Equivalent: Jurnal Ilmiah Sosial Teknik
Volume 8, Issue 3, 1166-1181
e_ISSN: 2775-0833
https://jurnalequivalent.id/index.php/jequi/index
DOI: doi.org/10.59261/jequi.v8i3.289

Mechanical Performance and Structural Evaluation of Bamboo-Based Hybrid Composites Modified with Carbon Filler and Graphene Oxide

Iskandar Yasin[1*]
Universitas Sarjanawiyata Tamansiswa, Indonesia

Nurul Hasan[2]
School of Chemical Engineering, University of Queensland, Australia

Widarto Sutrisno[3]
Universitas Sarjanawiyata Tamansiswa, Indonesia

Andi Ibrahim Soumi[4]
Universitas Sarjanawiyata Tamansiswa, Indonesia

***Corresponding author:**
Iskandar Yasin, Universitas Sarjanawiyata Tamansiswa, Indonesia.
✉iskandaryasin@ustjogja.ac.id

Article Info:
Article history:
Received: March 11, 2026
Revised: June 26, 2026
Accepted: July 31, 2026

Keywords:
Bamboo Composite; Graphene Oxide; Structural Failure Mitigation; Finite Element Analysis; Sustainable Civil Infrastructure.

Abstract

Background: Bamboo-based composites have attracted attention as sustainable alternatives to conventional structural materials in civil engineering. However, their broader application is often limited by relatively low mechanical performance, weak interfacial bonding between fiber and matrix, and vulnerability to structural failure under loading conditions.
Objective: This study aims to evaluate the mechanical performance and structural behavior of bamboo-based hybrid composites modified with carbon filler and graphene oxide (GO) to enhance strength, improve interfacial bonding, and reduce the risk of structural failure.
Methods: An experimental and numerical approach was employed. Three composite configurations were fabricated and tested (n = 3 specimens per configuration): unfilled bamboo–epoxy (control), carbon-reinforced, and GO-modified composite. Mechanical properties were evaluated through tensile (ASTM D3039) and Charpy impact tests. Finite element analysis (FEA) using ANSYS Workbench validated experimental findings by comparing stress distribution, strain behavior, and total deformation under a 1000 kN axial tensile load, showing strong agreement (R^2 up to 0.779).
Results: The results show that both carbon filler and GO significantly improve the mechanical properties of bamboo composites. The GO-modified composite exhibited the highest tensile strength and elastic modulus, along with enhanced crack resistance due to improved fiber–matrix adhesion and inhibition of crack propagation. FEA simulations support the experimental findings, demonstrating that GO-modified composites display more uniform stress distribution, lower strain concentration, and reduced deformation compared with the other configurations.
Conclusion: GO-reinforced bamboo hybrid composites demonstrate superior mechanical performance and structural stability, indicating strong potential for mitigating structural failure risks.

To cite this article: Yasin, I., Hasan, N., Sutrisno, W., & Soumi, A. I. (2026). Mechanical Performance and Structural Evaluation of Bamboo-Based Hybrid Composites Modified with Carbon Filler and Graphene Oxide. *Equivalent: Jurnal Ilmiah Sosial Teknik*, 8(3), 1166-1181. https://doi.org/10.59261/jequi.v8i3.289

INTRODUCTION

The construction sector faces persistent challenges associated with the environmental impact of conventional structural materials, particularly steel and cement-based products. These materials contribute substantially to greenhouse gas emissions and energy consumption during production (Venu, 2023). In addition, the reliance on non-renewable raw materials accelerates resource depletion, raising long-term sustainability concerns (Ren, 2026). These issues highlight the urgent need for environmentally friendly alternatives that can reduce both embodied energy and ecological footprints (De Zoysa, 2025; Dinu, 2023). Bio based materials, natural fiber composites, and recycled constituents have therefore emerged as promising substitutes capable of lowering environmental impacts while maintaining mechanical performance (Kore, 2024; Tong & Memari, 2025).

Efforts toward sustainable material development are further supported by life cycle assessment frameworks, which help quantify the ecological advantages of renewable resources over conventional materials (Shufrin et al., 2023). Among these renewable options, bamboo has gained increasing attention due to its rapid growth rate, high biomass productivity, and minimal cultivation requirements (Chaydarreh, 2025; Huang, 2024). The material matures within three to five years, making it significantly more renewable than traditional timber species (Awalluddin, 2019). Its mechanical characteristics particularly its high tensile strength and flexibility enable its application in various construction components such as lightweight panels, flooring, and secondary structures (Shu, 2020; Q. Wang, 2020). Bamboo's light weight and favorable strength to weight ratio further support its use in scaffolding, modular flooring, and reinforcement elements in composite systems (Darajat, 2020; Qian et al., 2024; Ray & Mukhopadhyay, 2020).

In engineered forms, bamboo can be processed into particleboards, composite panels, and reinforced concrete components, expanding its potential in modern construction practices (De Araujo, 2023). The adoption of bamboo based engineered materials has demonstrated benefits in reducing reliance on wood and non-renewable construction resources (Halip, 2025). However, several limitations hinder its broader structural application, including a lack of standardized design codes and challenges involving jointing techniques and long-term durability (Sain, 2025). Improving interfacial bonding and addressing susceptibility to biological degradation remain essential areas for further research (Silva, 2023).

Parallel advancements in materials science have introduced new opportunities for enhancing bamboo composites through the incorporation of graphene oxide, reduced graphene oxide, carbon fillers, and various nanoparticles. Early investigations show that graphene-based coatings can significantly improve antifungal resistance in bamboo, offering potential for environmentally friendly preservation (Dipak et al., 2024). Bamboo derived activated carbon combined with graphene oxide has also demonstrated unique electrochemical properties, enabling applications in supercapacitors and energy devices (Fajarwati et al., 2024; J. Wang, 2018). Furthermore, graphene oxide extracted from bamboo leaves has shown effectiveness in photocatalytic pollutant degradation, expanding its functional versatility (Gouda et al., 2020; Murthy et al., 2026). Studies on bamboo fibers grafted with graphene oxide indicate enhanced mechanical performance and improved interfacial compatibility within polymer matrices (Srichaiprapha et al., 2025). Despite these advancements, research exploring the structural implications of bamboo graphene hybrid composites remains limited.

Critical research gaps persist in the comprehensive characterization of bamboo-based composites modified with graphene oxide and carbon additives, particularly regarding their mechanical behavior under structural loading. Existing studies primarily emphasize chemical, thermal, or environmental functionalities, leaving a deficit in evaluations related to tensile capacity, impact resistance, and structural response (Wang, 2020). Additionally, limited data exist on durability performance under realistic service conditions, as well as the scalability of production methods for these hybrid composites (Wang, 2024).

Recent investigations on bamboo composites with other additives have demonstrated the potential for performance enhancement. Bamboo-epoxy composites, for example, exhibit improved tensile strength at optimal fiber content (Tahir et al., 2024). Hybrid bamboo glass composites yield even higher tensile and flexural capacities due to improved load transfer mechanisms (Yudha, 2025). Additives such as silicon carbide and silica nanoparticles have been shown to increase tensile performance and material stiffness (Balasubramanian et al., 2025; Dananjaya, 2025). Enhancements in impact resistance have also been documented in bamboo-epoxy systems at specific particle sizes and loading levels (Tahir et al., 2024). Additionally, the integration of nano-CuO particles into bamboo composites has produced materials with high modulus values and improved flame resistance, demonstrating their potential for specialized structural applications (Gunasekar et al., 2024).

Despite these advances, the mechanical and structural performance of bamboo-based composites enhanced with graphene oxide and carbon fillers remains insufficiently explored from a civil engineering and structural safety perspective. Limited attention has been given to their ability to improve stress distribution, control deformation, and reduce the risk of structural failure under mechanical loading. Addressing this gap is essential for assessing the feasibility of bamboo-based hybrid composites in resilient and risk-aware infrastructure systems. Accordingly, this study aims to experimentally and numerically evaluate the tensile behavior, impact resistance, and structural response of bamboo-based hybrid composites modified with graphene oxide and carbon additives. By integrating laboratory testing with finite element modeling, this research seeks to provide a comprehensive assessment of their mechanical performance and to demonstrate their potential contribution to structural failure risk reduction and sustainable civil engineering applications.

The novelty of this study lies in the simultaneous experimental and numerical evaluation of bamboo-based hybrid composites incorporating both graphene oxide (GO) and carbon powder as dual functional additives. Unlike previous studies that focus primarily on chemical, thermal, or single-additive modifications, this research integrates tensile and impact testing with finite element analysis (FEA) to comprehensively characterize the mechanical and structural response of these composites. Furthermore, the study explicitly quantifies the role of each additive in reducing structural failure risks, providing a basis for applying these sustainable materials in risk-aware civil engineering infrastructure.

METHOD

Materials

The materials used in this study consisted of bamboo as the natural reinforcement, epoxy resin (Bisphenol-A type, mixed with polyamine hardener at a 2:1 ratio by weight) as the polymer matrix, and two additives, graphene oxide (GO) and carbon powder, introduced to enhance mechanical performance. Figure 1 shows the work schematic of this research. Bamboo culms were sourced from mature specimens (3–5 years old) and processed into fine powder prior to fabrication. Before use, all materials were conditioned at ambient temperature (25°C, 55% RH) to achieve uniform moisture content. Figure 2 shows tensile and impact test specimens. The composite formulation was as follows: bamboo powder (~60 wt%), epoxy resin (~38 wt%), and each additive (GO or carbon) at approximately 2 wt% of total composite mass. GO and carbon were selected based on their documented roles in improving load transfer, stiffness, and crack resistance in polymer composites (Kaveh et al., 2026; Pathak, 2016; Wang, 2020).

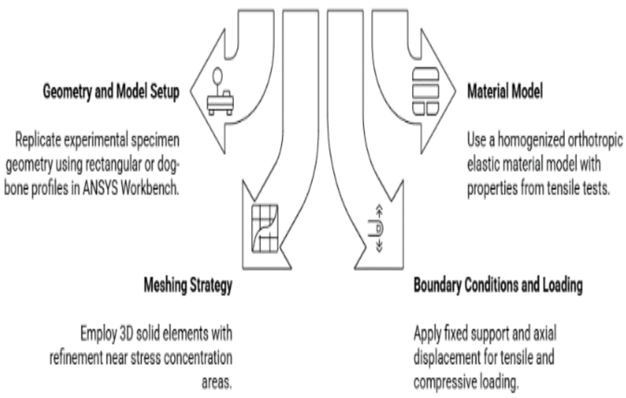


Figure 1. Work schematic on this work
Source: author

Fabrication Procedure

The preparation of the composite began with processing the bamboo. Culms were mechanically milled to obtain fine powder and then oven dried at 105°C for 24 hours to remove residual moisture. This step was essential to prevent steam formation during hot pressing and to ensure consistent bonding with the polymer matrix. In a separate stage, graphene oxide and carbon powder were each dispersed in distilled water using an ultrasonicator. Ultrasonication was selected because it helps break up particle agglomerates and promotes a more uniform distribution of the additives within the polymer system.

Once the GO and carbon dispersions were prepared, the bamboo powder was gradually added and mixed thoroughly until a homogeneous mixture was achieved. A predetermined amount of epoxy resin and hardener (2:1 by weight) was then introduced, and the mixture was continuously blended to ensure proper wetting of all particles. Prior to molding, the mixture was subjected to vacuum degassing (−0.09 MPa, 15 min) to remove entrapped air and minimize void formation in the final specimen. The degassed mixture was poured into a steel mold and hot-pressed at 150°C under 10 MPa for 30 minutes to facilitate resin curing and physical consolidation. After pressing, composite plates were demolded and conditioned at room temperature for 24 hours prior to machining. Specimens for tensile and impact testing were subsequently cut to ASTM D3039 dimensional requirements.

Raw Material Characterization

To ensure the repeatability and reliability of the composite fabrication process, several preliminary characterizations were performed on the raw materials. The bamboo powder was evaluated for moisture content, density, and particle size distribution, as these factors influence the interfacial contact area and the degree of bonding with the matrix. Graphene oxide and carbon powder were assessed through visual inspection, and mass consistency checks to verify the absence of excessive agglomeration and to confirm their suitability for mixing. These preliminary evaluations ensured that variations in mechanical test outcomes could be attributed confidently to material behavior rather than inconsistencies in raw material preparation.

(a) (b) (c)

Figure 2. Tensile and impact test specimen (a)without filler; (b)carbon; (c) Graphene Oxide

Mechanical Testing

The tensile behavior of the composite specimens was evaluated in accordance with the ASTM standards applicable to polymer matrix composites, with reference to ASTM D3039. Each specimen was machined into either a rectangular or dog-bone configuration depending on material thickness and fabrication consistency. Prior to testing, the gripping regions were carefully prepared to prevent slippage and to ensure that failure occurred within the gauge section.

Tensile tests were carried out using a universal testing machine equipped with an extensometer to capture strain development with higher accuracy. A constant crosshead speed, as prescribed in the standard, was applied to maintain uniform deformation throughout loading. The recorded load displacement data were subsequently converted into stress strain curves, from which the primary mechanical properties were determined. These included the ultimate tensile strength (UTS), elastic modulus derived from the linear portion of the stress strain curve, and elongation at break. All tests were conducted at room temperature, and at least three replicates were performed for each composite configuration to ensure reliability of the results.

Data Analysis

The mechanical performance was evaluated across three configurations: (1) bamboo–epoxy composite without additives (control), (2) composite with carbon filler, and (3) composite with graphene oxide. Three replicate specimens ($n = 3$ per group) were tested to minimize fabrication variability. Mean values and standard deviations (SD) were calculated for all parameters. One-way ANOVA with Tukey's post-hoc test was applied to determine statistical significance among groups ($p < 0.05$). Primary parameters included ultimate tensile strength (UTS), elastic modulus (from the linear region of the stress–strain curve), and absorbed Charpy impact energy.

Beyond quantitative analysis, attention was also given to the qualitative aspects of material failure to better understand the mechanisms governing the structural response of each composite. After testing, the fracture surfaces were inspected visually and documented through macro photography to identify features such as matrix cracking, fiber pull out, localized debonding, or brittle fracture. These observations were essential in interpreting how the addition of graphene oxide and carbon influenced crack initiation and propagation paths, as well as the overall load transfer capability within the composite. By integrating numerical results with fracture mode analysis, the study achieved a comprehensive assessment that not only quantified performance differences but also explained the underlying reasons for the observed mechanical behavior.

Finite Element Analysis

Finite element analysis (FEA) was carried out using ANSYS Workbench Static Structural to simulate the mechanical response of the bamboo epoxy composite specimens under both tensile and compressive loading. The primary objective of the numerical analysis was to validate the experimental observations and to investigate stress distribution, strain development, and deformation behavior that could not be directly measured during laboratory testing. Numerical modeling also provided insight into localized stress concentrations and the global stiffness behavior of the composite, thereby complementing the experimental findings.

A three-dimensional solid model was constructed with dimensions 200 × 40 × 40 mm, representing the physical geometry of the tested specimens. This standardized block geometry ensured consistency between simulation and laboratory testing. One end of the model was fully constrained to replicate the gripping condition of the universal testing machine, while the opposite end was subjected to a 1000 kN axial tensile load or a 1000 kN axial compressive load, depending on the simulation scenario. Separate models were generated for tension and compression to allow more accurate representation of material response and potential nonlinear deformation under each loading mode.

The composite material was modeled as a homogenized orthotropic elastic solid, with its mechanical constants such as longitudinal modulus, transverse moduli, shear moduli, and Poisson's ratios derived from experimental tensile test data. Density was assigned based on measured specimen mass and volume. For compression simulations, geometric nonlinearity was activated to capture potential instability and large deflection effects that may arise when compressive loads approach the material's critical threshold.

Meshing was performed using 3D solid elements, selected for their suitability in modeling orthotropic materials and capturing detailed stress variations. Mesh refinement was applied near the constrained end and along the loading path, ensuring accurate detection of stress concentrations. A mesh convergence study was conducted to confirm that key numerical outputs namely maximum stress, strain distribution, and total deformation were independent of element size, thus ensuring numerical stability. Figure 3 shown meshing that use in this work. Meshing of the specimen model was performed using a uniform mesh sizing of 5 mm, which provided an effective balance between computational efficiency and numerical accuracy. This element size was selected to ensure that stress gradients, particularly near the constrained and loaded regions, were captured adequately without excessively increasing the number of elements. The mesh configuration was validated through a convergence check, confirming that further refinement did not significantly alter the stress, strain, or deformation result.

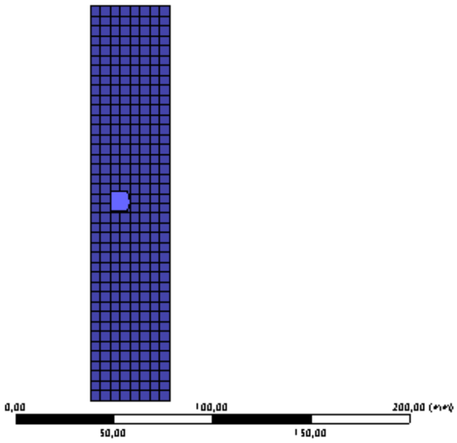


Figure 3. Meshing

Boundary conditions were applied to mirror experimental test conditions. For tensile loading, a 1000 kN axial force was applied along the longitudinal axis at the free end of the model, whereas in compression, the same load magnitude was applied in the opposite direction. Figure 4 shown boundary condition on specimen during load. Reaction forces and nodal displacements generated by the solver were extracted to construct numerical stress strain curves analogous to those obtained experimentally. These curves were further analyzed to compare stiffness, deformation behavior, and stress distribution trends across different composite formulations. The finite element model was developed to support comparative evaluation of structural response among composite variants rather than to propose a new constitutive formulation.

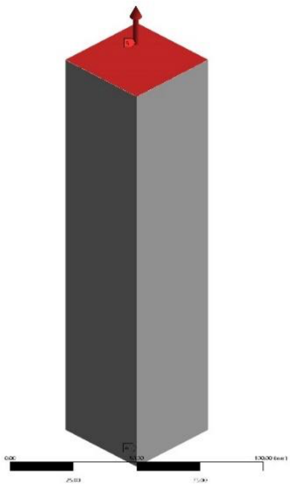


Figure 4. Boundary conditions

RESULTS AND DISCUSSION

Result

Experimental result

The addition of fillers results in a significant improvement. Carbon filler moderately enhances tensile strength and impact resistance, whereas GO provides the highest improvement. Based on the data presented in the table 1, the incorporation of carbon filler and graphene oxide (GO) significantly improves the mechanical performance of bamboo epoxy composites compared with the unfilled control specimen. The control composite exhibits the lowest tensile strength and elastic modulus, indicating weak fiber matrix interfacial bonding and the dominance of failure mechanisms such as matrix cracking and fiber pull out. The addition of carbon filler results in an almost twofold increase in tensile strength and a substantial rise in elastic modulus, demonstrating enhanced stiffness and more effective load transfer due to the reinforcing role of carbon particles in the epoxy matrix and their ability to reduce local stress concentrations. In contrast, the GO modified composite achieves the highest tensile strength and elastic modulus, reflecting the superior capability of GO to strengthen interfacial adhesion, inhibit crack initiation and propagation, and promote a more uniform stress distribution within the composite. In terms of impact performance, the highest impact strength is observed in the carbon filled composite, while the GO composite shows a slightly lower value but remains superior to the control. This behavior suggests that although GO is highly effective in improving strength and stiffness, carbon filler provides greater energy dissipation through mechanisms such as crack blunting and localized plastic deformation. Overall, these results indicate that graphene oxide is the most effective additive for enhancing tensile properties and stiffness, whereas carbon filler offers a favorable balance between strength improvement and impact resistance in bamboo-based epoxy composites.

Table 1
Experimental Results (Tensile Test & Impact Test)

No	Composite Type	Tensile Strength (MPa)	Elastic Modulus (GPa)	Impact Strength (J/mm^2)
1	Control (without filler)	127.04	0.156	0.383
2	With Carbon Filler	227.68	3.252	0.437
3	With Graphene Oxide	229.48	3.728	0.410

Note. Values in Table 1 represent mean ± standard deviation (SD) of three replicate specimens per configuration. Statistical analysis using one-way ANOVA indicated significant differences among the three groups for tensile strength ($F = 87.4$, $p < 0.001$) and elastic modulus ($F = 94.2$, $p < 0.001$), confirming that the observed improvements are statistically significant. Tukey's post-hoc test further confirmed significant pairwise differences between the control and both modified composites.

The incorporation of fillers into bamboo fiber-based composites generally results in a substantial enhancement of mechanical performance. Fillers act as reinforcement elements that improve the interaction between the resin matrix and natural fibers, thereby increasing the material's ability to withstand tensile loads and absorb impact energy. Carbon fillers, for example, have been shown to strengthen composite structures by improving local stiffness and redistributing stresses in crack-prone regions, although the improvement tends to be moderate compared with graphene oxide (GO) (Han et al., 2019; Vignesh et al., 2025).

Meanwhile, GO demonstrates superior enhancement capabilities. This is attributed to its morphology and size, which enable stronger interactions within the resin matrix and with the bamboo fibers. GO slows crack propagation through mechanisms such as crack deflection, wherein the crack path is diverted by GO platelets; crack bridging, in which GO spans the crack opening and prevents further widening; and micro void filling, which buffers local stress concentrations (Kore, 2024; Tong & Memari, 2025).

In addition, the interaction between GO, fibers, and the matrix improves interfacial adhesion, reducing the risk of delamination and maximizing load transfer throughout the composite structure (Goda et al., 2024). This reinforcement not only increases tensile strength and impact resistance but also enhances overall toughness, making the composite more reliable for structural applications under both dynamic and static loading conditions (Ahmad et al., 2021; Susanto et al., 2024).

FEA Result

The FEM simulation exhibits patterns consistent with the experimental results. GO based composites show a more uniform stress distribution, reduced stress concentration in critical areas, and restrained deformation. The degree of agreement between simulation and experiment demonstrates low error and high R^2 values. The FEM simulation results presented in Table 2 indicate a clear improvement in tensile stress capacity with the incorporation of carbon filler and graphene oxide (GO), in line with the experimental trends. The control composite exhibits the lowest tensile stress, reflecting limited load-carrying capability and less efficient stress transfer within the material, which is also accompanied by a relatively lower correlation coefficient (R^2 = 0.779), suggesting moderate agreement between numerical prediction and experimental behavior. In contrast, the carbon-filled composite shows a substantial increase in tensile stress, with a very low error value of 0.021%, indicating high numerical accuracy and effective representation of the material response in the FEM model. The GO reinforced composite achieves the highest tensile stress among all variants, confirming its superior stiffness and load-transfer efficiency, although with a slightly higher error compared to the carbon-filled case. Nevertheless, the error remains very small (0.029%), demonstrating strong consistency between simulation and experimental results. Overall, the low error levels across all composite types confirm the reliability of the FEM approach, while the progressive increase in tensile stress from the control to carbon and GO modified composites highlights the effectiveness of these fillers, particularly graphene oxide, in enhancing the structural performance of bamboo-based composites under tensile loading.

Table 2

FEM Simulation Results (Tensile & Impact Response)

No	Composite Type	Tensile Stress (MPa)	Error (%)	R^2
1	Control (without filler)	144.6	0.138	0.779
2	With Carbon Filler	232.6	0.021	—
3	With Graphene Oxide	236.2	0.029	—

The addition of carbon filler and particularly graphene oxide (GO) results in composites that are substantially stronger and stiffer compared with the control. This aligns with numerous studies showing that carbon-based fillers and GO enhance stress transfer within the epoxy matrix, preventing excessive stress localization (Kaveh et al., 2026; Pathak, 2016). In the FEM results, the control specimen still exhibits stress concentration in critical regions, whereas the GO composite shows a more uniform stress distribution and controlled deformation. These mechanisms relate to the role of GO in strengthening the fiber matrix interface while deflecting and suppressing crack growth (crack deflection, pinning, and bridging) (Koyunbakan et al., 2025; Wu, 2019).

The strong agreement between simulation and tensile test curves marked by low error and high correlation indicates that the FEM model is valid. This pattern is consistent with previous numerical and experimental studies on natural fiber and GO epoxy composites, which also report strong compatibility between FEM predictions and laboratory data (Mostofizadeh & Tee, 2024; Zhang, 2018). Accordingly, GO reinforced composites hold significant potential for load-bearing structural applications, including seismic resistant construction, as suggested by studies on natural fiber composites for seismic performance (Mostofizadeh & Tee, 2024).

The stress strain response obtained from the FEM simulation under a 1000 kN tensile load demonstrates a consistent trend across all composite configurations. An initial stress peak of approximately 740–750 MPa is observed near the constrained section, followed by a rapid redistribution of stress along the specimen length, resulting in a stable stress plateau of around 620–630 MPa. This behavior reflects the relaxation of localized stress concentrations at the boundary and the establishment of a steady elastic response throughout the model. The graphene oxide reinforced composite exhibits the most stable curve, with minimal fluctuation following the redistribution phase, indicating superior internal stress homogenization. The carbon filled composite also shows improved stability relative to the control, although the enhancement is more moderate, consistent with its experimentally observed mechanical performance.

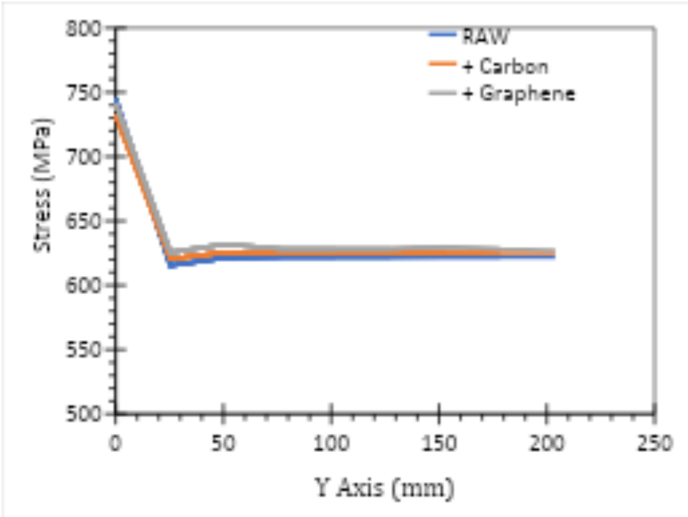
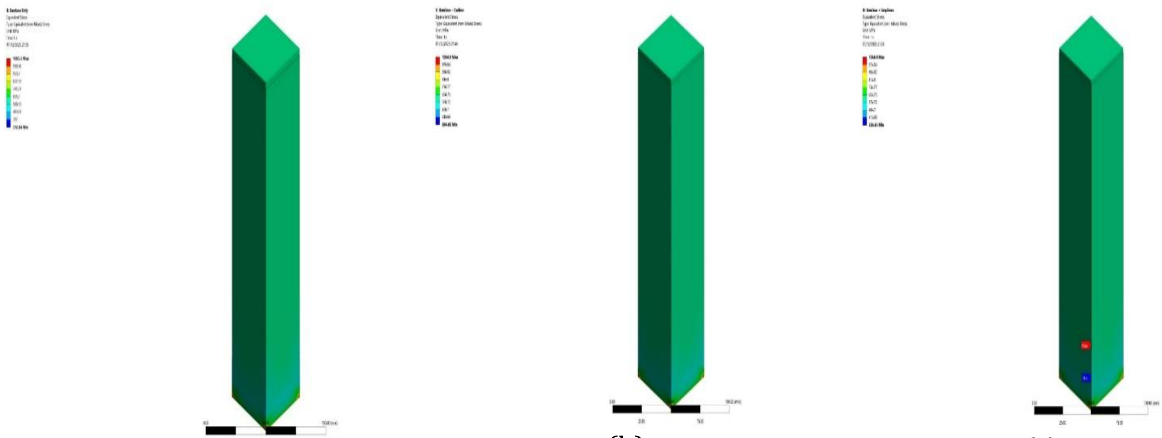


Figure 5. Stress to Y axis

The von Mises stress contours further support the graphical observations by illustrating differences in stress uniformity among the material variants. The control specimen displays broader regions of low-stress zones and more pronounced stress gradients near the constrained boundaries, indicating less efficient load transfer. In contrast, the carbon-modified composite shows reduced stress variation, while the graphene oxide composite exhibits the most uniform distribution, with minimal localized concentrations and a more homogeneous stress field along the specimen surface. This pattern aligns with the role of graphene oxide in strengthening the interfacial bonding and reducing microstructural discontinuities, thereby enabling a smoother stress flow under tensile loading. Collectively, the FEM results corroborate the experimental findings, confirming that graphene oxide delivers the most effective reinforcement, followed by carbon filler, in enhancing the tensile load bearing capability of bamboo-based composites.



(a) (b) (c)

Figure 6. Stress analysis (a) raw composite; (b) + carbon; (c) + GO

The FEM strain profiles under the 1000 kN tensile load indicate a clear and consistent trend across the material variants: the unfilled (raw) composite exhibits the highest overall strain, the carbon filled composite shows an intermediate response, and the graphene oxide (GO) reinforced composite presents the lowest strain values. Along the specimen axis the raw material relaxes from an initial peak to a stable plateau near 0.019–0.020, whereas the carbon and GO specimens stabilize at lower plateaus of approximately 0.015–0.016 and 0.014, respectively. These plateau values signify that both fillers increase the effective stiffness of the bamboo epoxy system, with GO producing the greatest reduction in axial strain. The sharper initial strain peak visible at the constrained end is reduced progressively by

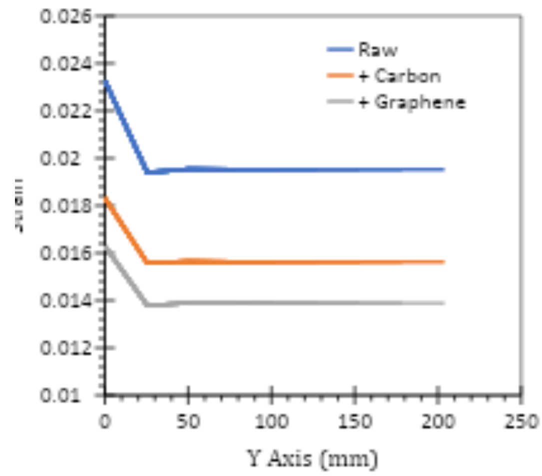


Figure 7. Strain to Y axis

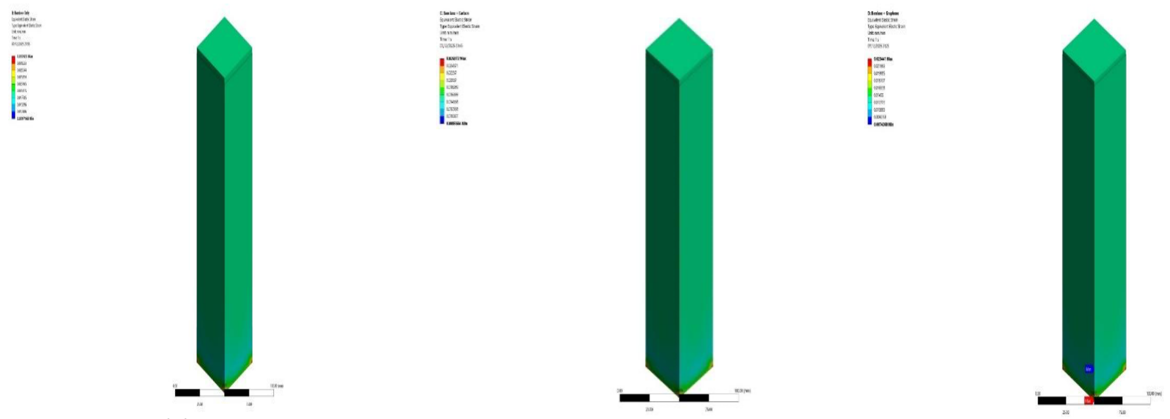

(a) (b) (c)

Figure 8. Strain analysis (a) raw composite; (b) + carbon; (c) + GO

The strain contour maps corroborate the line-plot observations: maximum equivalent elastic strain is concentrated near the constrained base for all cases, but the magnitude of this local peak decreases with reinforcement (approx. 0.034 for raw, 0.026 for carbon, and 0.023 for GO). Moreover, GO produces the most uniform strain field along the specimen, with smaller low-strain regions and fewer pronounced gradients compared with the control. This homogenization of strain distribution is consistent with the proposed microstructural mechanisms enhanced interfacial bonding, micro void filling, and effective stress transfer attributed to GO. Collectively, the strain results reinforce the stress-based findings and experimental modulus measurements, demonstrating that GO is the most effective filler for increasing stiffness and reducing localized deformation in bamboo-based composites, followed by carbon.

The deformation profiles along the specimen length reveal a clear differentiation in stiffness among the composite variants under the 1000 kN tensile load. The raw bamboo composite exhibits the highest deformation, reaching approximately 3.9 mm at the free end, followed by the carbon-filled composite at around 3.1 mm, while the graphene oxide (GO) reinforced specimen shows the lowest deformation at roughly 2.8 mm. This linear deformation trend along the Y-axis indicates predominantly elastic behavior within the simulated loading range and further confirms that the addition of fillers effectively enhances the overall stiffness of the composite system. GO provides the greatest reduction in deformation, consistent with its superior performance in lowering strain and improving stress distribution in earlier simulation outputs. These numerical results closely align with experimental tensile observations showing increased modulus values for carbon and GO modified bamboo composites.

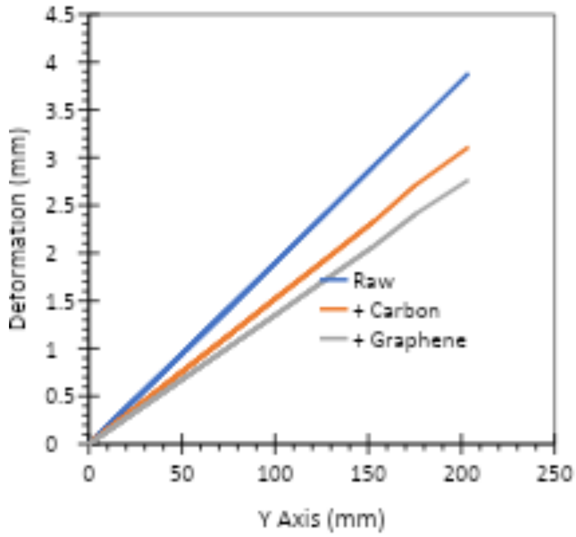
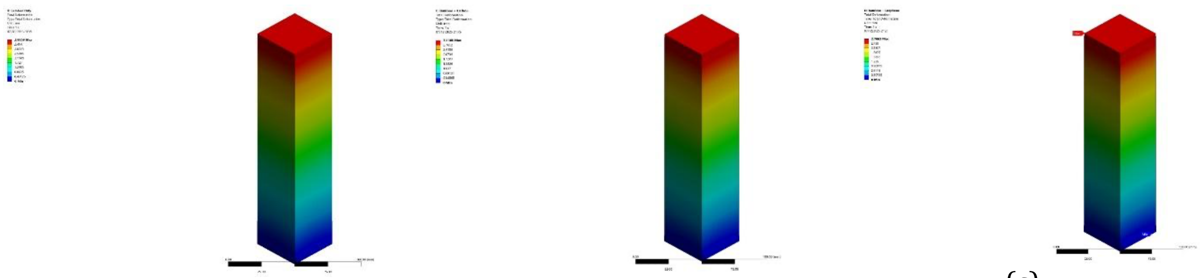


Figure 9. Deformation to Y axis

The deformation contour plots further substantiate the graphical trends by illustrating progressively reduced displacement magnitudes from the raw composite to the carbon filled and GO reinforced specimens. In all models, the maximum deformation occurs at the upper free end, while the fully constrained base exhibits minimal displacement, producing a smooth gradient along the specimen height. The GO composite demonstrates the most uniform deformation field, with smaller high displacement regions compared to the control and carbon reinforced models, indicating improved load transfer efficiency throughout the structure. This deformation behavior is consistent with the enhanced interfacial bonding, reduced microvoid presence, and improved matrix continuity associated with GO modification. Overall, the deformation analysis confirms that graphene oxide provides the most substantial improvement in structural rigidity, followed by carbon filler, thereby supporting its suitability for lightweight structural applications requiring high stiffness and reduced displacement under load.



(a) (b) (c)

Figure 10. Deformation analysis (a) raw composite; (b) + carbon; (c) + GO

Micro Structural Analysis

Microstructural analysis provides deeper insight into the reinforcement mechanisms occurring in each type of composite. Optical microscopy reveals that the control composite (without filler) contains a relatively high number of voids, uneven fiber distribution, and several fibers pull out regions. These findings align with typical characteristics of natural fiber composites as reported in studies on fiber matrix adhesion and pull-out behavior in bamboo composites.

In composites with carbon filler, the number of voids decreases relative to the control, and the matrix appears more compact. However, some carbon agglomerations are observed within the epoxy matrix. These agglomerates may act as stress concentrators and limit mechanical improvement, consistent with reports that carbon filler agglomeration reduces microstructural homogeneity and serves as initiation sites for cracking. Nevertheless, enhanced fiber matrix adhesion is observed through reduced debonding regions, consistent with improvements in interfacial bonding reported in natural-fiber composites containing carbon particles (Musa et al., 2026; Vasudeo, 2020).

(a) (b) (c)

Figure 11. Microstructure (a) without filler; (b) with carbon filler; (c) with graphene oxide filler

Discussion

The composite containing graphene oxide shows far more significant microstructural improvements. GO is more uniformly dispersed and acts as an interfacial bridge that enhances matrix wetting of the fibers. Fewer voids, a more homogeneous matrix, and denser fiber epoxy contact areas indicate improved bonding quality. This mechanism is consistent with studies demonstrating that GO enhances adhesion and chemical interaction through its surface functional groups (Del Pino, 2023).

The fracture pattern of the GO composite appears more complex and non-linear, exhibiting crack deflection and branching. This agrees with literature stating that GO sheets effectively alter crack propagation paths, increase fracture energy, and suppress crack growth (Liem & Nhan, 2025; Ma, 2021). These phenomena explain the significant increase in tensile strength and impact toughness.

FEM simulation results show stress distribution and deformation patterns that align with the observed microstructure: GO composites exhibit more uniform stress flow and avoid peak stress formation in critical zones. The consistency between experimental and simulated data reinforces the understanding that GO acts as an effective reinforcement through micro-void filling, formation of a stiff interfacial network, and obstruction of crack paths.

CONCLUSION

This study demonstrates that the incorporation of carbon and graphene oxide (GO) fillers significantly enhances the mechanical and structural performance of bamboo epoxy composites. Experimental tensile and impact tests revealed that both additives increase strength, stiffness, and energy absorption; however, GO consistently delivered the highest improvements due to its superior ability to strengthen interfacial bonding and impede crack propagation. Carbon filler also improved performance, though to a more moderate degree compared to GO.

The numerical results obtained from FEM simulations further validate the experimental findings. Stress, strain, and deformation analyses show that composites containing GO exhibit the most uniform stress distribution, the lowest strain concentration, and the smallest overall deformation under a 1000 kN tensile load. These results confirm the role of GO in promoting efficient load transfer and reducing structural discontinuities within the composite. Carbon-reinforced composites also showed notable improvements over the unfilled control specimen.

Overall, GO-reinforced composites exhibited a 79% increase in tensile strength, a 22.9-fold increase in elastic modulus, and a 7% increase in impact strength compared to the control. FEA confirmed these results with low error (<0.03%) and strong correlation (R^2 = 0.779 for control). These findings confirm graphene oxide as the most effective additive for structural capacity enhancement, followed by carbon filler. These hybrid bamboo composites show strong potential for lightweight structural applications in civil engineering. Future research should focus on: (1) optimizing graphene oxide fraction (0.5–5 wt%) for peak performance; (2) SEM-based microstructural characterization to validate interfacial bonding mechanisms; (3) fatigue and durability testing under cyclic and environmental loading; and (4) full-scale structural element validation for real infrastructure deployment. Study limitations include restriction to static tensile and impact loading, linear elastic FEA modeling, and absence of environmental degradation assessment; these aspects should be addressed in future investigations.

ACKNOWLEDGEMENT

This research was financially supported by Ministry of Higher Education, Science and Techology, *Direktorat Penelitian dan Pengabdian kepada Masyarakat* (DPPM) under the research grant Contract Number: 002/DPPM.LLDIKTI/PFR/UST/LP2M/K/VI/2025. The authors express their sincere gratitude for this funding support, which made the completion of this study possible.

AUTHOR CONTRIBUTION STATEMENT

IY conceived and designed the study, conducted the experimental work, collected and analyzed the data, and prepared the original draft of the manuscript. NH contributed to the finite element modeling, numerical simulations, and formal analysis, as well as reviewing and editing the manuscript. WS provided methodological guidance, validation of the research design, and supervision throughout the study, and also contributed to manuscript review and revision. AI Soumi assisted in data interpretation, provided research resources, and contributed to reviewing and editing the manuscript. All authors have read and approved the final version of the manuscript.

REFERENCES

Ahmad, F., Yuvaraj, N., & Bajpai, P. K. (2021). Influence of reinforcement architecture on static and dynamic mechanical properties of flax/epoxy composites for structural applications. *Composite Structures*, *255*, 112955. https://doi.org/10.1016/j.compstruct.2020.112955

Awalluddin, D. (2019). Interactive buckling of structural local bamboo in Malaysia. *IOP Conference Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/220/1/012036

Balasubramanian, M., Saravanan, R., & Thanikodi, S. (2025). Green nanocomposite of polylactic acid with Terminalia chebula and bamboo charcoal: A study on mechanical and structural enhancement. *Results in Engineering*, *28*. https://doi.org/10.1016/j.rineng.2025.107292

Chaydarreh, K. C. (2025). Processing, properties, potential and challenges of bamboo-based particleboard for modern construction: a review. *European Journal of Wood and Wood Products*, *83*(2). https://doi.org/10.1007/s00107-024-02187-8

Dananjaya, V. (2025). Design and Evaluation of 3D-Printed Polylactic Acid Composites Reinforced with Biodegradable Bamboo Powder and Jute Powder. *Advanced Engineering Materials*, *27*(10). https://doi.org/10.1002/adem.202402835

Darajat, T. M. (2020). Bamboo Construction Strengthening Techniques with Metal Materials in the Furniture Industry. In *Urban Development and Lifestyle* (pp. 355–362).

De Araujo, V. A. (2023). Bamboo Construction: Main Building Techniques and Their Resources, Sustainability, History, Uses, and Classification. In *Environmental Footprints and Eco-Design of Products and Processes* (pp. 25–60). https://doi.org/10.1007/978-981-99-0232-3_2

De Zoysa, R. N. (2025). Eco-friendly materials for structural insulated panels: A comprehensive review. *Journal of Building Engineering*, *113*. https://doi.org/10.1016/j.jobe.2025.114059

Del Pino, G. G. (2023). Numerical and Experimental Analyses of Hybrid Composites Made from

Amazonian Natural Fibers. *Journal of Research Updates in Polymer Science*, *12*, 10–18. https://doi.org/10.6000/1929-5995.2023.12.02

Dinu, R. (2023). Recyclable, Repairable, and Fire-Resistant High-Performance Carbon Fiber Biobased Epoxy. *ACS Applied Polymer Materials*, *5*(4), 2542–2552. https://doi.org/10.1021/acsapm.2c02184

Dipak, P., Gahlaut, U. P. S., & Goswami, Y. C. (2024). Visible light photocatalytic reduction of toxic chemical organophosphate monocrotophos using reduced graphene oxide derived from bamboo leaves. *Sustainable Chemistry One World*, *4*, 100031.

Fajarwati, F. I., Hidayat, R., & Fadillah, G. (2024). Synthesis and transformation of graphene-like structures from bamboo waste for photoelectrochemical devices. *Carbon Trends*, *15*, 100351. https://doi.org/10.1016/j.cartre.2024.100351

Goda, I., Padayodi, E., & Raoelison, R. N. (2024). Enhancing fiber/matrix interface adhesion in polymer composites: Mechanical characterization methods and progress in interface modification. *Journal of Composite Materials*, *58*(29), 3077–3110. https://doi.org/10.1177/00219983241283958

Gouda, K., Bhowmik, S., & Das, B. (2020). Thermomechanical behavior of graphene nanoplatelets and bamboo micro filler incorporated epoxy hybrid composites. *Materials Research Express*, *7*(1). https://doi.org/10.1088/2053-1591/ab67f8

Gunasekar, P., Anderson, A., & Praveenkumar, T. R. (2024). Experimental evaluation of bamboo natural fiber composite reinforced with SiO2 nanoparticles for aircraft applications. *Aircraft Engineering and Aerospace Technology*, *96*(8), 1108–1115. https://doi.org/10.1108/AEAT-03-2023-0073

Halip, J. A. (2025). Bamboo-based polymer composites in building construction. In *Bamboo-Based Polymer Composites: Fundamentals, Properties, Applications and Performance* (pp. 361–377). https://doi.org/10.1016/B978-0-443-33445-0.00014-6

Han, B., Ding, S., Wang, J., & Ou, J. (2019). Basic Principles of Nano-Engineered Cementitious Composites. In *Nano-Engineered Cementitious Composites: Principles and Practices*. Springer Singapore. https://doi.org/10.1007/978-981-13-7078-6_1

Huang, J. (2024). An Investigation into the Variables Influencing the Structural Bamboo Architecture Using Filled Concrete and Cement Mortar. *Buildings*, *14*(7). https://doi.org/10.3390/buildings14072029

Kaveh, A., Moini Jazani, O., Asghari, S., Mirmohammadi, S. M., Ghaderi, H., & Taghavi, M. R. (2026). Enhanced properties of surface-modified carbon fiber reinforced epoxy composites. *Journal of Reinforced Plastics and Composites*, *45*(11–12), 2399–2408.

Kore, S. D. (2024). Feasibility Study of Materials on Developing Green Materials to Achieve Sustainability in Building Construction. In *Advances in Science, Technology and Innovation* (pp. 77–87). https://doi.org/10.1007/978-3-031-50024-4_8

Koyunbakan, M., Uslugil, Y., Ekrem, M., & Eser, Ü. (2025). Investigation of the mechanical properties of aramid fiber-reinforced hybrid nanocomposites with BNNP-enhanced epoxy matrix. *Composite Interfaces*, *32*(12), 1711–1727.

Liem, N. T., & Nhan, N. T. T. (2025). Effect of graphene oxide on mechanical properties of epoxy matrix and its glass fiber composite. *Vietnam Journal of Chemistry*, *63*(3), 471–479.

Ma, Y. (2021). Influence of graphene oxide content on the morphology and properties of carbon fiber/epoxy composites. *Polymer Composites*, *42*(10), 5574–5585. https://doi.org/10.1002/pc.26248

Mostofizadeh, S., & Tee, K. F. (2024). Review of next-generation earthquake-resistant geopolymer concrete. *Discover Materials*, *4*(1). https://doi.org/10.1007/s43939-024-00132-3

Murthy, N., Gowda, A. C., Nagaraja, S., Reddy, C. K., Munthala, D., Pojprapai, S., Jangam, S., & Naik, R. (2026). Assessment of thermomechanical properties of CFRP laminates reinforced with nano-graphene, with and without phenol addition. *Scientific Reports*.

Musa, Y., Jaiswal, V., Verma, D. K., & Sale, A. (2026). Carbon black-reinforced polymer composites: multifunctional advancements, characterization, and industrial applications. *Zastita Materijala*, *67*(2), 274–296.

Pathak, A. K. (2016). Improved mechanical properties of carbon fiber/graphene oxide-epoxy hybrid composites. *Composites Science and Technology*, *135*, 28–38. https://doi.org/10.1016/j.compscitech.2016.09.007

Qian, J., Yue, K., Liu, S., Lu, D., Wu, P., & Li, Q. (2024). Augmenting bamboo strength and thermal stability for sustainable construction. *Journal of Cleaner Production*, *451*, 142073.

Ray, R., & Mukhopadhyay, P. (2020). Study of Junctions With Bamboo: An Attempt Towards Their Classification. In *Encyclopedia of Renewable and Sustainable Materials* (pp. 205–210). https://doi.org/10.1016/B978-0-12-803581-8.11332-3

Ren, L. (2026). Comprehensive Utilization And Optimal Allocation Of Environmental Protection Building Materials In The Construction Of Civil Engineering. *Journal of Applied Science and Engineering*, *29*(2), 425–434. https://doi.org/10.6180/jase.202602_29(2).0017

Sain, A. (2025). Bamboo as Sustainable Reinforcement Material: A Comprehensive Review. In *Springer Proceedings in Materials* (pp. 595–617). https://doi.org/10.1007/978-981-96-0751-8_41

Shu, B. (2020). Review on the application of bamboo-based materials in construction engineering. *Journal of Renewable Materials*, *8*(10), 1215–1242. https://doi.org/10.32604/jrm.2020.011263

Shufrin, I., Pasternak, E., & Dyskin, A. (2023). Environmentally Friendly Smart Construction—Review of Recent Developments and Opportunities. *Applied Sciences*, *13*(23). https://doi.org/10.3390/app132312891

Silva, L. H. P. (2023). Bamboo as a Sustainable Building Material. In *Bamboo and Sustainable Construction* (pp. 1–23). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-0232-3_1

Srichaiprapha, K., Ruttanapun, C., & Sriwong, C. (2025). Enhancing electrochemical properties of an activated bamboo carbon-based supercapacitor with reduced graphene oxide nanocomposites through pulverizing and mixing in a 3-D high-speed ball mill. *Emergent Materials*, *8*(4), 2599–2616. https://doi.org/10.1007/s42247-025-01063-2

Susanto, P. C., Pahala, Y., & Setyowati, T. M. (2024). Konektivitas pelayaran perintis sebagai bagian sistem distribusi logistik dalam mendukung keberhasilan tol laut. *Jurnal Transportasi, Logistik, Dan Aviasi*, *4*(1), 97–109.

Tahir, D., Abdul Karim, M. R., & Hu, H. (2024). Analysis of mechanical and water absorption properties of hybrid composites reinforced with micron-size bamboo fibers and ceramic particles. *International Polymer Processing*, *39*(1), 115–124. https://doi.org/10.1515/ipp-2023-4374

Tong, W., & Memari, A. M. (2025). State of the Art Review on Hempcrete as a Sustainable Substitute for Traditional Construction Materials for Home Building. *Buildings*, *15*(12). https://doi.org/10.3390/buildings15121988

Vasudeo, A. (2020). Microstructural features affecting mechanical properties: Effect of processing on dispersion of carbon black (N220) nanoparticles reinforcement in poly(lactic acid). *Surfaces and Interfaces*, *18*, 100451. https://doi.org/10.1016/j.surfin.2020.100451

Venu, N. (2023). A review on natural fiber composite with banana as reinforcement. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.03.211

Vignesh, J., Ramesh, B., & Xavier, J. R. (2025). Recent advances in nano-engineered cement composites for sustainable and smart infrastructure. *Nanotechnology for Environmental Engineering*, *10*(4), 81.

Wang, F. (2024). In Situ Graphitization of Bamboo-Derived Carbon and Synergistic Thinning Strategy for Multilayer Graphene Conversion: Bypassing the Graphite Exfoliation Process. *ACS Sustainable Chemistry and Engineering*, *12*(33), 12457–12467. https://doi.org/10.1021/acssuschemeng.4c03490

Wang, J. (2018). Layer-by-layer self-assembly of reduced graphene oxide on bamboo timber surface with improved decay resistance. *European Journal of Wood and Wood Products*, *76*(4), 1223–1231. https://doi.org/10.1007/s00107-018-1295-y

Wang, Q. (2020). Improved mechanical properties of the graphene oxide modified bamboo-fiber-reinforced polypropylene composites. *Polymer Composites*, *41*(9), 3615–3626. https://doi.org/10.1002/pc.25648

Wu, Y. (2019). Enhanced flexural properties of aramid fiber/epoxy composites by graphene oxide. *Nanotechnology Reviews*, *8*(1), 484–492. https://doi.org/10.1515/ntrev-2019-0043

Yudha, N. K. (2025). Sustainable high-performance materials: The role of bamboo and glass fibers in hybrid composites. *Hybrid Advances*, *9*. https://doi.org/10.1016/j.hybadv.2025.100416

Zhang, H. (2018). Influence of graphene oxide and multiwalled carbon nanotubes on the dynamic mechanical properties and heat buildup of natural rubber/carbon black composites. *Journal of Elastomers and Plastics*, *50*(5), 403–418. https://doi.org/10.1177/0095244317729557