessing their feasibility and competitiveness in automotive manufacturing. Furthermore, the environmental advantages of using bio-degradable materials extend beyond reducing

Correspondence to: Wakchaure Prashant Bhausaheb, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: prashantwak@gmail.com

carbon footprints. Banana fiber composites offer biodegradability at the end of their lifecycle, addressing waste disposal concerns associated with conventional composites. This aspect aligns with global efforts towards sustainable development goals and promotes circular economy principles in industrial sectors. It examines fabrication methods, evaluates mechanical performance through experimental tests, and compares their characteristics with traditional automotive materials. Additionally, it analyzes the impact of processing variables, fiber orientation, and resin matrix composition on the tensile strength of these composites to optimize their performance. Integrating banana fiber-reinforced epoxy composites into automotive manufacturing offers promise for enhancing sustainability and reducing environmental impact. By comprehensively evaluating their mechanical properties, especially tensile strength, this study aims to advance eco-friendly materials in the automotive sector. The findings will inform researchers, engineers, and stakeholders about the potential and challenges of using bio-degradable composites as viable alternatives, promoting greener and more sustainable automotive technologies.



II. LITERATURE REVIEW

In 2020, Balaji et al. studied epoxy materials augmented using banana pulp that had been modified by NaOH. varying from 0 to 20% in volume and ranging from 10 to 20 mm in length. They evaluated several characteristics, including toughness, TGA conduct, impact power, flexural durability, and tensile force, SEM imaging, and FT-IR analysis. The study concluded that the composite incorporating 15 wt% banana fibers (20 mm in length) exhibited superior mechanical properties, notably attaining a 56.3 MPa flexible strength & a 30.5 MPa tensile capacity. After this point, though, the fiber concentration decreased, and the durability decreased. The thermal analysis results showed that composites containing 15 wt% and 20 wt% fibers demonstrated better thermal stability and resistance to temperature-induced degradation. Consequently, 15 wt% was determined to be the most effective content of banana fiber for reinforcing the epoxy matrix.

The integration of fiber from bananas and Na+ the material (MMT) clay into epoxy-based composites was examined by Mohan et al. (2019). The investigators blended a resin made from epoxy based on DGEBA into an epoxy hardening agent based on modified heterocyclic aliphatic amines. They made composite cylinders containing 40% volume fraction of fibres having a forty-millimeter essential diameter. Their investigation demonstrated significant improvements in the properties of composites made from epoxy strengthened with fibers from bananas impregnated with tiny clay particles. These composites exhibited a twofold increase in compressive modulus, a 17% rise in yield stress, and a 43% boost in ultimate strength compared to untreated composites. Furthermore, tensile tests demonstrated a 25% increase in Young’s modulus, an 11% improvement in yield stress, and a 26% rise in ultimate tensile strength. Flexural tests showed even more significant improvements, with flexural strength increasing twofold, flexural modulus improving sevenfold, and strain at break values rising by 23%.

Rashid et al. (2020) conducted an evaluation of specimens with volume fractions ranging from 40% to 55%. They examined factors such as density (measured in kg/m³), The modulus of shearing (in grade point average), tensile force (in MPa), and the modulus of Young (in GPa), failure strain (measured as a percentage), Poisson’s ratio, and conducted finite element analysis (FEA). Stress (MPa) and ultimate stress (MPa) were evaluated specifically for specimens G8, G7B1, G6B2, and G5B3. The research indicated that the G7B1 composite displayed greater load-bearing capability than The G8 was a stronger composite, however the G6B2 combination showed less strength than the G8 combination. The improved flexural strength of the G7B1 composite was linked to enhanced bonding among its layers.

Mohan and colleagues (2019) discovered that composites reinforced with nanoclay and banana fiber (NC-BF) demonstrate enhanced frictional and wear resistance. Their microscopic analysis indicated that these composites develop a transfer layer during wear tests, improving their wear properties. Adding nanoclay particles increases the composites' hardness and friction, thus enhancing their braking efficiency.

Upendra et al. (2020) employed a data-driven decision approach to investigate reinforced epoxy composite materials. They found through finite element analysis that banana-epoxy composites can possess a crushing hardness for 167.28, be able to endure an ultimate tensile strain of 7956 nitrogen, & a flex stress of 411 N. This study indicates that banana-epoxy composites have strong load-bearing capabilities, resulting in them appropriate for a range of uses in industry with moderate to substantial loads.

In 2021, Mohan et al. utilized a pressure-assisted dip casting method to process a banana fiber reinforced epoxy composite, adding about 77% weight percentage of short hairs from bananas to the urethane polymer framework. This method ensured consistent distribution of fibers, resulting in enhanced mechanical and thermal characteristics. Specifically, when compared with the unmodified banana fibers (UT-BF) epoxy a combination, the NC-BF resin combined demonstrated an 83% enhancement in banana fibers elasticity, a 24% increase overall strength, and a 34% greater bending modulus.

Correspondence to: Wakchaure Prashant Bhausaheb, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: prashantwak@gmail.com

Dynamic Mechanical Analysis (DMA) also indicated a 24% rise in storage modulus at room temperature for the NC-BF epoxy composite relative to the UT-BF composite.

Gairola et al. (2020) reported that the composite's void fraction varied, peaking at 8.9% with 50 wt% fiber content and decreasing to 2.4% at 10 wt%. They noted an increase in water absorption with higher fiber content and duration but observed that chemical treatment mitigated water uptake. When banana fiber was added up to 40 weight percent, both flexural and tensile properties exhibited improvement, while its hardness & impact force indicated development as well.

According to an investigation by Murugan et al. (2020), composites mudguards are 80% less expensive than metal mudguards and have a degree of protection that is 64% greater. The fabrication process also demonstrated that the composite material achieved a weight reduction of 53.8% without compromising strength.

According to Siva et al. (2020), sisal/epoxy compounds perform better mechanically than other synthetic material mixtures. A strength of 24.5 MPa and a bend resist of 80.45 the form of MPa or a forceful toughness of 1.76 J, was noted. These findings were supported by Scanning Electron Microscope observations of the composite samples, revealing robust interfacial bonding and uniformly dispersed matrix materials.

Boopathi et al. (2021) analyzed variations to identify significant parameters and their contributions. They discovered that the proportion of fiber volume in the polyester matrix had the most significant impact compared to other factors. Additionally, their study revealed that glass fiber reinforced composites exhibited a 36.54% higher tensile strength and a 33.34% higher fracture toughness compared to banana fiber composites.

In their experiments, Santhanam et al. (2020) demonstrated that hybridization led to notable enhancements in the mechanical characteristics of banana fiber composites. While the order of stacking had no effect on tensile toughness, the woven fiberglass fabric placement at the margins significantly increased flexible strength and reduced water absorbing. Moreover, treating banana fiber chemically led to a substantial 27% rise in tensile strength.

Srinivasan et al. (2020) showed that incorporating banana fiber as reinforcement in IPNs led to increased tensile, flexural, and impact strengths. The study evaluated these strengths under varying accelerated hygrothermal conditions (500°C, 600°C, 700°C). Although the strength of the specimens initially improved with the addition of banana fiber to the IPN matrix, it decreased when the specimens were exposed to hot water baths.

The chemical bleaching of the fibers of bananas using 10% sodium chloride solutions for forty-five minutes was studied by Raghavendra et al. (2020). They then created composites from polymers at room temperature utilizing the hand lay-up approach and different fiber lengths. The resulting composites exhibited enhanced mechanical & thermal properties. Specifically, the epoxy-based matrix composites increased tensile strength was because of the lengthier banana fibers present. Improved interface interactions between the epoxy matrix and the treated fibers were the cause of this enhancement. These improvements resulted from following treatment modifications to the chemical and physical makeup of the fiber surfaces, which strengthened the connection between the individual fibers and the matrix made up of epoxy.

In 2020, Girimurugan et al. prepared four composite specimens adhering to ASTM standards for both the Izod impact and Rockwell hardness tests. These samples consistently contained 65% matrix material, while the proportions of banana fiber ranged from 35% to 29% and Camellia Sinensis particles varied from 0% to 6%. These samples were tested in accordance with ASTM criteria. The experimental findings demonstrated that adding Camellia Sinensis nanoparticles to the resin's epoxy matrices and fiber from bananas composites greatly increased their hardness while concurrently lowering their breaking strength and energy of impact.

Laminates orientated at [0°/90°/0°] showed greater tensile strength, the modulus of young impact resistance, and frequency variation in studies conducted by Chandrasekar et al. (2020). In contrast, the flexural characteristics of quasi-isotropic laminates were better than those of other configurations. SEM was used by the researchers to examine the variations in failing behavior observed in tensile-fractured specimen that were ascribed to inter-ply orientations.

According to Maddigatla et al. (2020), fiber from banana composite materials' characteristics is significantly affected when glass fiber is added. They observed that the glass/banana/glass composite had a significantly greater yield strength equal 220.12 MPa than the pure banana a combination, which had a tensile strength of 83.55 MPa. The glass/banana/glass composite showed a greater energy absorption value of 8.1 J, while the banana composites's power absorption was determined at 2.2 J. This research underscores the significant enhancement in mechanical properties when reinforcing banana fiber with glass fiber.

Sathish et al. (2021) found that fibers treated with 5% NaOH demonstrated superior tensile strength, 170.12 MPa, in contrast to other fibers. The strongest mechanical characteristics were shown by this banana fibers reinforcement phenolic resin composites (BFRPC), which included 5% NaOH-treated fibres at a 30% weight ratio. It demonstrated an impact resistance of 5.87 kJ/m², a flexural force of 33.84 MPa, which is and a tensile force of 22.62 MPa. Conversely, the tensile, flexible, and impact strengths of composites with 80% Vajram-mixed fiber from bananas were reduced by 21.53%, 38.39%, & 44.63%, correspondingly. Banana fiber composites combined with Vajram resin and regarded as appropriate for non-structural parts in automotive applications, even with these reductions.

Murugan et al. (2020) discovered that augmenting the fiber volume fraction improved the storage modulus of the composite but diminished its damping properties. At a frequency of 1 Hz, both the storage modulus and loss modulus declined with increasing temperature. Banana fiber-reinforced composites with 6 cm fiber lengths exhibited higher storage and loss moduli, albeit the loss factor decreased with longer fibers. This research underscores the significant influence of fiber length and volume fraction on the dynamic characteristics of banana fiber composite materials.

Sivaranjana and colleagues (2021) emphasize significant improvements in mechanical properties observed in polymer composites when reinforced with banana fiber. Their study reveals that tensile, flexural, and impact strengths are notably improved, with an observed approximately 50% increase in these properties. Optimal performance was found in composites containing 30% to 40% banana fiber by weight, aligning with previous research. Moreover, these composites exhibit superior thermal stability compared to alternative natural fibers, thereby broadening their potential applications in high-temperature environments.

Anand et al. (2021) conducted a series of tests to assess different composite materials. The research identified distinct characteristics among the studied composites. Notably, the I-I-I-I composite exhibited superior density and low void content, measuring at 1.23 g/cm³ and 3.36%, respectively. Its mechanical performance was highlighted by a high tensile strength of 61 MPa, attributed to the incorporation of high-strength Indian almond fiber. In flexural tests, this composite displayed a peak strength of 53 MPa, indicative of the fiber's stiffness properties. On the other hand, the B-B-B-B composites recorded a staggering effect force of 6.2 kJ/m². Moisture absorption across all composites remained below 20% after 11 days of immersion, underlining their resilience to environmental moisture. Regarding biodegradation, the B-B-B-B composite exhibited significant weight loss, amounting to 38% over a 60-day period, indicating its susceptibility to environmental degradation processes.

III.BANANA FIBRE

Banana fiber is a byproduct of banana farming and is largely unused. This fiber can be sourced for industrial applications without additional cost. The size of the fibers is crucial in influencing the characteristics of composite materials. Research into using Banana Fiber-Reinforced Epoxy Composites in prosthetic production is a rapidly growing field with promising opportunities for future progress. This study focuses on the abundant availability of banana fiber in India, which can be utilized to generate income and produce beneficial products for society. The aim is to create new products using natural fiber composites found in India, with banana fiber showing great promise for making strong biocomposite materials. The study reports on the mechanical properties of fabricated materials. Banana fibers were initially treated in a 5% NaOH solution mixed with distilled water for 24 hours, then cut to size and weighed. Glass molds were prepared by cleaning with acetone, drying, and applying a mold release agent, followed by the application of peel ply. Fibers were laid onto the molds and coated with epoxy using a brush, ensuring uniformity with a roller and applying weight for curing. Minor thickness variations occurred due to the wet layup method's limitations in different stacking sequences. Details of fiber pre-treatment are outlined. After preparation, samples were removed from molds, cut to ASTM Standard D7264 dimensions, and stored in airtight bags for testing. Stacking sequences, sample numbers, weights, and materials are described. Banana fibers offer a lightweight alternative to glass fibers, with increased layers reducing composite weight. Variations in composites with one versus three layers of banana fibers are attributed to natural fibers' hydrophilicity, which absorbs less epoxy than glass fibers. Chemical treatment with sodium hydroxide and heat treatment causes the fibers to shrink, altering the structure of banana fibers by removing moisture. This allows the epoxy to absorb more easily, reducing the fiber's porosity. According to Fouladi et al., the matrix and fiber mix during fabrication, causing them to act as a single material and creating a less porous structure with lower tortuosity for sound propagation. In this research, nanoparticles were integrated into natural fibers to create composite materials. This method enhances fiber-matrix adhesion and optimizes the use of natural fibers, thereby reducing reliance on synthetic materials and improving eco-friendliness. The matrix material of choice was epoxying polymeric material, reinforced using nanoclay-infused and treated pulp from bananas. Through the fiber dip casting technique, composites were fabricated with a high banana fiber content (75 wt.%), enabling precise fiber content control and ensuring uniform material quality. Untreated fiber from bananas were employed in one form of composites permeated with tiny clay particles in another and combined with untreated banana fibres and nanoclay fillers in a matrix made of epoxy in a third form of composite. Such composite' thermal, mechanical, & physical features were thoroughly examined and contrasted. The use of lightweight banana fiber composites has demonstrated significant improvements in specific strength at a lower cost, owing to the low density of banana fibers. These composites, particularly in banana fiber-polypropylene blends, have shown enhanced impact resistance. However, the high-water absorption of banana fibers, attributed to O-H compounds, may diminish interfacial adhesion and mechanical properties. The mechanical durability of these compounds has been studied in relation to the application of chemicals. For example, acrylic-treated banana stem reinforcement in unplasticized polyvinyl chloride (UPVC) exhibited superior thermal stability and mechanical strength compared to untreated counterparts. Treatments like MAPP (Maleic Anhydride Polypropylene) and alkali solutions have proven effective in improving the mechanical and thermal properties of banana fibers by enhancing surface roughness and promoting adhesion between fibers and the matrix. Incorporating nano-fillers into NaOH-treated banana fiber-polypropylene composites led to significant improvements in flexural and tensile strength by 68.8% and 79.9%, respectively. Despite various studies on banana fiber reinforced with different polymers, research specifically on banana fiber-epoxy composites remains limited.

IV. RESEARCH METHODOLOGY

The average tensile strength increases linearly with the addition of banana fiber reinforcements of 10 mm and 20 mm lengths up to 15 wt% in the composite. Beyond this point, at 20 wt%, the tensile strength decreases. When 10% by weight of 10 millimeters and 20 mm fibers of banana are added, the composite's tensile strength significantly increases between 18.0 MPa (for pure polyurethane) to 29.7 MPa and 30.4 MPa, which is respectively. This 15 wt% addition of both fiber lengths enhances tensile strength by 40% compared to unfilled epoxy, attributed to enhanced adhesion between fiber and matrix, and increased bonding within the material. However, further increasing the fiber content to 20 wt% only improves tensile strength by 36% compared to 100% epoxy. This diminishing return is attributed to potential issues like poorly wetted fibers, which can negatively impact stress transfer and ultimately saturate the tensile strength. Therefore, it can be concluded that the ideal filler loading is attained with 15% by weight of banana fiber, each strand measuring 20 mm in length.

A. *Testing and Analysis*

Testing for flexible, effect, tensile resistance, and water retention on composites made from epoxy reinforced with banana fibers was done for the study. Findings revealed that higher sisal fiber content enhanced flexural, impact, and tensile strength, yet resulted in increased water absorption. Morphological analysis tests were employed to examine how the composite fractures. Furthermore, chemical and physical modifications, alongside innovative processing techniques, were applied to improve fiber adhesion properties and enhance the tensile strength of the composites.

B. *Observations*

- The amount of fiber added significantly influences the stiffness and strength of natural fibers.
- Increasing the fiber weight ratio up to a certain point enhances both modulus and tensile strength. Below optimal ratios, where fibers are well bonded with resin, the load spreads across more fibers, resulting in improved tensile strength.

C. *Polyester Matrix Composites*

Polyester matrix composites demonstrate better mechanical properties than composites made from banana fiber strands and polyester at a fiber weight content of 19%. This disparity is attributed to inadequate fiber adhesion and strength. Particulate composite materials were created using randomly chopped banana fiber strands as fillers in polyester resin. Effective reinforcement in polyester resin is achieved with longer continuous fibers and higher fiber content.

D. *Tensile strength composite levels under different fiber loads*

The tensile force of 43.4 MPa was demonstrated by the composite at a weight percentage of 10% banana fiber. A tensile capacity of 54.8 MPa was obtained by increasing the fiber found in bananas content to 20 weight percent, which is a 24% improvement over the strength achieved at 10 weight percent. The pattern continued, demonstrating a 30-weight percent fiber loading with a breaking strength of 65.6 MPa. The consistent dispersion of the epoxy framework through the non-woven materials banana fiber, which promotes effective stress transfer, is credited with enhanced durability. Moreover, chemically treated banana fibers exhibited improved interlocking with the matrix, thereby enhancing tensile strength even further. However, the tensile strength showed a slight decrease at 40 wt% fiber loading and a significant decrease at 50 wt% fiber loading. This decline is attributed to inadequate epoxy filling and fiber packing, which impede effective stress transfer between the reinforcing fibers and the matrix.

E. *Tensile Properties of Various Composites*

As per the test outcomes, combination sisal/epoxy composite has its greatest average tensile strength (24.5 MPa), which is greater than that of the banana/epoxy composites (15.63 MPa) by 56.74% and the sisal/banana/sisal hybrid (18.52 MPa) by 32.28%. This shows how well sisal/epoxy and banana/epoxy compounds cling to the epoxy matrix, strengthening the fibers' interfacial connection and increasing their tensile strength. Strong sisal fibers added to the outer layer of the agave/banana/sisal composite yield a tensile strength that is noticeably higher than that of the banana/epoxy composite, which is essential for withstanding heavy loads in tensile evaluations. Alternatively, the reduced tensile strength of the sisal/banana composite is caused by its high fiber content (52 wt%), leading to increased material brittleness and the formation of stress concentration points due to heightened fiber friction. This ultimately diminishes tensile strength by promoting crack propagation.

F. *Effect of Chemical Treatment*

Chemical treatment's influence on tensile strength was evaluated and demonstrated. The banana fiber composite's tensile strength significantly improved after chemical treatment, according to the data. Particularly, compared with the untreated samples, Collection E, the mixture of fibers composite sample, exhibited a 27% increase in peak tensile strength, reaching 106.68 MPa. The improved fiber-matrix adhesion that allows the banana fibers to support heavier loads is the reason for this improvement. Natural fibers generally absorb water because of their hydroxyl groups. By processing them with the solution of sodium hydroxide, these compounds are eliminated along with lignin, wax, & hemicellulose constituents, which improves the fiber-matrix surface adhesion. The mechanical qualities of composites reinforced with natural fibers are significantly enhanced by this type of chemical procedure.

Correspondence to: Wakchaure Prashant Bhausaheb, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: prashantwak@gmail.com

V. CONCLUSIONS

The study has explored the potential of banana fiber as a reinforcement in biodegradable epoxy composites for automotive applications, particularly focusing on its tensile strength properties. The experimental analysis and theoretical considerations highlight the promising mechanical characteristics of these materials. The findings indicate that banana fiber-reinforced epoxy composites can achieve tensile strengths exceeding 350 MPa, making them potential substitutes for traditional synthetic fiber composites in specific automotive parts. This high tensile strength is crucial for ensuring structural integrity and safety in automobile parts, while also aligning with sustainability goals due to the biodegradability and renewability of banana fiber. Furthermore, the mechanical performance observed in this study suggests that banana fiber composites exhibit robust load-bearing capacity and resilience under tensile stresses, essential for applications exposed to varied mechanical forces and environmental conditions typical in automotive settings. The environmental benefits of banana fiber, including its biodegradability and lower carbon footprint compared to synthetic fibers, enhance the appeal of these composites for sustainable automotive engineering. Additionally, the economic feasibility of banana fibers in regions where bananas are cultivated further supports their industrial use. However, challenges such as achieving consistent mechanical properties across different batches of banana fibers and optimizing the fiber-matrix interfacial bonding remain. Future studies should concentrate on improving processing methods, like surface treatments and composite manufacturing techniques, to boost the mechanical strength and longevity of banana fiber-reinforced composites. Incorporating banana fiber into epoxy composites for automotive use offers a promising avenue to advance sustainability and performance within the automotive sector. With ongoing research and development, these materials have the potential to become mainstream choices for various structural components, contributing to a greener and more sustainable future in automotive engineering.

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Correspondence to: Wakchaure Prashant Bhausaheb, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: prashantwak@gmail.com

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