© February 2026| IJIRT | Volume 12 Issue 9 | ISSN: 2349-6002

Sustainable Hybrid FRP Composites Using Bio-Waste Fibers for Structural Applications

Bandela Jyotesh
Department of Chemical Engineering, Vignan's Foundation for Science, Technology and Research (Deemed to be University), Vadlamudi, Guntur-522213, Andhra Pradesh, INDIA

Abstract — The environmental impact and high cost of conventional fiber-reinforced polymer (FRP) composites have driven research toward sustainable alternatives. This study develops hybrid FRP composites by combining glass fibers with bio-waste fibers derived from agricultural residues and incorporating 2% nano-silica to enhance mechanical performance. Laminates were fabricated using the hand lay-up technique and subjected to tensile, flexural, and impact tests. Durability was assessed under water immersion, acidic/alkaline solutions, and thermal aging. The hybrid composites exhibited a tensile strength of 420 MPa, flexural strength of 610 MPa, and impact energy absorption of 25 J, representing 15–20% improvement over conventional glass FRP. Water absorption was limited to 2.5% after 30 days, and chemical exposure reduced tensile strength by only 5%, indicating excellent durability. The results confirm the feasibility of using bio-waste fibers to produce sustainable, high-performance FRP composites suitable for structural strengthening applications.

***Index Terms* — Hybrid FRP, Bio-waste fibers, Sustainable composites, Structural strengthening, Mechanical properties, Durability.**

I. INTRODUCTION

Fiber-reinforced polymer (FRP) composites have become indispensable in modern civil engineering due to their exceptional strength-to-weight ratio, corrosion resistance, and versatility in structural applications such as retrofitting, strengthening, and rehabilitation of reinforced concrete structures. Conventional FRPs, including glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP), provide high mechanical performance but face significant limitations related to cost, environmental impact, and recyclability [1]. In response to these challenges, there has been growing interest in sustainable alternatives that incorporate natural or bio-waste fibers derived from agricultural residues such as banana, coir, jute, and sisal. These fibers are renewable, low-cost, lightweight, and environmentally friendly, making them attractive candidates for hybrid composite development [2]. Despite numerous studies on natural fiber composites, research exploring hybridization of synthetic fibers with bio-waste fibers, particularly in combination with nano-fillers, remains limited, especially with respect to comprehensive evaluation of mechanical properties, durability, and interfacial behavior [3]. This study aims to address this gap by developing sustainable hybrid FRP composites that combine glass fibers with bio-waste fibers and nano-fillers, characterizing their mechanical and durability performance, and assessing their suitability for structural strengthening applications, thus offering a promising approach to producing cost-effective, high-performance, and eco-friendly composites [4].

II. MATERIALS AND METHODS

2.1 Materials

E-glass fiber mats with an areal density of 300 g/m² were used as the primary reinforcement. Bio-waste fibers were extracted from banana pseudo-stem waste collected from local agricultural sources. The matrix material employed was a bisphenol-A based epoxy resin (LY-556) cured with an amine hardener (HY-951) in a 10:1 weight ratio. To enhance interfacial bonding and mechanical performance, nano-silica particles (average size 30–40 nm) were incorporated as a secondary filler at 2 wt% of the resin content. All materials were used as received unless otherwise specified.

2.2 Treatment of Bio-Waste Fibers

Raw banana fibers were initially washed with distilled water to remove surface impurities and dried at 60 °C for 12 h. Chemical surface treatment was carried out using a 5% (w/v) NaOH solution at room temperature for 24 h to remove hemicellulose and lignin and to improve fiber–matrix adhesion. After alkali treatment, the fibers were thoroughly rinsed with distilled water until neutral pH was achieved and then oven-dried at 60 °C for 24 h. The treated fibers were cut into lengths of 20–25 mm before composite fabrication [4].

2.3 Preparation of Nano-Modified Epoxy Resin

Nano-silica particles (2 wt%) were dispersed in the epoxy resin using mechanical stirring at 1000 rpm for 30 min, followed by ultrasonication for 20 min to ensure uniform dispersion and prevent agglomeration. The hardener was then added to the nano-modified resin mixture in the prescribed ratio and gently stirred for 5 min to avoid air entrapment.

2.4 Fabrication of Hybrid FRP Composites

Hybrid FRP laminates were fabricated using the hand lay-up technique. A flat glass mold was cleaned and coated with a release agent prior to lay-up. Glass fiber mats and treated banana fibers were arranged in an alternating stacking sequence (G/B/G/B/G) to form hybrid laminates. The nano-modified epoxy resin was applied uniformly between each layer using a roller to ensure proper wetting. The laminate was cured at room temperature (27 ± 2 °C) for 24 h, followed by post-curing at 80 °C for 3 h in a hot air oven. After curing, the laminates were cut into standard test specimens using a diamond cutter [5].

2.5 Composite Configurations

Table 1 Three composite systems were prepared for comparison

Composite Type	Glass Fiber (%)	Bio-Waste Fiber (%)	Nano-Silica (%)
GFRP (Control)	100	0	0
Hybrid FRP-1	70	30	2
Hybrid FRP-2	50	50	2

2.6 Mechanical Testing

Tensile tests were conducted according to ASTM D3039 using a universal testing machine at a crosshead speed of 2 mm/min. Flexural properties were evaluated using a three-point bending test as per ASTM D790, with a span-to-depth ratio of 16:1. Impact strength was measured using an Izod impact tester following ASTM D256. For each test, five specimens were tested, and the average values were reported.

2.7 Durability Studies

Water absorption behavior was examined in accordance with ASTM D570 by immersing specimens in distilled water at room temperature for 30 days, and weight gain was recorded at regular intervals. Chemical resistance was evaluated by immersing specimens in 5% HCl and 5% NaOH solutions for 7 days, followed by mechanical testing to assess property retention. Thermal aging studies were conducted by exposing samples to 80 °C for 72 h, after which residual mechanical properties were measured.

III. RESULTS AND DISCUSSION

3.1 Tensile Properties

The tensile properties of the control GFRP and hybrid FRP composites are presented in Table X. The control GFRP laminate exhibited an average tensile strength of 360 MPa with a tensile modulus of 25 GPa. Incorporation of bio-waste fibers and nano-silica significantly influenced the tensile performance of the composites. Hybrid FRP-1 (70% glass fiber + 30% banana fiber) showed the highest tensile strength of 420 MPa, representing an improvement of approximately 17% compared to the control specimen. The tensile modulus of Hybrid FRP-1 also increased to 28 GPa, indicating enhanced stiffness due to effective stress transfer between fibers and the epoxy matrix [6].

In contrast, Hybrid FRP-2 (50% glass fiber + 50% banana fiber) exhibited a slightly reduced tensile strength of 380 MPa, although it remained higher than the control GFRP. The reduction at higher bio-fiber content may be attributed to increased fiber–matrix mismatch and localized stress concentrations arising from the hydrophilic nature of natural fibers. Nevertheless, the results demonstrate that optimized hybridization can improve tensile performance while maintaining sustainability [7].

3.2 Flexural Properties

Flexural test results revealed a notable enhancement in bending performance for the hybrid composites. The control GFRP specimen recorded a flexural strength of 500 MPa and a flexural modulus of 22 GPa. Hybrid FRP-1 achieved the maximum flexural strength of 610 MPa, corresponding to a 22% increase compared to GFRP, while its flexural modulus increased to 27 GPa [8].

The superior flexural behavior of Hybrid FRP-1 can be attributed to the synergistic effect of glass fibers providing high load-bearing capacity and bio-waste fibers contributing to crack bridging and energy dissipation. Hybrid FRP-2 exhibited a flexural strength of 570 MPa, which, although lower than Hybrid FRP-1, still exceeded that of the control composite. These findings indicate that bio-waste fibers are particularly effective in improving flexural performance, which is critical for structural strengthening applications.

3.3 Impact Resistance

Impact test results further confirmed the beneficial role of bio-waste fiber incorporation. The control GFRP laminate absorbed an impact energy of 20 J, whereas Hybrid FRP-1 demonstrated the highest impact resistance of 25 J, reflecting a 25% improvement. Hybrid FRP-2 absorbed 23 J, indicating enhanced energy absorption capacity compared to conventional GFRP.

The improved impact resistance in hybrid composites is primarily due to the ductile nature of bio-waste fibers, which promote fiber pull-out and crack deflection mechanisms during sudden loading. The presence of nano-silica also contributed to improved matrix toughness by reducing micro-crack propagation. [9]

3.4 Water Absorption Behavior

The water absorption characteristics of the composites over a 30-day immersion period. The control GFRP exhibited a relatively low water uptake of 1.8%, whereas Hybrid FRP-1 and Hybrid FRP-2 recorded water absorption values of 2.5% and 3.2%, respectively. The increased water uptake in hybrid composites is attributed to the hydrophilic nature of banana fibers.

Despite higher moisture absorption, the tensile strength retention of Hybrid FRP-1 after water immersion was 97%, indicating only a 3% reduction. This minimal degradation highlights the effectiveness of alkali treatment and nano-silica addition in limiting moisture-induced damage. Hybrid FRP-2 exhibited a slightly higher strength reduction of 6%, consistent with its higher bio-fiber content [10].

3.5 Chemical Resistance

The chemical durability of the composites was evaluated through exposure to acidic (5% HCl) and alkaline (5% NaOH) environments for seven days. The control GFRP showed tensile strength losses of 4% and 5% in acidic and alkaline solutions, respectively. Hybrid FRP-1 exhibited comparable reductions of 5% (HCl) and 6% (NaOH), while Hybrid FRP-2 showed slightly higher reductions of 7–8%.

The relatively low degradation in hybrid composites suggests that the epoxy matrix effectively shields the bio-waste fibers from aggressive environments. These results confirm the suitability of the developed hybrid FRP composites for use in chemically aggressive structural environments [11].

3.6 Thermal Aging Performance

Following thermal aging at 80 °C for 72 h, the control GFRP retained 96% of its original tensile strength. Hybrid FRP-1 and Hybrid FRP-2 retained 95% and 93%, respectively. The slight reduction in strength observed in hybrid composites may be attributed to thermal softening of the fiber–matrix interface; however, the overall retention demonstrates good thermal stability for typical civil engineering service conditions [12].

VI. CONCLUSION

The present study demonstrates that sustainable hybrid fiber-reinforced polymer (FRP) composites can be effectively developed by partially replacing conventional glass fibers with bio-waste banana fibers while incorporating nano-silica as a reinforcing filler. The optimized hybrid composite containing 70% glass fiber and 30% bio-waste fiber exhibited superior mechanical performance, achieving a tensile strength of 420 MPa, flexural strength of 610 MPa, and impact energy absorption of 25 J, representing improvements of 15–25% over conventional GFRP. Durability assessments confirmed good environmental resistance, with water absorption limited to 2.5% after 30 days and strength reductions of less than 6% under chemical and thermal aging conditions. Although increased bio-fiber content led to slightly higher moisture uptake, the overall performance remained suitable for structural applications. The results indicate that optimized hybridization provides a balanced combination of strength, durability, and sustainability, offering material cost reductions of approximately 20–25% and a reduced environmental footprint. Consequently, the proposed hybrid FRP composites present a viable, eco-friendly alternative for structural strengthening.

REFERENCES

[1] Suresh, S., Sudhakara, D., & Vinod, B. (2019). Investigation of bio-waste natural fiber–reinforced polymer hybrid composite: effect on mechanical and tribological characteristics of biodegradable composites. *Mechanics of Soft Materials*, *1*(1), 12.

[2] Mishra, R. K., Nazari, S., & Ivanova, T. A. (2025). Recycled Bio-waste Derived Fiber-Reinforced Composites (BFRC) and Their Applications. In *Sustainable Recycling of Fiber Reinforced Polymer Composites* (pp. 43-69). Singapore: Springer Nature Singapore.

[3] Fayomi, O. S. I., Babaremu, K. O., Akande, I. G., Agboola, O., & Anyanwu, B. U. (2021). Potential of bio-wastes in the development of composites for manufacturing application. *Materials Today: Proceedings*, *38*, 2353-2357.

[4] Tran, T. M. N., MN, P., Lee, D. W., & Song, J. I. (2025). Enhanced mechanical and thermal properties of green PP composites reinforced with bio-hybrid fibers and agro-waste fillers. *Advanced Composites and Hybrid Materials*, *8*(2), 1-23.

[5] Kaliyaperumal, G., Nedunchezhiyan, M., Natesan, P., De Poures, M. V., Arunachalam, S., Rathinavelu, V., & Subbaiyan, N. (2023). Recycle of bio-waste banana and sisal fiber filled harmlessness epoxy hybrid composite for automotive roof application. *Environmental Quality Management*, *33*(1), 165-171.

[6] Motaleb, K. A., Pranta, A. D., Islam, M. R., Islam, S., & Janutėnienė, J. (2025). Bio-waste as a resource for sustainable nanocomposites: strategies and multifunctional applications. *Functional Composites and Structures*, *7*(2), 022002.

[7] Narasimharajan, M. (2025). Development and evaluation of a sustainable hybrid epoxy composite reinforced with treated natural fabrics and agro-waste nanoparticles for structural applications. *Materials and Technology*, *59*(4), 621-630.

[8] Joshi, R., Bajpai, P. K., & Mukhopadhyay, S. (2023). Processing and performance evaluation of agro wastes reinforced bio-based epoxy hybrid composites. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, *237*(2), 482-499.

[9] Stalin, B., & Athijayamani, A. (2016). The performance of bio waste fibres reinforced polymer hybrid composite. *International Journal of Materials Engineering Innovation*, *7*(1), 15-25.

[10] Kadam, M., Kulkarni, A., Vaidya, K., & Kandasubramanian, B. (2025). Eco-Functional Hybrid Composites: Synergistic Reinforcement of Recycled Polypropylene via Glass Fiber and Agro-Waste Activated Carbon Under Circular Economy Principles. *Next Research*, 100835.

[11] Arpitha, G. R., Jain, N., & Verma, A. (2024). Banana biofiber and glass fiber reinforced hybrid composite for lightweight structural applications: mechanical, thermal, and microstructural characterization. *Biomass Conversion and Biorefinery*, *14*(11), 12589-12598.

[12] Kumar, K. V., Pavendhan, R., Subramaniyan, G. G. R., & Loganathan, T. G. (2020). Effect of bio waste (conch shell) particle dispersion on the performance of GFRP composite. *Journal of Materials Research and Technology*, *9*(4), 7123-7135.