STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Issue 2, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Experimental Investigation of Hybrid Natural Fiber Reinforced Epoxy Composites Using Banana and Sugar Palm Fibers

Shekhar Rahane[1], Krupal Pawar[2,]*, Prafull Dhole[3], Vishwajit Bhagwat[4], Balaprasad Kurpatwar[5]

Abstract

This paper is a research study that examines the mechanical and morphological properties of hybrid natural fiber reinforced epoxy composites manufactured from banana fibers (BF) and sugar palm fibers (SPF). Because the use of sustainable, lightweight, and cost effective materials in engineering continues to grow, many engineers are looking at the possibility of utilizing natural fiber reinforced polymer composites as alternatives to traditional man-made fiber composites. Hybrid composite laminate samples were produced by hand lay-up technique and tested to determine how the combined effects of BF length (6mm, 12mm, 18mm) and SPF weight ratio affect the mechanical properties of the hybrid composite. Tensile strength, flexural strength, and impact resistance were determined according to ASTM D638, ASTM D790, and ASTM D256 respectively to provide consistent and reliable test data. Scanning Electron Microscopy (SEM) testing was performed to evaluate the fracture surface and microstructure of each sample. The SEM images indicated stronger fiber-matrix interfacial bonding than observed in either individual BF or SPF samples, and less fiber pullout was observed in the hybrid samples, which indicates better stress transfer efficiencies. It was demonstrated through this study that the banana/sugar palm hybrid composite will have greater mechanical properties than its individual BF and SPF counterparts. The optimal hybrid configuration resulted in a tensile strength of approximately 25MPa and a flexural strength of approximately 58MPa, which represents a 30-40% increase in these properties over neat epoxy resin. The results indicate the synergistic effect of hybridizing banana and sugar palm fibers and provides evidence that banana-sugar palm hybrid composites have potential for manufacturing sustainable lightweight structural components in various engineering applications such as automotive, construction, and packaging.

***Author for Correspondence**
Krupal Pawar
E-mail: krupalpawar@gmail.com

[1]Assistant Professor, Department of Basic Sciences, Nutan Maharashtra Institute of Engineering and Technology, SPPU, Pune, Maharashtra, India
[2]Assistant Professor, Department of Mechanical Engineering, Rajiv Gandhi College of Engineering, Karjule Harya, SPPU, Ahilyanagar, Maharashtra, India
[3]Assistant Professor, Department of Automation & Robotics, MGM, College of Engineering, Nanded, Maharashtra, India
[4]Assistant Professor, Department of Mechanical Engineering, TSSM's Bhivarabai Sawant College of Engineering & Research, Polytechnic, Narhe, Pune, Maharashtra, India
[5]Assistant Professor, Department of Mechanical Engineering, Adsul Technical Campus, SPPU, Chas, Ahilyanagar, Maharashtra, India

Received Date: March 17, 2026
Accepted Date: March 25, 2026
Published Date: April 11, 2026

Citation: Shekhar Rahane, Krupal Pawar, Prafull Dhole, Vishwajit Bhagwat, Balaprasad Kurpatwar. Experimental Investigation of Hybrid Natural Fiber Reinforced Epoxy Composites Using Banana and Sugar Palm Fibers. Journal of Polymer & Composites.2026;14(2):195–205p.

Keywords: Banana fiber composite, Sugar palm fiber, Hybrid composite, Flexural strength, Tensile strength, Impact strength, Scanning electron microscopy, Hand lay-up, Epoxy matrix

INTRODUCTION

The global push for sustainable engineering has generated a lot of research into natural fiber reinforced polymer (NFRP) composites to replace synthetic fiber composites in traditional applications. High-strength, stiffening fibers embedded in a polymer matrix create fiber-reinforced polymers (FRPs) that outperform other composite materials based upon a number of factors including specific strength and specific stiffness, thus making them very desirable for structural applications [1]. Unfortunately, the environmental burdens created through the production and disposal of glass and carbon fibers has stimulated the investigation of environmentally friendly reinforcements [2, 3]. Natural fibers are categorized as either mineral-based (asbestos), animal-based (silks and wools) or plant-based (jute, hemp, sisal, coconut, banana and sugar palm). The largest body of literature relates to plant-based fibers due to their relatively low densities, renewable nature, biodegradable characteristics, and competitive mechanical properties when compared to those found in other fibers [4, 5]. Several recent studies demonstrate that, with proper surface treatment to enhance fiber–matrix bonding, plant-based fibers may be able to support tensile moduli and tensile strengths sufficient for use in semi-structural applications [6, 7].

Hybridization utilizing two or more discrete fiber types in a single matrix is one of the most popular approaches used today to reduce the inherent shortcomings of individual natural fibers, including high moisture absorption and relatively lower stiffness than many man-made fibers. Hybridization provides the composite design engineer the flexibility to alter the mechanical properties of the composite based upon the type of fiber used, fiber orientation, and fiber weight fraction [8, 9]. Some examples of notable hybrid combinations studied in the literature include jute/glass [10], kenaf/glass [2], oil palm/jute [11] and flax/epoxy [12] composites. Musa sapientum, commonly known as banana fibers, exhibit tensile strengths of approximately 529–914 MPa and Young's moduli of 27–32 GPa, however, the properties exhibited at the composite level will be highly dependent upon processing conditions [13]. Arenga pinnata, or sugar palm fibers, are a new generation of reinforcement material that is characterized by its relatively low density of 1.21 g/cm^3 and make them an attractive option for use in lightweight applications [14]. Although there is increasing interest in using each of the individual fibers, the literature contains minimal information about banana-sugar palm hybrid epoxy composites and specifically the synergies associated with varying the proportions of each fiber. This study aims to address the knowledge gaps identified above by producing hybrid banana fiber/sugar palm fiber epoxy composites with varying fiber length and weight ratio and testing their tensile, flexural and impact properties. In addition to the property evaluations, scanning electron microscopy (SEM) will be utilized to evaluate the fracture morphology and quality of the fiber-matrix interface. The results of the study will help contribute to the development of cost effective, eco-friendly composite materials that can be used for lightweight structural applications.

LITERATURE REVIEW

A large amount of research has evaluated the mechanical characteristics of natural fiber composite materials as well as hybrid composites using both single fiber and hybrid configurations. In addition to identifying the effects of surface treatments and hybridization on the mechanical performance of natural fiber-polymer composites, Ratna Prasad and Mohana Rao [5] indicated that these two approaches provide the highest degree of improvement in fiber-matrix compatibility. Misri *et al.* [15] evaluated woven glass/sugar palm fiber reinforced unsaturated polyester hybrid composites made from compression molded composites. They found that hybridizing with glass fibers resulted in significant improvements in tensile and impact strength over those measured for the same type of composites produced using only sugar palm fibers. This demonstrates the potential for a hybrid effect to be utilized in this specific material system. Additionally, Nurazzi et al. [16] provided additional information regarding the evaluation of sugar palm fiber composites and pointed out the effectiveness of sodium hydroxide (NaOH) in alkali treatment to decrease moisture content and improve fiber-matrix bond formation. Jawaid et al. [17] investigated oil palm empty fruit bunch (EFB), jute fiber and epoxy hybrid composites made using the hand lay-up process. Their findings demonstrated that the best flexural strength was achieved with EFB-Jute fiber ratios of 1:4 over composites that contained only oil palm fibers; however, pure EFB composites displayed better impact energy absorption, illustrating the complexity of fiber type and failure mechanisms.

Furthermore, the characterization of banana fiber composites has also been reported in numerous studies. Rao et al. [1] assessed goat hair/banana fiber hybrid composites reinforced with a polyester matrix and demonstrated a positive hybrid effect in terms of tensile properties when optimal fiber weight fractions were selected. Hari et al. [6] investigated banana-coir hybrid composites through experimental means and finite element analysis, and demonstrated that short fiber lengths and weight fractions had strong influences on both tensile and flexural properties. Mohammed et al. [18] created sugar palm fiber

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

reinforced thermoplastic polyurethane composites and demonstrated excellent crack resistance for specimens 250 mm in length; therefore, they may serve as a basis for comparisons with systems containing thermosets. Chaudhary and Ahmad [4] wrote a detailed review of plant fiber reinforced thermoset polymers; specifically, they stated that epoxy matrices have better mechanical properties and bonding than polyester matrices due to low cure shrinkage and superior chemical resistance. Most recently, Jumaidin et al. [19] evaluated the physical and mechanical properties of thermoplastic starch composites reinforced with sugar palm fibers, while Praveen Kumar et al. [20] reviewed the characterization of sugar palm nanocrystalline cellulose reinforced composites, and demonstrated that sugar palm is a versatile reinforcing agent used in multiple types of matrix systems.

Further, there is a substantial amount of data available on the properties and applications of each of the individual plant based composite systems, however there has been very little done to develop hybrid composite systems that will utilize the benefits of two or more natural fiber composite materials to create a composite system that is either stronger and/or lighter than either of the individual composite systems.

The banana fiber (Musa sapientum) has some unique properties that would make it an excellent candidate for use as a polymer composite reinforcement. The banana fiber exhibits a good cellulose content of 60–65%, which provides it with its good mechanical performance; along with a low density of about 1.35g/cm^3, which makes it suitable for light weight applications [21]. Also, the surface morphological structure of banana fibers consists of microfibrils that are arranged at a low spiral angle. This arrangement provides for an effective way for the stresses developed during testing to be transferred into the polymer matrix. Similarly, the sugar palm fibers (Arenga pinnata), also provide a favorable reinforcement characteristic. Some of the other favorable characteristics include a high cellulose content; good thermal stability; a low density of 1.21g/cm^3[14]; and a hydrophilic nature due to the presence of the hydroxyl groups that exist in the cellulose and hemicellulose. When surface treatments are used that take advantage of these hydrophilic groups, they facilitate the formation of a bond between the polymer matrix and the fibers [22].

When comparing the mechanical properties of banana fibers and sugar palm fibers, they show similar and different characteristics. Generally speaking, banana fibers exhibit a higher tensile strength (529 – 914MPa at the fiber level) and a larger Young's Modulus (27-32GPa) than do sugar palm fibers. However, sugar palm fibers exhibit lower tensile strength (190 – 290MPa) but have a notably larger strain to failure (elongation at break ~5.75%) [13, 14]. In terms of the composite level, Palanisamy and Kalimuthu [22] found that the mechanical properties of natural fiber composites were influenced by fiber loading and length. Specifically, the tensile and flexural properties of the composites exhibited a strong relationship to the aspect ratio of the fibers. On the other hand, sugar palm fibers contributed to a composite exhibiting superior energy absorption and impact resistance due to their increased ductility. The combination of the mechanical advantages of each type of fiber is the basic premise of hybridizing the two fiber types. Banana fibers will provide the stiffening and tensile reinforcing to the composite, while sugar palm fibers will add the toughness and impact resistance. Together, this hybrid composite will exhibit a more well-rounded mechanical property profile than either fiber could provide independently [23].

MATERIALS AND METHODOLOGY

Raw Materials

The banana fibers were extracted from the pseudo stems of Musa sapientum plants that were sourced locally. The sugar palm fibers (SPF) were obtained from Arenga pinnata trees grown in Maharashtra, India. The epoxy resin utilized was LY556 (bisphenol A diglycidyl ether, DGEBA) mixed with the hardener HY951 (triethylenetetramine, TETA) at a weight ratio of resin to hardener of 10:1 as is specified by the manufacturer. Figure 1 shows the natural fibers that were collected; and Table 1 lists the major physical characteristics of these fibers.

Figure 1 (a, b). Collected natural fibres.

Table 1. Physical properties of banana fibers and sugar palm fibers [13, 14].

Physical property	Banana fiber	Sugar palm fiber
Density (g/cm³)	1.35	1.21
Young's Modulus (GPa)	3.48	3.70
Tensile Strength (MPa)	54	15.5
Flexural Modulus (GPa)	2–5	—
Elongation at Break (%)	1.5–9	5.75
Moisture Absorption (%)	10–15	~20

Fiber Preparation and Surface Treatment

The sugar palm fiber (SPF) was cleaned and purged of surface contaminants by washing it in distilled water and drying it in a circulating oven under air flow at 60°C for 48 hours. The dried sugar palm fiber (SPF) was crushed and pulverized into fine powder form using a plastic crusher and then passed through a sieve to produce SPF particulate in the particle diameter range of 125–250 µm. Similar procedures were used to dry banana fibers, cutting them to lengths of 6 mm, 12 mm, and 18 mm. Prior to the fabrication of composites all fibers were dried in an oven at 60°C for 24 hours to prevent excess moisture from forming voids during curing [5] as would be expected when fibers are subjected to an alkali treatment.

Mould Preparation

An aluminum mold with internal dimensions of 200 x 200 x 50 mm was developed in order to create flat composite laminate panels. Prior to molding, each surface of the mold was first cleaned with acetone; then each surface was coated with a mold release coating (polyvinyl alcohol) and allowed to dry for 30 minutes to ensure that the molded panel would easily be removed from the mold. The mold design included a means to resist the compressive force applied during consolidation without undergoing any deformation.

Composite Fabrication

Hybrid composite laminates were manufactured via a manual hand layup process. Banana fibers of varying length (6 mm, 12 mm, 18 mm) were individually combined with SPF particles (125–250 µm) at various weight percentages of SPF/BF; specifically, 40% SPF/60% BF, 50% SPF/50% BF, and 60% SPF/40% Banana. The total fiber content was held constant at 30% by weight of the final composite. The epoxy–hardener mixture was then prepared, and layered on top of the fiber blend and manually consolidated to eliminate air pockets. The laminates were then allowed to cure at ambient temperature (28±2°C) for 24 h, and then post-cured at 60°C for 2 h. After curing, the laminates were removed from the mold and test specimens were created via a precision diamond tipped saw to meet the specifications outlined within the respective ASTM standards. Reference single fiber composites (Banana/Epoxy and Sugar Palm/Epoxy) and neat epoxy specimens were produced in accordance with the exact manufacturing process used for the hybrid composites.

TESTING METHODOLOGY

Tensile Test

The tensile properties of the composites were assessed according to ASTM D638 (Standard Test Method for Tensile Properties of Plastics). A UTM was used as the test apparatus; the crosshead rate of the UTM was set at 2 mm/min. Five or more dog-bone shaped tensile test samples were evaluated for each composite configuration. The average value from these tests is reported below (Table 2).

Flexural Test

Three-point bending experiments were performed according to ASTM D790-03 (Standard Test Method(s) for Flexural Properties of Un-reinforced and Reinforced Plastics) on a Universal Testing Machine (UTM) using a 16:1 span-to-thickness ratio and a 60 mm total span length. The samples used were rectangular-shaped and had the following measurements; width = 80 mm, thickness = 3.2 mm, height = 12.7 mm. The flexural strength and the flexural modulus were determined from the force-displacement curves obtained during testing.

Impact Test

The Charpy impact test is according to ASTM D256 (Standard Test Methods for Determination of the Izod Pendulum Impact Resistance of Plastics). The samples were made of rectangular shapes (80 mm × 12 mm × 6 mm) and contained a notch of dimensions (2 mm deep). Each specimen had at least five for each test configuration and an average of the results were reported as J/m.

Scanning Electron Microscopy (SEM)

The fracture surface on tensile tested samples was evaluated using a Scanning Electron Microscope (SEM) that operated at an accelerating voltage of 10 KV. Gold coating was applied as a thin layer before the examination to avoid charge buildup. SEM images were used to evaluate the mechanism of failure, the quality of the interface between fibers and matrix, the pull out of fibers from the matrix, and the mechanisms of crack propagation.

RESULTS AND DISCUSSION

Tensile Properties

Figures 2 and 3 present the tensile strength and tensile modulus of all composite configurations. The neat epoxy showed a tensile strength and modulus of about 15 MPa and 2.5 GPa respectively. The single-fiber composites with sugar palm and banana fibers showed tensile strengths of 24 MPa and 19 MPa and tensile moduli of 2.9 GPa and 2.7 GPa respectively. Hybrid banana/sugar palm composites showed tensile strengths of 16 MPa, 19 MPa and 25 MPa for banana fiber lengths of 6 mm, 12 mm and 18 mm respectively; and corresponding tensile moduli of 2.5 GPa, 3.0 GPa and 3.2 GPa respectively. The higher performance of the 18 mm fiber length configuration is consistent with the idea of a critical fiber length below which efficient load transfer from the matrix to the fiber cannot occur [8]. Sugar palm particles also acted as secondary stress concentrators which arrested crack growth and contributed to the banana fibers' ability to carry loads. At 18 mm banana fiber length, the 60 wt.% banana fiber / 40 wt.% SPF composite configuration demonstrated the highest tensile properties and are therefore consistent with results of Rao et al. [1], which stated that when the optimal ratio of hybrid fibers is achieved, tensile performance is enhanced by a synergistic effect.

Flexural Properties

Table 3 and Figure 4 display the flexural strength and flexural modulus for the analyzed composites. Neat epoxy exhibited a flexural strength of 23 MPa, and flexural modulus of 2.5 GPa. The banana/sugar palm hybrid composite showed an average flexural strength of 58 MPa, and flexural modulus of 3.1 GPa, indicating a significant increase of about 152% and 24% compared to neat epoxy, respectively (Figure 5). The improvement in flexural performance in the hybrid composite was primarily due to the improved stress distribution through the complementary mechanical characteristics of the two fiber species. Sugar palm fibers are known for their high elongation at break (5.75%) which provides the capability of absorbing energy during bending, while banana fibers provided stiffness. This synergy corresponds to previous reports from Jawaid et al. [17], who reported on a similar effect of synergy of oil palm and jute fibers in hybrid epoxy composites. The gradual increase in flexural strength as a function of the length of the fibers (from 6 mm to 18 mm) is attributed to a better efficiency of the fiber-matrix interfacial stress transfer [9].

Impact Properties

The results of the impact strength of all composite systems are illustrated in Table 4 and Figure 6. Compared with 3 J of neat epoxy, 4 J of sugar palm/epoxy, and 6 J of banana fiber/epoxy, the hybrid banana/sugar palm showed an enhanced impact strength of 7 J. According to [18], the enhanced performance in terms of the dissipated energy due to plastic deformation of the sugar palm fibers and their larger elongation is considered as the reason behind the improved impact resistance of the hybrid composite system.

Water Absorption Behavior

Natural fiber reinforced polymer composites require careful attention to water absorption because when too much moisture enters a composite, it degrades the bond between the reinforcement (natural fibers) and the matrix (polymer). Additionally, water entering the composite may cause it to expand/contract or lose its original dimensions; however, the most detrimental effects of water absorption occur when a composite loses its mechanical properties. Natural fibers (such as banana and sugar palm) are naturally hydrophilic (absorbent to water) due to the presence of hydroxyl groups within their cellulosic components. Therefore, controlling moisture absorption is one of the major concerns when using natural fibers as composite reinforcement. As shown in Table 1, sugar palm fibers exhibit higher moisture absorption capabilities (about 20%) than banana fibers (about 10-15%) primarily due to higher hemicellulose content and the more porous structure of sugar palm fiber bundles. Sugar palm particulate additions to banana fiber hybrids can also modify the total moisture absorption potential of the composite by creating tortuous diffusion paths that slow the rate at which water molecules enter the composite matrix.

Water absorption has significant impacts beyond just the mechanical integrity of a composite. Water absorption will affect how stable the dimensions of a composite remain. Palaniappan et al. [24] demonstrated that the surface treatment of natural fibers with a sodium lauryl sulphate (SLS) surfactant can decrease the sensitivity of the fibers to moisture by reducing the amount of wax and hemicellulose on the surface of the fibers, thus increasing the number of cellulose surfaces available for bonding to the epoxy matrix. Ramasubbu et al. [25] demonstrated that adding inorganic filler phases to the epoxy matrix of natural fiber reinforced composites can reduce water absorption of the composite and improve mechanical properties. Similarly, the incorporation of waste-derived reinforcing fillers into thermoplastic composites has also been shown to enhance moisture resistance and dimensional stability

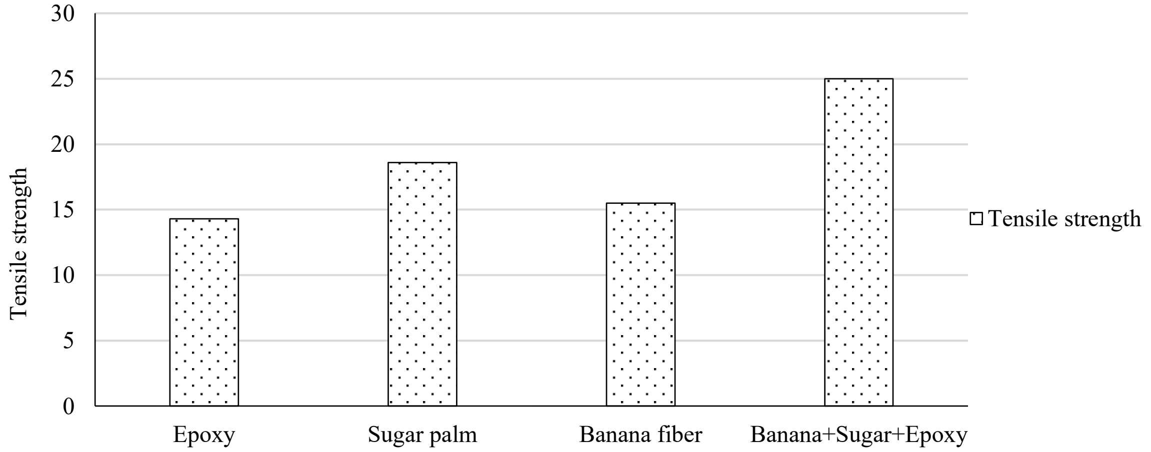

Figure 2. Tensile strength of hybrid composites.

Journal of Polymer & Composites
Volume 14, Issue 2
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

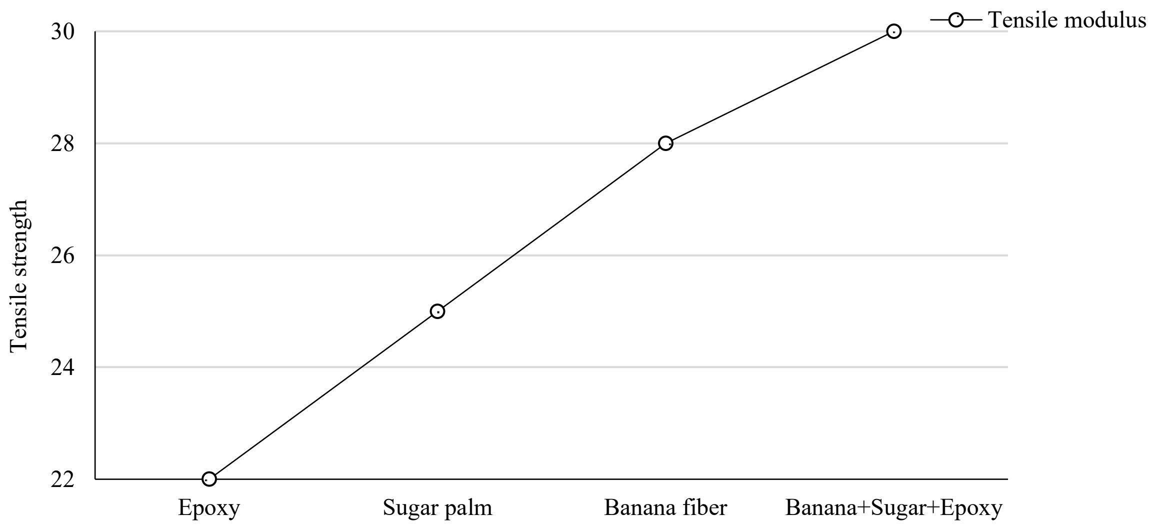

Figure 3. Tensile modulus of hybrid composites..

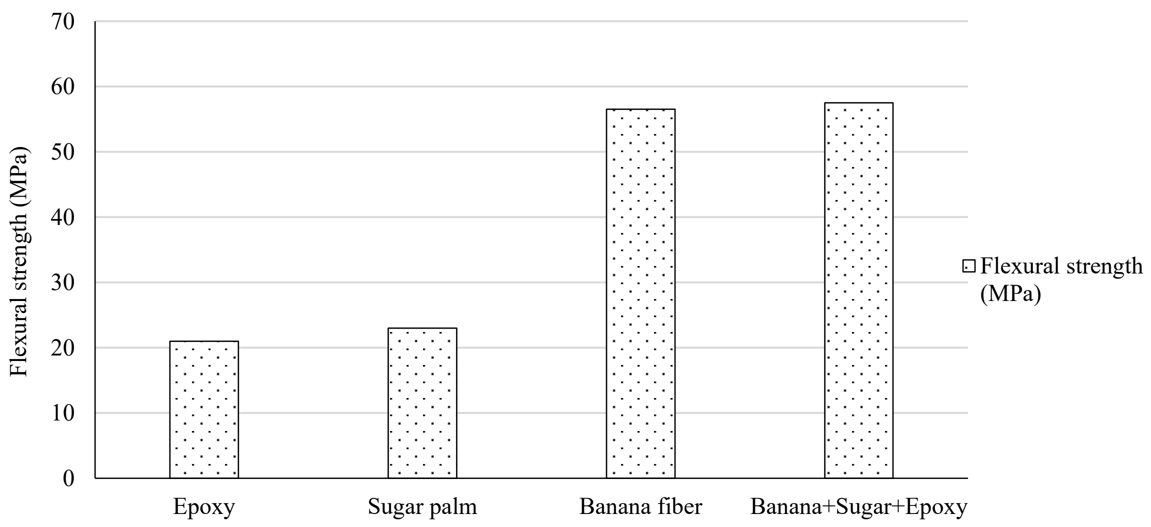

Figure 4. Flexural strength of composites.

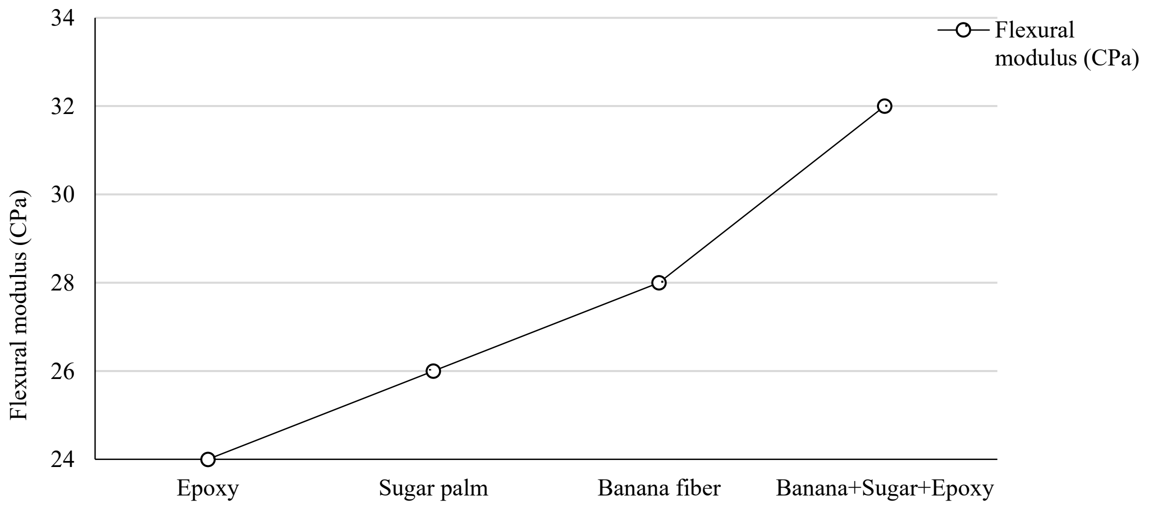

Figure 5. Flexural strength and flexural modulus of hybrid composites.

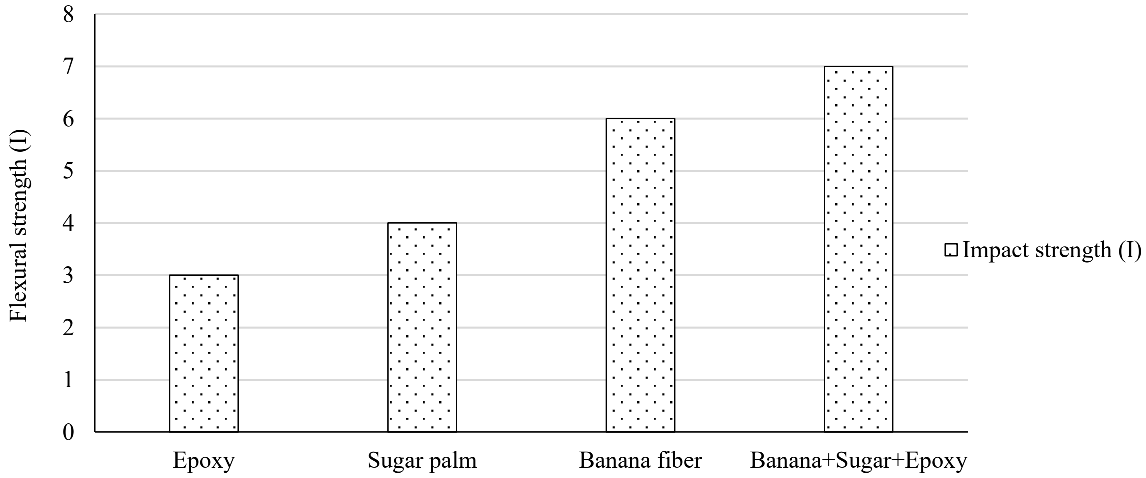

Figure 6. Impact strength of hybrid composites.

Table 2. Flexural strength and flexural modulus of composite specimens.

Composite Configuration	Flexural Strength (MPa)	Flexural Modulus (GPa)
Neat Epoxy	14.3	2.3
Sugar Palm / Epoxy	18.6	3.1
Banana Fiber / Epoxy	15.5	2.6
Banana Fiber + Sugar Palm / Epoxy (Hybrid)	25.0	3.3

Table 3. Flexural strength and flexural modulus of composite specimens (Detailed).

Composite configuration	Flexural strength (MPa)	Flexural modulus (GPa)
Neat Epoxy	23	2.5
Sugar Palm / Epoxy	56	2.9
Banana Fiber / Epoxy	24	2.7
Banana Fiber + Sugar Palm / Epoxy (Hybrid)	58	3.1

Table 4. Impact strength of composite specimens.

Composite Configuration	Impact Strength (J)
Neat Epoxy	3
Sugar Palm / Epoxy	4
Banana Fiber / Epoxy	6
Banana Fiber + Sugar Palm / Epoxy (Hybrid)	7

[26]. The pre-drying of both banana and sugar palm fibers at 60°C for 24 hours prior to composite fabrication was done to remove excess moisture from the fibers to reduce the likelihood of voids being formed at the fiber-matrix interface during the curing process. Future work should examine the long term hygrothermal aging of these hybrid composites under accelerated moisture exposure conditions to assess the ultimate durability consequences of water absorption on mechanical performance, as discussed by Mylsamy et al. [23].

SEM Fractography

The SEM micrographs from the fractured surfaces (Figures 7 & 8) show the failure modes of the banana fiber and sugar palm fiber composites separately. SEM images from single fiber banana fiber composites (Figure 7) clearly show the fiber pull-out and fiber-matrix debonding that occurred in the composites due to the relatively poor fiber-matrix interface bonding. Conversely, SEM images of hybrid composite (Figure 8) indicate less fiber pull out, lower void contents and a more even stress distribution than those of single fiber composites which is consistent with the experimental results of the mechanical properties of hybrid composites as compared to those of single fiber composites. The SEM images shown above are consistent with Ratna Prasad and Mohana Rao [5] which indicated that the hybrid composite exhibited better interfacial characteristics than single fiber composites due to the complimentary chemical surface states of the hybrid composite fibers. The crack path for sugar palm composites (Figure 8) has a tortuous path around the fiber bundles which indicates an increase in the fracture toughness of the hybrid composite as compared to that of the single fiber composite.

CONCLUSION

The hybrid banana–sugar palm composite demonstrates promising mechanical performance comparable to other natural fiber composites such as jute/epoxy systems, suggesting its potential for lightweight structural applications. The main findings of this study were:

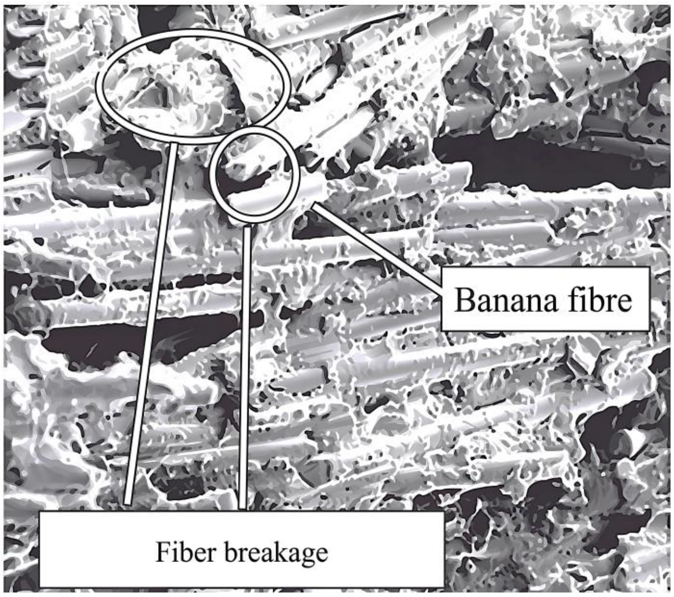

Figure 7. SEM Micrograph of Cracks Developed in the Banana Fiber.

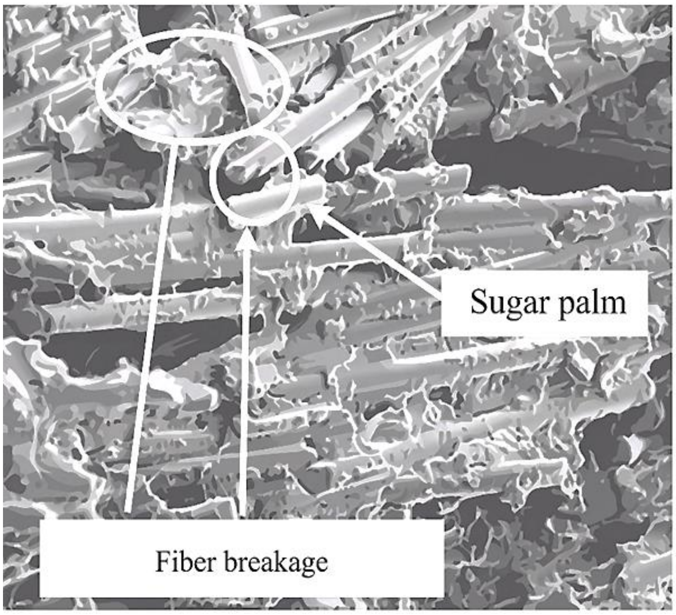

Figure 8. SEM Micrograph of Cracks Developed in the Sugar Palm.

i. Tensile strength of the hybrid composite was found to be 25 MPa with a tensile modulus of 3.2 GPa; both values are approximately 25–35% higher than those of the single-fiber composites;
ii. The flexural strength and modulus of the hybrid composite were measured at 58 MPa and 3.1 GPa, respectively; flexural strength of the hybrid composite was 152% higher than that of neat epoxy;
iii. Hybrid composite had an impact strength of 7 J, greater than both of the single-fiber configurations, showing increased energy absorption due to the complementary properties of banana and sugar palm fibers.
iv. SEM evaluation demonstrated that hybridization decreases fiber pullout and increases the quality of fiber/matrix interface; this is the primary mechanism contributing to the mechanical advantages of the hybrid composite.
v. Increased length of banana fibers, from 6 mm to 18 mm, resulted in consistent improvement of all mechanical properties; the increased length is believed to allow more efficient load transfer beyond the critical fiber length.

The banana-sugar palm hybrid epoxy composite appears to have potential application in various lightweight semi-structural applications including automotive interior paneling, packaging, sports equipment and low-load building components. Further research should include the effect of chemical surface treatments (alkali, silane), the hygrothermal aging characteristics and the fatigue responses of these composites to confirm their applicability to engineering applications.

Data Availability Statement

No datasets were generated or analyzed during the current study.

Conflict of Interest

The corresponding author declares, on behalf of all authors, that there is no conflict of interest.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

REFERENCES

1. Rao DN, Mukesh G, Ramesh A, Anjaneyulu T. Investigations on the mechanical properties of hybrid goat hair and banana fiber reinforced polymer composites. Mater Today Proc. 2020; 27: 1703–1707.
2. Kumar AP, Shunmugasundaram M, Sivasankar S, Sankar LP. Static axial crushing response on the energy absorption capability of hybrid Kenaf/Glass fabric cylindrical tubes. Mater Today Proc. 2020; 27: 783–787.
3. Sanjay MR, Madhu P, Jawaid M, et al. Characterization and properties of natural fiber polymer composites: A comprehensive review. J Clean Prod. 2018; 172: 566–581.
4. Chaudhary V, Ahmad F. A review on plant fiber reinforced thermoset polymers for structural and frictional composites. Polym Test. 2020; 91: Article 106792.
5. Ratna Prasad AV, Mohana Rao K. Mechanical properties of natural fiber reinforced polyester composites: Jowar, sisal and bamboo. Mater Des. 2011; 32(8): 4658–4663.
6. Hari T, Prasad D, Dharmalingam G, Raj P. Study of mechanical properties of banana-coir hybrid composite using experimental and FEM techniques. J Mech Eng Sci. 2013; 4: 518–531.
7. Prakash S, Paul RC. Mechanical properties of natural fiber (human hair) reinforced polymer composite. Asian J Res Soc Sci Humanit. 2016; 6: 2052.
8. Gunti R, Nadh B, Guduru R. Evaluating tensile properties of animal and hybrid fiber reinforced polyester composites. IOP Conf Ser Mater Sci Eng. 2018; 390: Article 012011.
9. Gupta MK, Choudhary N, Agrawal V. Static and dynamic mechanical analysis of hybrid composite reinforced with jute and sisal fibres. J Chin Adv Mater Soc. 2018; 6(4): 666–678.

10. Jawaid M, Abdul Khalil HPS, Abu Bakar A. Woven hybrid composites: Tensile and flexural properties of oil palm-woven jute fibres based epoxy composites. Mater Sci Eng A. 2011; 528(15): 5190–5195.
11. Coroller G, Lefeuvre A, Le Duigou A, et al. Effect of flax fibres individualisation on tensile failure of flax/epoxy unidirectional composite. Compos Part A Appl Sci Manuf. 2013; 51: 62–70.
12. Vijayakumar K, Rajmohan T, Palanikumar K, et al. The effect of fibre loading and graphene on the mechanical properties of goat hair fibre epoxy composite. IOP Conf Ser Mater Sci Eng. 2017; 282: Article 012018.
13. Ilyas RA, Sapuan SM, Ishak MR, Zainudin ES. Development and characterization of sugar palm nanocrystalline cellulose reinforced sugar palm starch bionanocomposites. Carbohydr Polym. 2018; 202: 186–202.
14. Ishak MR, Sapuan SM, Leman Z, et al. Sugar palm (Arenga pinnata): Its fibres, polymers and composites. Carbohydr Polym. 2013; 91(2): 699–710.
15. Misri S, Leman Z, Sapuan SM, Ishak MR. Mechanical properties and fabrication of small boat using woven glass/sugar palm fibres reinforced unsaturated polyester hybrid composite. IOP Conf Ser Mater Sci Eng. 2010; 11: Article 012015.
16. Nurazzi NM, Khalina A, Sapuan SM, Rahmah M. Development of sugar palm yarn/glass fibre reinforced unsaturated polyester hybrid composites. Mater Res Express. 2018; 5(4): Article 045308.
17. Jawaid M, Abdul Khalil HPS, Abu Bakar A. Mechanical performance of oil palm empty fruit bunches/jute fibres reinforced epoxy hybrid composites. Mater Sci Eng A. 2010; 527(29–30): 7944–7950.
18. Mohammed AAS, Bachtiar D, Siregar JP, et al. Physicochemical study of eco-friendly sugar palm fiber thermoplastic polyurethane composites. BioResources. 2016; 11(4): 9438–9451.
19. Jumaidin R, Sapuan SM, Jawaid M, et al. Characteristics of thermoplastic sugar palm starch/agar blend: Thermal, tensile, and physical properties. Int J Biol Macromol. 2016; 89: 575–581.
20. Praveen Kumar AP, Mohamed MN, Philips KK, Ashwin J. Development of novel natural composites with fly ash reinforcements and investigation of their tensile properties. Appl Mech Mater. 2016; 852: 55–60.
21. Manickaraj, K., Thirumalaisamy, R., Palanisamy, S., Ayrilmis, N., Massoud, E. E. S., Palaniappan, M., & Sankar, S. L. (2025). Value-added utilization of agricultural wastes in biocomposite production: Characteristics and applications. Annals of the New York Academy of Sciences, 1549(1), 72–91. https://doi.org/10.1111/nyas.15368
22. Palanisamy, S., & Kalimuthu, M. (2023). Effects of fiber loadings and lengths on mechanical properties of Sansevieria cylindrica fiber reinforced natural rubber biocomposites. Materials Research Express, 10(8), Article 085301. https://doi.org/10.1088/2053-1591/acefb0
23. Mylsamy, B., Aruchamy, K., Shanmugam, S. K. M., Palanisamy, S., & Ayrilmis, N. (2025). Improving performance of composites: Natural and synthetic fibre hybridisation techniques in composite materials—A review. Materials Chemistry and Physics, 334, 130439. https://doi.org/10.1016/j.matchemphys.2025.130439
24. Palaniappan, M., Palanisamy, S., Murugesan, T. M., Tadepalli, S., Khan, R., Ataya, S., & Santulli, C. (2024). Influence of washing with sodium lauryl sulphate (SLS) surfactant on different properties of ramie fibres. BioResources, 19(2), 2609–2625. https://doi.org/10.15376/biores.19.2.2609-2625
25. Ramasubbu, R., Kayambu, A., Palanisamy, S., & Ayrilmis, N. (2024). Mechanical properties of epoxy composites reinforced with Areca catechu fibers containing silicon carbide. BioResources, 19(2), 2353–2370. https://doi.org/10.15376/biores.19.2.2353-2370
26. Ayrilmis, N., Kanat, G., Yildiz Avsar, E., Palanisamy, S., & Ashori, A. (2024). Utilizing waste manhole covers and fibreboard as reinforcing fillers for thermoplastic composites. Journal of Reinforced Plastics and Composites, 44(17–18), 1108–1118. https://doi.org/10.1177/07316844241238507

