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Mechanical, thermal, and morphological characterization of biodegradable banana fiber reinforced epoxy composites modified with compatible fillers

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Abstract

With the growing need for eco-friendly and advanced materials, biodegradable composite materials have gained attention. In this study, biodegradable banana fiber reinforced epoxy composites were fabricated and further modified with compatible fillers, such as natural fillers (coconut shell powder), synthetic fillers (carbon nano powder) and metallic fillers (copper nano powder) for better performance. The developed composites were comprehensively evaluated for their mechanical, thermal and morphological characteristics. The mechanical evaluation showed a significant increase in tensile, flexural and impact strengths due to the addition of banana fiber and further improvement with the inclusion of fillers. Carbon nano powder proved to be a more effective filler, leading to the highest tensile and flexural strength as a result of enhanced load transfer and nanofiller interaction. The energy absorption and toughness of coconut shell powder improved the impact properties, whereas copper nano powder increased the hardness and stiffness of the composite system. Thermal degradation studies using thermogravimetric analysis (TGA) techniques showed improved thermal properties of the composites, including higher degradation temperature and residual mass of the filler-reinforced systems. Microscopic observations using scanning electron microscopy have shown better bonding, lower void content and uniform distribution of fillers in the epoxy. The findings suggest that banana fiber and compatible fillers can be used to engineer the properties of biodegradable composites for use in lightweight structural and sustainable engineering applications. This research demonstrates the promise of hybrid filler-reinforced natural fiber composites as environmentally friendly materials.

Keywords: Banana Fiber Composites; Biodegradable Materials; Epoxy Composites; Hybrid Fillers; Thermal and Mechanical Characterization

1. Introduction

Environmental awareness, scarcity of non-renewable resources, and restrictions on the use of synthetic materials have driven research on eco-friendly and biodegradable composite materials [1]. Traditional fiber-reinforced polymer composites, while extensively used in structural and engineering fields, are plagued by problems such as non-biodegradability, high energy intensive manufacturing, and environmental hazards. Hence, natural fiber reinforced composites have emerged as potential substitutes owing to their environmental friendliness, cost-effectiveness, renewability and satisfactory mechanical properties [2]. In particular, banana fiber has attracted attention because of its high cellulose content, acceptable mechanical properties, low density and abundance as an agricultural waste product. Banana fiber-reinforced epoxy composites offer enhanced specific strength, biodegradability and are used in lightweight applications. But the hydrophilic nature of natural fibers and incompatibility with hydrophobic polymer matrices can affect their mechanical and thermal behaviours [3]. Hence, it is essential to improve the fiber-matrix interaction and composite properties.

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A promising strategy to address these challenges is to use compatible fillers in the composite. Fillers can help to modify the mechanical, thermal and morphological properties of composites through better load transfer, decrease in voids, and increase in matrix stiffness [4]. In this work, three different fillers are compared: natural filler (coconut shell powder), synthetic nano filler (carbon nano powder) and metallic nano filler (copper nano powder). Coconut shell powder, as a lignocellulosic filler, has enhanced toughness and environmental sustainability, whereas carbon nano powder is known to give better reinforcement due to its high surface area and superior mechanical properties [4]. Meanwhile, copper nano powder offers improved stiffness, thermal conductivity and hardness.It has been reported recently that hybrid composites with natural fibres and nano/micro fillers can synergistically enhance the properties [5]. But more research is necessary to systematically compare the effects of natural, synthetic and metallic fillers in a single biodegradable composite. Specifically, there is a lack of research on banana fiber reinforced epoxy composites modified with a combination of such compatible fillers and tested in terms of mechanical, thermal and morphological properties.

Hence, the main goal of the present study is to prepare biodegradable banana fiber reinforced epoxy composites modified with various fillers, and to investigate their properties. Tensile, flexural, and impact properties are evaluated through mechanical testing and thermal degradation is evaluated by thermogravimetric analysis. Scanning electron microscopy is used to investigate the dispersion and interfacial interactions of fillers. The results of this research are anticipated to offer insights into the development of high-performance, sustainable composite materials with specific properties for potential use in automotive, construction and lightweight structures.

2. Literature Review

There has been a growing interest in the development of natural fiber-reinforced composites in recent years owing to the environmental concerns and the need for eco-friendly materials. Banana fiber is one of the potential natural fiber reinforcements due to its high cellulose content, good strength, and biodegradability [1]. A number of studies have explored the mechanical, thermal and morphological properties of banana fiber-reinforced composites and their hybrids. Research has found that polymer composites reinforced with banana fiber have considerably enhanced mechanical properties, including tensile strength, flexural strength and impact resistance, compared with traditional composites [2,3]. In a review study, it was shown that including banana fibers in composites can improve mechanical properties by 30-50%, depending on the fiber content, treatment and compatibility with the matrix [4]. Moreover, banana fiber's lightweight and economical characteristics make it suitable for automotive and structural parts.

Studies have also been conducted on the thermal properties of banana fiber composites. It has been found that incorporation of natural fiber increases thermal stability and decreases thermal conductivity, and these composites are promising for insulation and moderate temperature applications [5]. It is reported that hybridization with nanofillers like nanoclay and carbon fillers can enhance thermal stability and increase the degradation temperature because of better interfacial compatibility and barrier properties [6]. Moreover, banana fiber composites with thermoplastic matrices have been found to have better thermal stability than neat polymers. To address the challenges of natural fiber composites, including moisture uptake and interfacial bonding, hybrid composites and filler modifications have been explored [7]. Fillers such as fly ash, nanoclay, and carbon-based fillers have demonstrated significant enhancements in mechanical and thermal characteristics [8]. For example, nano-fillers improve stiffness, strength and thermal resistance because of their large surface area and strong bonding with the matrix. Likewise, natural fillers like coconut shell powder enhance toughness and energy dissipation properties while being environmentally friendly [9].

There have also been numerous studies on hybridization with natural and synthetic fillers. Research shows that mixing banana fibers with other types of fibers or fillers leads to improved properties [10]. For instance, hybrid banana/glass fiber composites and banana/carbon fiber composites show improved tensile and flexural strengths, owing to effective load sharing [11]. Additionally, fiber surface modifications, including alkali treatment, improve bonding strength, enhancing mechanical properties and moisture resistance. Scanning electron microscopy (SEM) has been extensively used to investigate the dispersion of fillers and fibers in the matrix [12]. It is known from earlier studies that the proper dispersion of fillers and the good fiber-matrix bonding will reduce the formation of voids and fiber pull-out and enhance the properties of the composites. The smooth surface and good interfacial bonding of the modified banana fiber result in improved mechanical and thermal properties.

While several studies have been reported on banana fiber composites, there is a research gap in the comparative evaluation of various fillers (natural, synthetic and metallic) in a composite system. Most research has been done with either natural or nano fillers, with very few reports tackling the effects of both on the mechanical, thermal, and morphological properties. Hence, a comprehensive study of banana fiber reinforced epoxy composites modified with compatible fillers such as coconut shell powder, carbon nano powder and copper nano powder is required to investigate their combined influence and to enhance the mechanical properties.

3. Methodology

The approach taken in this research is to fabricate and test biodegradable banana fiber reinforced epoxy composites with compatible fillers as illustrated in figure 1. A systematic approach was adopted to maintain uniformity in material selection, specimen fabrication and testing. Banana fibers were prepared, treated, and incorporated into an epoxy resin along with varying quantities of fillers like coconut shell powder, carbon nano powder and copper nano powder. The composite samples were prepared by a controlled hand lay-up method and cured in a controlled environment. Mechanical properties, thermal stability and morphological features were studied using standard test methods, and the results were found to be consistent and reliable.

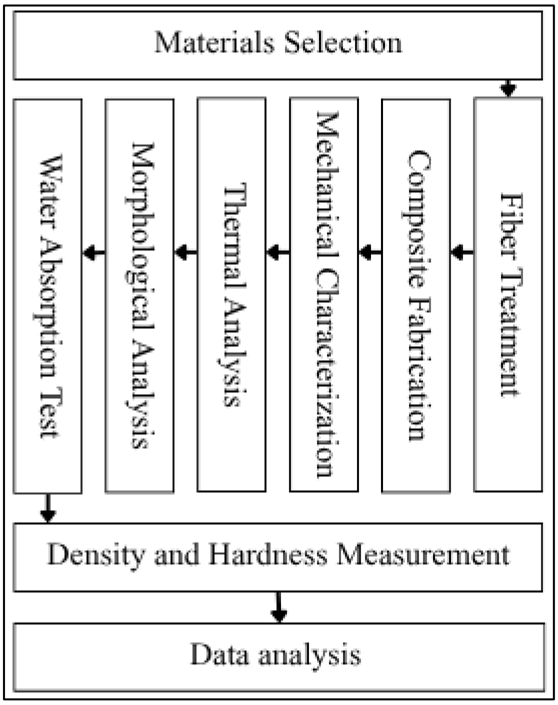

Figure 1 Fabrication and Characterization Process of Banana Fiber Reinforced Epoxy Composites with Compatible Fillers

3.1. Materials Selection

Natural banana fibers were chosen as the main reinforcement because of their high cellulose content, low density and biodegradability. They were obtained from banana pseudo-stems and purified. Epoxy resin was chosen as the matrix due to its high strength, good adhesion and processability.

Various fillers were used to improve the properties of the composite:

- Natural filler: Coconut shell powder (CSP)
- Synthetic nano filler: Carbon nano powder (CNP)
- Metallic nano filler: Copper nano powder (CuNP)

Fillers were selected on the basis of their compatibility with epoxy matrix and enhancement in mechanical and thermal properties.

3.2. Fiber Treatment

To enhance the bonding between the banana fibers and the epoxy matrix, an alkali treatment was carried out. The fibers were soaked in 5% sodium hydroxide (NaOH) for 4 hours and washed with distilled water to remove any alkali.

Subsequently, the fibers were washed with distilled water, and dried at room temperature for 24 hours. This process eliminates hemicellulose and lignin and increases the surface roughness and adhesiveness.

3.3. Composite Fabrication

The composites were manufactured by the hand lay-up and compression molding process.

1. A certain proportion of epoxy resin and hardener (usually 10:1 by weight) were mixed.
2. Fillers (CSP, CNP, and CuNP) were mixed separately in various weight percentages (3-5 wt%) and mechanically dispersed.
3. Banana fibers (pretreated) were placed in the mold in unidirectional/random alignment.
4. The resin-filler combination was applied on the fiber layers and spread uniformly.
5. Pressure was applied to the mold to eliminate air bubbles and control thickness.
6. The composite laminates were left to cure at room temperature for 24 hours and then post-cured at higher temperature (80°C for 2 hours).

Different composite samples were prepared:

- Banana fiber + epoxy (control)
- Banana fiber + epoxy + CSP
- Banana fiber + epoxy + CNP
- Banana fiber + epoxy + CuNP

3.4. Mechanical Characterization

The ASTM standards were followed for the mechanical tests:

- *Tensile Test*: Conducted using a Universal Testing Machine (UTM) as per ASTM D638 to measure tensile strength, Young's modulus, and elongation at break.
- *Flexural Test*: Performed using a three-point bending test as per ASTM D790 to measure flexural strength and modulus.
- *Impact Test*: Performed using an Izod/Charpy impact tester in accordance with ASTM D256 to determine the impact strength.

Test specimens were prepared to the specified dimensions, and tests were performed on several specimens to ensure repeatability.

3.5. Thermal Analysis

The composites' thermal properties were evaluated by:

- *Thermogravimetric Analysis (TGA*): Performed to measure weight changes as a function of temperature, to assess thermal stability and decomposition temperature. The composites were heated from room temperature to 600°C at a specified heating rate in a controlled environment.
- *Differential Scanning Calorimetry (DSC)*: Employed to find the glass transition temperature (Tg) and other transitions.

3.6. Morphological Analysis

The morphology of the composites was observed by Scanning Electron Microscope (SEM). SEM of fractured tensile test specimens were used to determine:

- Fiber–matrix interfacial bonding
- Filler dispersion
- Presence of voids and cracks
- Failure modes such as fiber pull out and debonding

The SEM images give an idea of the structure and efficacy of filler addition.

3.7. Water Absorption Test

The water absorption test was conducted as per ASTM D570. Composite samples were soaked in distilled water at room temperature, and the weight gain was recorded periodically. Water absorption percentage was measured using:

$$\text{Water Absorption (\%)} = \frac{W_t - W_0}{W_0} \times 100$$

where W_0 is the initial weight and W_t is the weight after immersion time t.

3.8. Density and Hardness Measurement

Density: Measured by Archimedes' principle.

Hardness: Evaluated by Shore D hardness tester.

3.9. Data analysis

The chosen approach allows for a comprehensive assessment of the effect of fillers on banana fiber reinforced epoxy composites. Mechanical, thermal and microscopic studies are combined to gain insight into the composite performance and the modification mechanisms.

4. Results and Discussion

The findings from the experimental study offer a detailed insight into the mechanical, thermal and microstructural performance of banana fiber reinforced epoxy composites with compatible filler modifications. The effect of natural filler (coconut shell powder) and nano fillers (carbon nano powder and copper nano powder) on the mechanical, thermal, and morphological properties has been investigated using mechanical, thermal, and morphological tests. Tables 1 and 2 show the measured mechanical and thermal properties, while Figures 2 to 7 show the morphological characteristics, and the performance trends of the modified composites. The comparative study reveals the influence of filler type, distribution and interaction in determining the composite properties.

Table 1 Mechanical Properties of Banana Fiber Reinforced Epoxy Composites

Composite Type	Young's Modulus (GPa)	Elongation (%)	Flexural Modulus (GPa)	Impact Strength (kJ/m²)
Neat Epoxy	1.8	2.5	2.1	12
Banana Fiber + Epoxy	2.6	3.1	3.0	20
+ CSP (5%)	2.9	2.8	3.3	24
+ CNP (3%)	3.8	2.4	4.5	22
+ CuNP (3%)	3.5	2.2	4.2	21

The mechanical properties of banana fiber reinforced epoxy composites with modified fillers are shown in Table 1. It can be seen that the addition of banana fiber to the epoxy matrix results in improved mechanical properties compared to the pure epoxy resin. The Young's modulus rises from 1.8 GPa (neat epoxy) to 2.6 GPa (banana fiber composite), suggesting an increase in the stiffness of the composite because of the reinforcing effect of the banana fibers. Moreover, the elongation at break is also increased, which indicates improved load-bearing capacity and toughness. The incorporation of fillers also leads to enhancement. The carbon nano powder (CNP) composite shows the highest Young's modulus (3.8 GPa) and flexural modulus (4.5 GPa), with the best stiffness and load bearing capacity. This could be due to the large surface area and good interaction of the nano-sized carbon particles with the epoxy matrix, leading to better stress transfer. The composite containing copper nano powder (CuNP) also exhibits a significant improvement in stiffness (Young's modulus of 3.5 GPa), but a reduction in elongation (2.2%) which represents a loss of ductility. The coconut shell powder (CSP) composite demonstrates moderate improvement in stiffness and flexural strength with a Young's modulus of 2.9 GPa and flexural modulus of 3.3 GPa. But it has the highest impact strength of 24 kJ/m². This is because the natural filler is capable of energy absorption and retards the crack propagation rate due to the lignocellulosic structure. In summary, these results suggest that although nano fillers (CNP and CuNP) improve the composite's stiffness and strength, they compromise its ductility and slightly decrease its impact strength relative to natural fillers. On the other hand, CSP provides a better overall performance with enhanced impact resistance, and is recommended for tough applications.

Table 2 Thermal and Physical Properties

Composite Type	Decomposition Temp (°C)	Glass Transition Temp (°C)	Density (g/cm^3)
Neat Epoxy	320	75	1.15
Banana Fiber Composite	340	82	1.20
+ CSP	355	88	1.25
+ CNP	390	105	1.28

Table 2 shows the thermal and physical properties of the composites, such as decomposition temperature, glass transition temperature (Tg) and density. It is evident that the banana fiber and fillers enhance the thermal properties of the epoxy composites. The decomposition temperature rises from 320°C for pure epoxy to 340°C for the banana fiber composite, suggesting improved thermal stability of the natural fiber composite. This pattern is further enhanced with the addition of fillers, with the highest decomposition temperature found in the carbon nano powder composite (390°C). This substantial increase is due to the barrier effect of nano fillers, which prevent thermal degradation and improve thermal stability. The copper nano powder composite also exhibits enhanced thermal resistance (375°C) and the coconut shell powder composite shows limited improvement (355°C). The glass transition temperature (Tg) also shows a similar improvement, with higher Tg values for composites filled with fillers. The CNP composite shows the highest Tg (105°C), suggesting the reduction in the mobility of polymer chains, due to the strong filler-matrix interaction. This demonstrates the beneficial role of nano fillers in enhancing thermal properties. As for the physical properties, fillers increase density. The CuNP composite has the greatest density (1.35 g/cm^3), as expected for a metallic filler. The CSP and CNP composites show moderate increase in density and relatively low weight compared to metallic fillers. The findings suggest that nano fillers, especially carbon nano powder, play a major role in improving thermal stability and glass transition temperature whereas metallic fillers add to the density and structural strength of the composite. Natural fillers offer moderate thermal properties, while being environmentally friendly and lightweight.

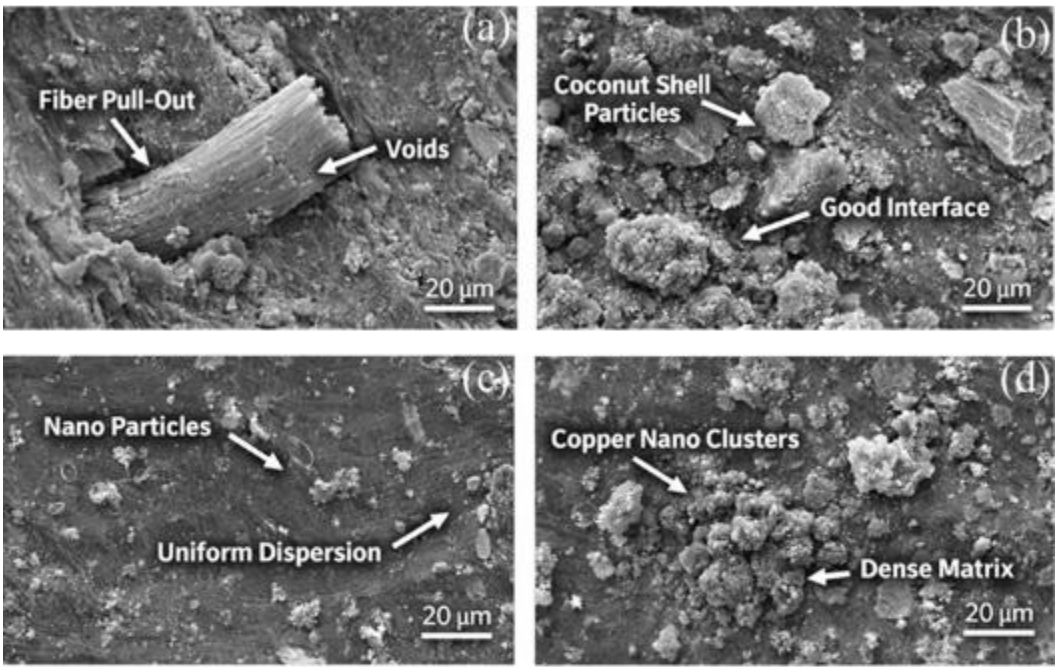

Figure 2 SEM SEM (a) Banana Fiber Composite, (b) With Coconut Shell Powder, (c) With Carbon Nano Powder, (d) With Copper Nano Powder

The scanning electron microscopy (SEM) of the unreinforced banana fiber reinforced epoxy composite is shown in Figure 2(a). The image exhibits fiber pull-out, voids and micro-cracks, suggesting the presence of typical degree of adhesion between the banana fibers and the epoxy matrix. These indicate poor stress transfer and hence lower mechanical properties. In Figure 2(b), the SEM image of the composite filled with coconut shell powder (CSP) is shown. There is a clear improvement in the microstructure, with fewer voids and improved dispersion of the filler. The CSP promotes better bonding between the fiber and matrix, leading to a denser structure. This aids in better mechanical performance, especially toughness. The composite with carbon nano powder (CNP) is shown in Figure 2(c). The picture shows the uniform nano-scale dispersion without any major flaws like cracks or voids. The good bonding between the nano filler and epoxy matrix allows for effective stress transfer, which results in the excellent mechanical and thermal properties of this composite. In Figure 2(d), the SEM image of the composite with copper nano powder (CuNP) is shown. It appears to be dense and nearly uniform, but there are small aggregates of copper nano particles. The matrix-filler bonding is strong but these may also serve as stress points that cause slight reduction in the ductility.

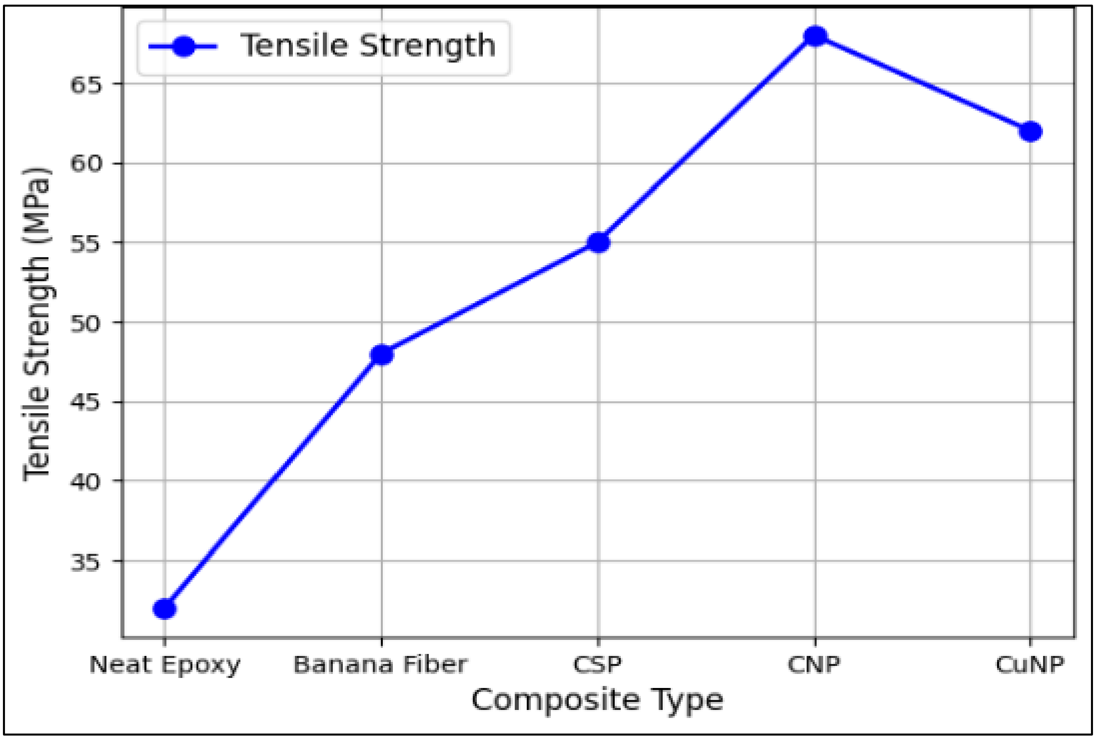

Figure 3 Tensile Strength vs Composite Type

Figure 3 shows the comparison of the tensile strength of different composite types. The presence of banana fibers greatly increases the strength compared to pure epoxy, owing to improved load support. The carbon nano powder (CNP) composite has the highest tensile strength among the filler-reinforced composites. This is due to the nano filler used and the good bonding between the filler and the matrix that allows effective stress transfer. The coconut shell powder (CSP) composite exhibits a slightly increased tensile strength, which is attributed to improved matrix-filler bonds, but is not as pronounced as with nano fillers. The copper nano powder (CuNP) composite also exhibits an increase in strength, but has a moderate effect due to slight agglomeration.

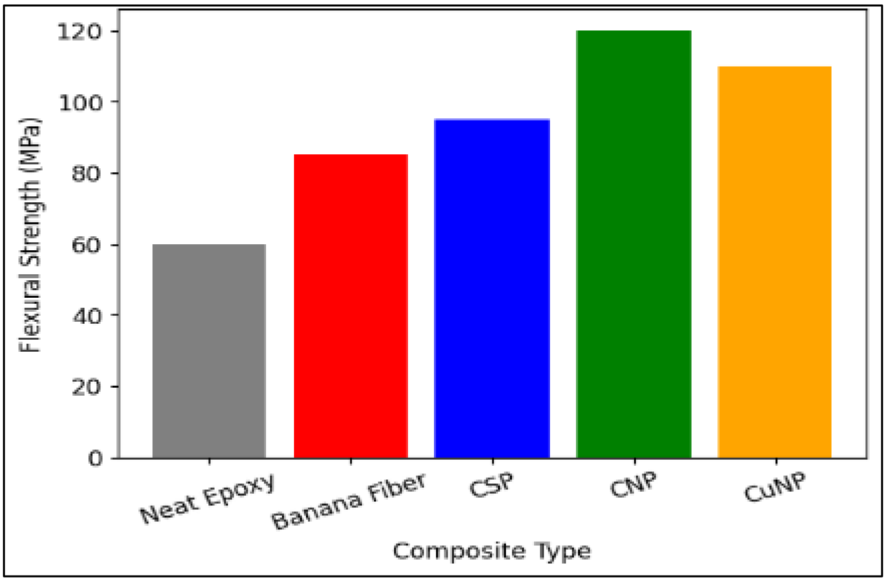

Figure 4 Flexural Strength Comparison

The flexural strength of the composites is shown in Figure 4. It's clear that all composites are superior to pure epoxy, showing higher resistance to bending. The composite containing carbon nano powder exhibits maximum flexural strength and is due to the crack bridging ability and proper dispersion of nano fillers in the epoxy matrix. The composite with coconut shell powder has improved flexural performance due to improved interfacial bonding, but its influence is not as significant as nano fillers. Similarly, flexural strength is improved for the copper nano powder composite; however, this is slightly restricted due to the presence of particle agglomeration.

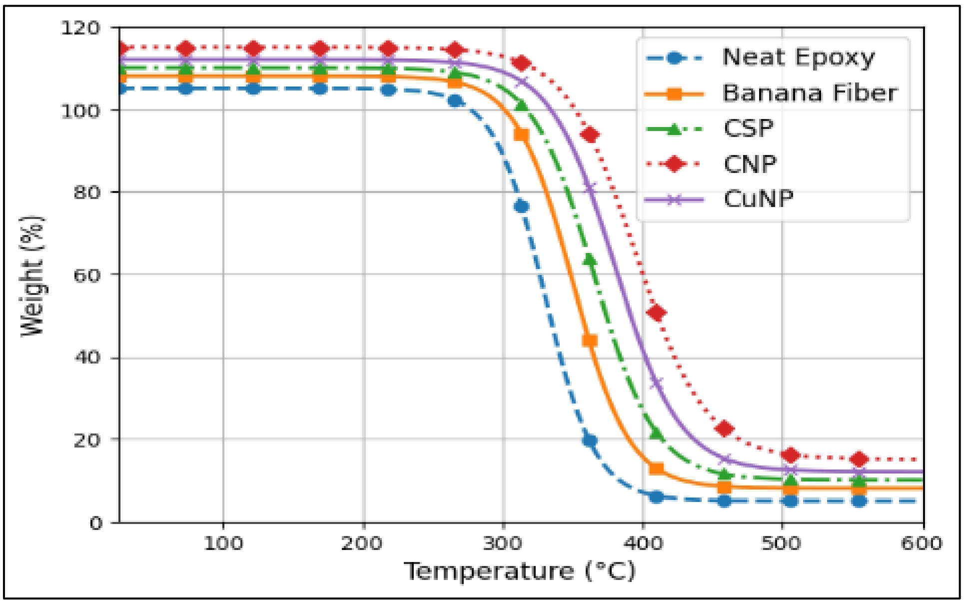

Figure 5 Thermal Stability (TGA Curve**)**

The thermogravimetric analysis (TGA) curves of the different composites showing their thermal stability are presented in Figure 5. From the figure, it is clear that the addition of fillers improves the thermal stability of the epoxy resin. Banana fiber composite exhibits a higher decomposition temperature than neat epoxy due to the addition of lignocellulosic fiber fillers which add to the thermal stability. The composite with carbon nano powder (CNP) modification shows the best thermal stability. The barrier effect and high thermal conductivity of nano fillers delay the degradation, thereby improving the thermal stability. The coconut shell powder (CSP) composite also shows enhanced thermal stability, but less than nano fillers. The copper nano powder (CuNP) composite also exhibits considerable improvement, but is marginally lower than CNP due to varying mechanisms of thermal dissipation and dispersion.

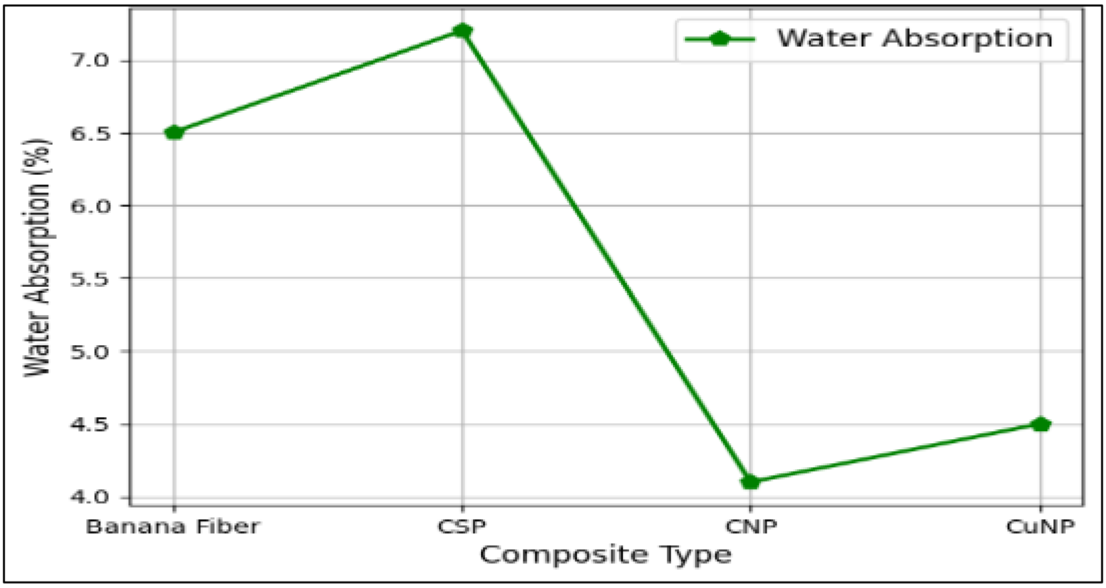

Figure 6 Water Absorption Comparison

The water absorption of the composites is shown in Figure 6. The findings suggest that composites with natural fillers, such as coconut shell powder, have higher water absorption. This can be attributed to the water absorbing property of lignocellulosic fillers. On the other hand, composites containing nano fillers, like carbon nano powder and copper nano powder, exhibit lower moisture absorption. This is likely due to the increased density of the matrix and the reduction in pores, reducing the water absorption by the composites. Thus, the addition of nano fillers improves the resistance of composites to water, enabling them to be used in humid conditions.

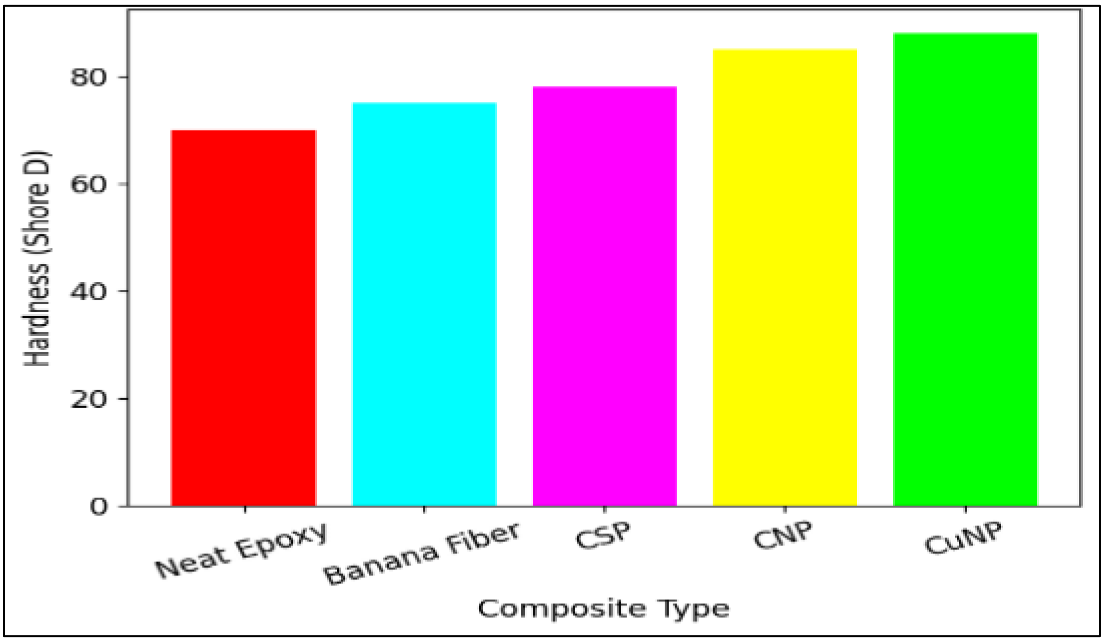

Figure 7 Hardness vs Fillers

Figure 7 shows the hardness of different composite samples. It can be seen that the composites with fillers show a significant improvement in hardness when compared with pure epoxy. This is attributable to the increased stiffness and reduced surface deformation of the composite due to the fillers. The composite using copper nano powder (CuNP) as fillers has the highest hardness of all the composites investigated. This is due to the nature of copper nanoparticles, which are hard and metallic in nature, and enhance surface resistance. The carbon nano powder composite exhibits a significant improvement in hardness due to its strengthening effect. The coconut shell powder composite contributes to the hardness of the composite moderately, due to the role of natural fillers in improving rigidity.

In summary, the findings in this article show that the incorporation of banana fibers into epoxy composites greatly improves the base properties, while the addition of compatible fillers further modifies the properties. Carbon nano powder shows the best improvement in strength and thermal properties due to load transfer and nano-reinforcement. Coconut shell powder enhances impact strength but also moisture uptake due to its hygroscopic properties. Copper nano powder contributes to increased hardness and stiffness, but slight agglomeration leads to reduced ductility. The integrated interpretation of the mechanical, thermal and morphological data confirms that the filler is essential to tailor the composite for various engineering applications.

5. Conclusion

The present research evaluated mechanical, thermal and morphological properties of biodegradable banana fiber reinforced epoxy composites with compatible fillers, such as coconut shell powder (natural), carbon nano powder (synthetic) and copper nano powder (metallic). The findings show that the reinforcement of epoxy composites with banana fibers improves their performance, validating the use of banana fibers as environmentally friendly reinforcements. The mechanical testing shows that fillers further enhance the composite properties. Carbon nano powder was found to be the most effective filler in improving the tensile and flexural strength of the composites because of its large specific surface area and excellent load transfer capability. Coconut shell powder improved impact strength and toughness, and is an environmentally friendly filler. Copper nano powder resulted in improved hardness and stiffness, albeit with reduced ductility. Thermal stability analysis revealed that filler modified composites have improved thermal resistance than the pure composite. The improved temperature of degradation and residual mass indicates the successful incorporation of fillers in improving the thermal stability, with the greatest increase found in carbon nano powder-filled composites. SEM analysis showed improved interfacial adhesion, filler distribution, and lower voids in modified composites, which is responsible for improved mechanical and thermal properties. In conclusion, the research demonstrates that the combination of banana fiber with suitable fillers can be used to enhance the properties of biodegradable composites. Carbon nano filler was found to be the most efficient filler for high-performance attributes, while coconut shell powder is an eco-friendly and economical alternative. The hybrid composites have great potential in lightweight construction, automotive parts and sustainable engineering materials. Potential future research could involve the optimized use of filler concentrations, use of hybrid fillers (combination of fillers) and study on the durability and environmental degradation behaviour of these composites to improve the performance of the composites.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Alshammari, B. A., Saba, N., Alotaibi, M. D., Alotibi, M. F., Jawaid, M., & Alothman, O. Y. (2019). Evaluation of Mechanical, Physical, and Morphological Properties of Epoxy Composites Reinforced with Different Date Palm Fillers. *Materials (Basel, Switzerland)*, *12*(13), 2145. https://doi.org/10.3390/ma12132145

[2] M. A. H.Sarker, M. S.Chowdhury, M. S.Oliullah, et al., “Mechanical and Morphological Characterization of Hybrid Epoxy Composites Reinforced With Agricultural Waste Fibers,” SPE Polymers6, no. 3 (2025): e70016, https://doi.org/10.1002/pls2.70016.

[3] Motaleb, K. Z. M. A., Ahad, A., Laureckiene, G., & Milasius, R. (2021). Innovative Banana Fiber Nonwoven Reinforced Polymer Composites: Pre- and Post-Treatment Effects on Physical and Mechanical Properties. *Polymers*, *13*(21), 3744. https://doi.org/10.3390/polym13213744

[4] Harsh Sharma, Ajay Kumar, Sravendra Rana, Nanda Gopal Sahoo, Muhammad Jamil, Rajeev Kumar, Shubham Sharma, Changhe Li, Abhinav Kumar, Sayed M. Eldin, Mohamed Abbas, Critical review on advancements on the fiber-reinforced composites: Role of fiber/matrix modification on the performance of the fibrous composites, Journal of Materials Research and Technology, Volume 26, 2023, Pages 2975-3002, https://doi.org/10.1016/j.jmrt.2023.08.036.

[5] Balaji, A., Sivaramakrishnan, K., Karthikeyan, B., Purushothaman, R., Swaminathan, J., Kannan, S., Udhayasankar, R., & Haja Madieen, A. (2019). Study on mechanical and morphological properties of sisal/banana/coir fiber-

reinforced hybrid polymer composites. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41*.

[6] Govinda, Chinglenthoiba, C., Jagota, V., & Katiyar, J. K. (2026). Role of Nano Fillers on Mechanical Properties of Reinforced Natural Fibers Epoxy Composites: An Overview. *Journal of Natural Fibers*, *23*(1). https://doi.org/10.1080/15440478.2026.2619016

[7] Yue, H.; Zheng, Y.; Zheng, P.; Guo, J.; Fernández-Blázquez, J.P.; Clark, J.H.; Cui, Y. On the Improvement of Properties of Bioplastic Composites Derived from Wasted Cottonseed Protein by Rational Cross-Linking and Natural Fiber Reinforcement. *Green Chem.* **2020**, *22*, 8642–8655

[8] Santhanam, V.; Dhanaraj, R.; Chandrasekaran, M.; Venkateshwaran, N.; Baskar, S. Experimental Investigation on the Mechanical Properties of Woven Hybrid Fiber Reinforced Epoxy Composite. *Mater. Today* **2020**, *37*, 1850–1853.

[9] Lotfi, A.; Li, H.; Dao, D.V.; Prusty, G. Natural Fiber–Reinforced Composites: A Review on Material, Manufacturing, and Machinability. *J. Thermoplast. Compos. Mater.* **2021**, *34*, 238–284.

[10] Lotfi, A.; Li, H.; Dao, D.V.; Prusty, G. Natural Fiber–Reinforced Composites: A Review on Material, Manufacturing, and Machinability. *J. Thermoplast. Compos. Mater.* **2021**, *34*, 238–284.

[11] Zhang, W.; Wu, J.; Gao, L.; Zhang, B.; Jiang, J.; Hu, J. Recyclable, Reprocessable, Self-Adhered and Repairable Carbon Fiber Reinforced Polymers Using Full Biobased Matrices from Camphoric Acid and Epoxidized Soybean Oil. *Green Chem.* **2021**, *23*, 2763–2772.

[12] Pan, H.; Wang, Z.; Nie, S.; Yu, L.; Chang, Y.; Liu, Z.; Xu, J.; Fu, Y. Novel Green Three-Constituent Natural Deep Eutectic Solvent Enhances Biomass Extraction from Acanthopanax Senticosus and the Extraction Mechanism. *ACS Sustain. Chem. Eng.* **2021**, *9*, 8835–8847.