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ORIGINAL ARTICLE

Banana biofiber and glass fiber reinforced hybrid composite for lightweight structural applications: mechanical, thermal, and microstructural characterization

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Abstract
To address the global environmental pollution problems, the application of biodegradable agricultural waste as a reinforcing material in the development of composite materials is one of the prominent solutions for sustainable development. Following that in the present investigation, a hybrid epoxy–based composite is fabricated using banana and glass fibers as reinforcing materials for lightweight structural applications. The main purpose of this research article is to utilize banana fiber (a biodegradable agricultural waste) as a reinforcing material in composite fabrication because of its low cost, non-abrasive, and eco-friendly nature. Herein, the fabricated composite material was characterized by various tests such as tensile, flexural, hardness, impact, thermal conductivity, and scanning electron microscopy. The effects of volume fraction and sequence of banana and glass fiber layers on mechanical properties such as tensile strength, hardness, flexural, and impact strengths were also investigated. Our results showed that for sample with alternating layer of banana and glass fibers and 1 wt.% charcoal, the epoxy-based composite exhibited the highest tensile, flexural and impact strengths of about 80.9 N/mm^2, 145.4 N/mm^2, and 3.5 kJ/m^2, respectively. The same sample also reported the highest hardness of 56 VH. Furthermore, with the addition of banana fibers, the thermal conductivity of the laminates also increased. This enhancement in the mechanical and thermal properties with amalgamation of biodegradable banana fiber, strong glass fiber and water-resistant epoxy resin may help in manufacturing of lightweight composite domains for automobile and structural applications.

Keywords Banana biofiber · Epoxy resin · Composite · Glass fiber · Mechanical tests · Microstructural analysis

1 Introduction

Nowadays, various researchers are utilizing the biodegradable materials such as agricultural wastes to produce composite materials [1–6]. In agricultural-based countries such as India, Russia, Brazil, and France, major challenges prevail in using the abundant agricultural wastes. Specifically, banana is the oldest cultivated crop in the world with a global production of about 70 million tons, mainly grown in tropical and subtropical regions [7–9]. As per the investigation of Kulkarni et al. [10], banana fiber has four cell types: xylem, sclerenchyma, parenchyma, and phloem. In terms of mechanical properties of various natural fibers, Rao and Rao [11] conducted a detailed study and found that the average tensile strength and percent elongation of banana fiber were 600 MPa and 3.36%, respectively. Nguyen et al. [12] fabricated a polylactic acid-based composite reinforced with banana fiber, with aim of producing a complete eco-friendly composite material. They reported the optimum mechanical properties at 20 wt.% banana fiber. Ramesh et al. [13] fabricated epoxy-based composites reinforced with banana fibers with emphasis on environmental friendliness. The maximum tensile and flexural strength were obtained for a composite having 50% banana and 50% epoxy resin were 112.58 MPa and 76.53 MPa, respectively. Kusic et al. [14] extracted banana fibers from the agricultural wastes of the

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Canary Island. In their work, they investigated the thermomechanical properties of different polymer-based (acrylonitrile–butadiene–styrene, polystyrene, and high-density polyethylene) composites reinforced with banana fibers. They found that with the increase of banana fibers, the glass transition temperature of the laminate decreased. On the other hand, tensile and flexural strength of the laminate increased with increasing the banana fiber content.

Some researchers also used banana fibers to prepare hybrid polymer–based composites to replace inorganic mineral fillers. Nayak [15] fabricated a banana/glass fiber hybrid composite with a polypropylene matrix using the melt blending technique. This article was mainly concerned with the biodegradability study and flammability analysis of the hybrid composite. Samal et al. [16] fabricated a banana fiber–based hybrid composite with polypropylene matrix. The results showed an enhancement in the mechanical properties at 30 wt.% of both fibers in the ratio of 15:15 wt.%. Batu and Lemu [17] fabricated a hybrid composite using false banana and glass fibers as reinforcing material in epoxy matrix. A volume ratio of 50:50 between fibers and epoxy resin was selected. Two main factors (namely the fiber orientation and fiber volume fraction of the false banana) were investigated, and were studied for the tensile, compressive, and flexural strengths. The maximum tensile and flexural strength was obtained at 0°, and the minimum at 90° orientation of the false banana fiber. Hariprasad et al. [18] prepared a banana/coir hybrid composite to use natural fibers as reinforcing material for composite development. The tensile, flexural and impact strength of the hybrid composite were found to be 16.43 MPa, 20.52 MPa, and 0.76 N-m, respectively. Kumar et al. [19] fabricated a banana fiber–based hybrid composite with a woven coconut sheath using compression molding technique. The objective of the research work was to investigate the vibration behavior of the hybrid composite. The effects of the layering pattern (three-layer CCC, BCB, CBC, CCB, BBC, CBC, and BBB; where B is the banana fiber and C is the coconut sheath layer) on the mechanical properties were studied in detail. The highest tensile strength was found for the BBC hybrid composite, while the highest flexural strength was found for the CBC hybrid composite. They showed that the vibration behavior of the hybrid composite is affected by the layer pattern, and the highest natural frequency was found for the CBC hybrid composite.

Recently in 2022, Saxena and Chawala [20] performed the stress, directional, and rotational analysis of banana fiber–based hybrid composite using ANSYS software. In their work, weight percentage of sisal and banana fiber was varied with constant amount of glass fiber. Moreover, orientation of the fibric layers was also varied. Results show that that minimum deformation is obtained for sisal-banana-glass-sisal (SBGS) at 90°, +45°, −45°, and 90° orientation, respectively. Balaji et al. [21] investigated the thermos-mechanical properties of banana fiber (BF) and banana particle (BP)–reinforced epoxy composite. Results showed that the hybrid composite having both BF and BP hold the superior mechanical properties. Deepan et al. [22] fabricated the banana/epoxy composite with rice husk as a filler material to address the issue of environmental pollution. Their results showcased that better mechanical properties were obtained at 30 wt.% of banana fiber and 10 wt.% of rice husks. At mentioned composition, the tensile, flexural, and impact strengths were 210 MPa, 264 MPa, and 436.1 J/m respectively. Jagadeesan et al. [23] incorporated the cellulose micro-fillers obtained from sesame oil cake in basalt/banana hybrid composite. With the increase in microcellulose content mechanical properties of composite increased. At 5 wt.% of microcellulose content, the tensile strength, flexural strength, impact strength, and hardness were reported to be 48.83 MPa, 237.66 MPa, 93.17 kJ/m^3, and 101 HRRW, respectively. Gupta et al. [24] fabricated the epoxy-based composite reinforced with low pressure argon (Ar) gas plasma–modified banana fiber. Low pressure Ar plasma was applied on the banana fiber with the aim of increase in the surface roughness that improved the mechanical properties of overall composite domain. Perinbakannan et al. [25] studied the effect of banana and Indian almond fiber on physical and mechanical properties of epoxy-based composite. Results showed that the Indian almond fiber–based composite had a higher tensile and flexural strength; whereas, banana fiber composite have higher impact strength and moisture absorption as compared to Indian almond fiber–based composites.

The chief objective of this paper is to use an agricultural-based biodegradable reinforcing material for the development of composite materials for lightweight structural applications. As the environmental pollution is a major challenge in front of fast developing countries. To address this critical issue, the use of biodegradable agricultural waste as a reinforcing material is one of the prominent solutions for the development of structural materials for sustainable development. In the present work, the focus is on the preparation of a hybrid composition by reinforcing the epoxy matrix with banana and glass fibers. The aim is to address the problem of agricultural waste disposal and environmental issues. The effects of volume fraction and sequence of banana and glass fiber layers on mechanical properties such as tensile strength, hardness, flexural, and impact strengths were also reported.

2 Materials and methods

2.1 Materials

In the present investigation, banana fiber and E-glass fabrics were used as reinforcement materials with epoxy resin matrix. Banana fibers (250 g weight) were purchased from the Sri Lakshmi group exports and imports, Guntur, India. These fibers come under the category of bast fiber obtained from bark of banana tree. Glass fibers having a density of about 2.54 gm/cm^3, plain woven style, 250 g weight and thickness of around 0.46 mm were purchased from the Suntech fiber Ltd., Bangalore, India. Charcoal powder of about 100 mesh size having molecular weight of 12.01 was purchased online from the Sigma-Aldrich. Here in, Lapox L-12 resin and K-6 hardener were used, and this was provided by the Yuje Marketing Ltd., Bangalore, India. Epoxy is the cured end product of epoxy resins, as well as a colloquial name for the epoxide functional group. Epoxy is also a common name for a type of strong adhesive used for sticking things together [26–40].

2.2 Methods

For fabrication of the composite, firstly the banana and glass fibers were first cut in the dimensions of 300×300 mm^2, and then arranged accordingly. The quantity of epoxy was a constant for all the 5 samples made, i.e., (80% epoxy) and the quantities of banana fibers, charcoal powder, glass fibers, and hardener were varied. The various proportions of reinforcing materials were used in precise amounts using a precision balance (in grams), as shown in the Table 1. The surface of the laminates was cleaned with acetone; then the reinforcing materials were placed in the laminates in different compositions with respect to the epoxy resin. Afterwards, the laminates were cured for 24 h, with post-curing of the laminates at 100 °C. Once the samples were dried up, for characterization of prepared composite specimens were cut by waterjet cutting as per the dimensions required for various characterization tests. After the water-jet cutting was done, the laminate samples were checked for smooth finishing and voids.

2.3 Characterization

Kalpak computerized universal testing machine of model KIC-2–1000-C was employed to conduct the tensile and flexural tests. Five specimens were tested for same composition to obtain statistically significant results. ASTM D638-03 [41] and ASTM D790-07 [42] standards were employed to perform the tensile and flexural tests, respectively. All the tests were carried out at crosshead speed of 2 mm/min and at room temperature. Matsuzawa make-MMT-X7A hardness testing machine was employed to determine the Vickers microhardness. Square pyramidal shape indenter of 100 HV having apical angle of 136° was used at 100 gf for 15 s dwell time. The Vickers hardness values were directly recorded by digital tester. Izod impact test was used to determine the impact strength of all the samples. Five specimens were tested for same composition to obtain statistically significant results. ISO 8301:1991 standard was employed to determine by the thermal conductivity of fabricated composites through HFM 436 Lambda instrument supplied by NETZSCH. Three samples were tested for each composition. Specimens were placed between heating and cooling plate which were maintained a consistent temperature differential and allows heat to pass over the sample at constant pace. Thermal conductivity is measure in term of W/mK on the basic of the material to the flow of heat. FEI Quanta 200 FEG scanning electronic microscope was employed to determine the scanning electron microscopy (SEM) morphology of fractured surfaces of specimens [43–51]. Gold coating of fractured surface is done for examination the fiber dispersion in matrix and their interfacial bonding [52–55].

3 Results and discussion

3.1 Tensile test

Tensile tests were performed for various epoxy resin-based laminates on a universal testing machine (represented in Fig. 1); and the corresponding values of ultimate tensile strength and Young's modulus (YM) are stated in Table 2. The tensile strength of neat epoxy reinforced with 2 wt.% charcoal is about 3.2 N/mm^2. Lowest tensile strength was obtained for a laminate with a single glass fiber layer and 2 wt.% charcoal powder (which is about 2.9 N/mm^2); whereas the maximum tensile strength was obtained (80.9 N/mm^2)

Table 1 Specification of various samples

Sample No.	Matrix material	Reinforcement material	Description
1	Epoxy	B + B + B	Consist of three layer of banana fibers in epoxy matrix
2		G + B + G + B	Consist of four layers of glass fiber and banana fiber alternately in epoxy matrix
3		B + G + B + G + 1% C	Consist of four layers of banana fiber and glass fiber alternately with 1 wt.% charcoal in epoxy matrix
4		2% C	2 wt.% charcoal reinforced in epoxy matrix
5		G + 2% C	Glass fiber layer and 2 wt.% charcoal reinforced in epoxy matrix

B Banana biofiber layer, *G* glass fiber layer, *C* charcoal

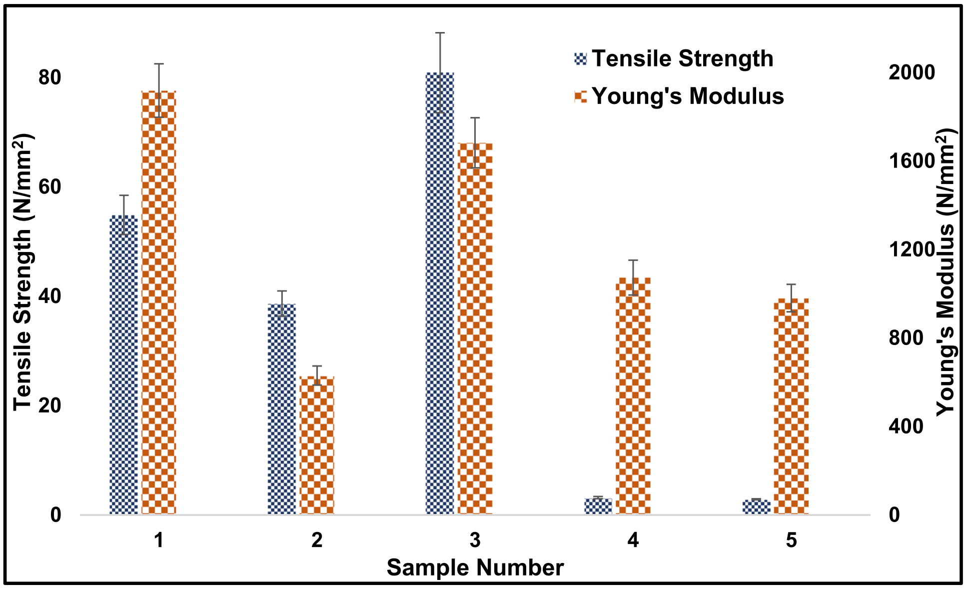

Fig. 1 Tensile strength and Young's modulus of epoxy-based laminates

for sample 3, that consisted of four layers of banana fibers and glass fibers in an alternating manner and 1 wt.% charcoal powder. This showed that hybridization of banana fibers with glass fibers improves the strength of the laminate. Samples 1 and 2 had moderate tensile strength of about 54.9 N/mm^2 and 38.7 N/mm^2, respectively. YM of epoxy having 2 wt.% charcoal is approximately 1073.6 N/mm^2. Maximum value of YM obtained for sample 1 consists of three layers of banana fiber. With the addition of glass fiber layers, the YM decreased, but there was not any particular trend. When charcoal powder was added, an enhancement of YM was observed. As for samples 2 and 3: sample 2 has four layers of glass and banana fibers (alternatively) without any charcoal and possessed a YM of about 630.4 N/mm^2, while sample 3 consisted of alternate four layers of banana and glass fibers with 1 wt.% charcoal and had a YM of about 1682.6 N/mm^2. Thus, it was found that the tensile properties of laminates depend on the interfacial adhesion between the matrix and reinforcing material, as well as on the properties of individual fibers, their orientation, sequence, etc. [56–60].

3.2 Flexural test

Flexural test was performed on different epoxy-based laminates on a universal testing machine through three-point bending set-up, and values of the flexural strength and flexural modulus are stated in Table 2 (represented in Fig. 2). Similar behavior is shown by different epoxy-based laminates as shown in the tensile test. Sample 4 has flexural strength of about 56.3 N/mm^2, whereas addition of glass fiber layer in sample 5 results in decrement in flexural strength which is about 54.3 N/mm^2. Moreover, result shows that addition of glass fiber layer results in decrease in flexibility of the laminates. This is indicated by samples 1 and 2, as sample 1 (having all three layers of banana fiber) possess higher flexural strength of 87.5 N/mm^2; whereas sample 2 (where banana fiber layer is replaced by glass fiber) has a lower flexural strength of 61.5 N/mm^2. Sequence of glass and banana fibers also affect the flexural strength, as shown in the samples 2 and 3. From the results, it can be observed that as the sequence changes flexural strength

Table 2 Mechanical properties of epoxy-based laminates

Sample no.	Tensile strength (N/mm^2)	Young's modulus (N/mm^2)	Flexural strength (N/mm^2)	Flexural modulus (GPa)	Hardness (VH)	Impact strength (kJ/m^2)
1	54.9 ± 3.6	1919.4 ± 121.2	87.5 ± 6.3	19.2 ± 0.45	54 ± 3	3.3 ± 0.2
2	38.7 ± 2.3	630.4 ± 43.2	61.5 ± 3.4	8.1 ± 0.21	49 ± 3	2.9 ± 0.1
3	80.9 ± 7.3	1682.6 ± 113.4	145.4 ± 11.2	7.4 ± 0.19	56 ± 4	3.5 ± 0.3
4	3.2 ± 0.2	1073.6 ± 78.4	56.5 ± 3.1	4.1 ± 0.14	18 ± 1	2.0 ± 0.1
5	2.9 ± 0.1	980.8 ± 62.3	54.3 ± 2.7	4.0 ± 0.1	17 ± 1	1.9 ± 0.1

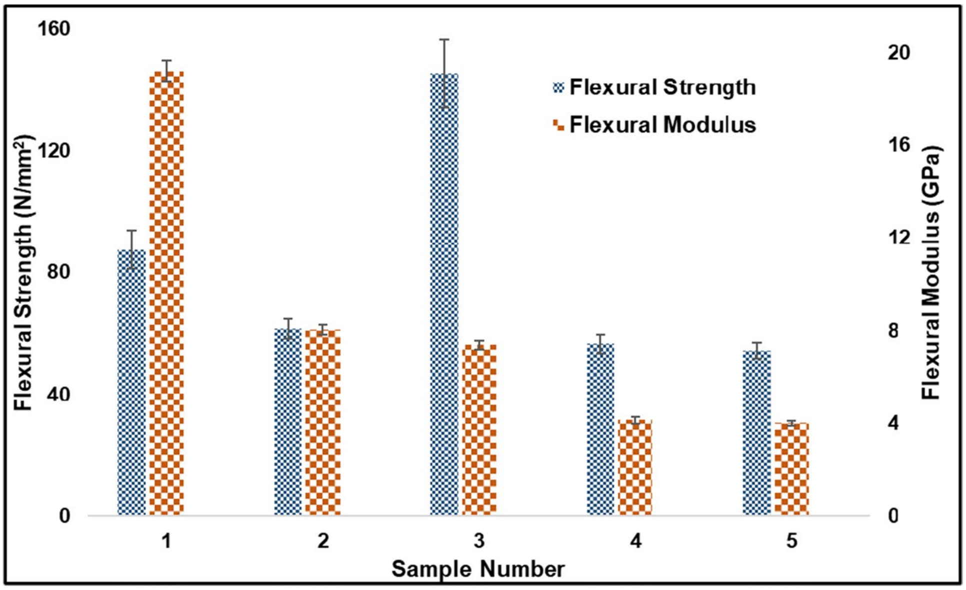

Fig. 2 Flexural strength and modulus of epoxy-based laminates

increases from 61.5 to 145.4 N/mm^2 for the samples 2 and 3, respectively.

3.3 Hardness test

Hardness test was performed on different epoxy-based laminates on Vickers microhardness testing machine (results represented in Fig. 3), and values of hardness are tabulated in the Table 2. The results show that the banana fiber reinforced laminates have higher hardness than laminates with glass fibers. Sample 1, which is hybrid with only banana biofiber as the reinforcing material, has a hardness value of about 54 VH. Moreover, the hardness of the laminate decreases when the banana fiber layer is replaced with glass fibers, i.e., in sample 2 that a hardness value of about 49 VH. On the other hand, addition of about 1 wt.% charcoal powder leads to an improvement in the hardness of the laminates, as in samples 2 and 3, where hardness value increases from 49 to 56 VH for samples 2 and 3, respectively.

3.4 Impact test

Impact test was performed on different epoxy-based laminates, and the values have been reported in Table 2 (plotted in Fig. 4). The results show that banana fiber reinforced laminates possess higher impact strength than laminates with

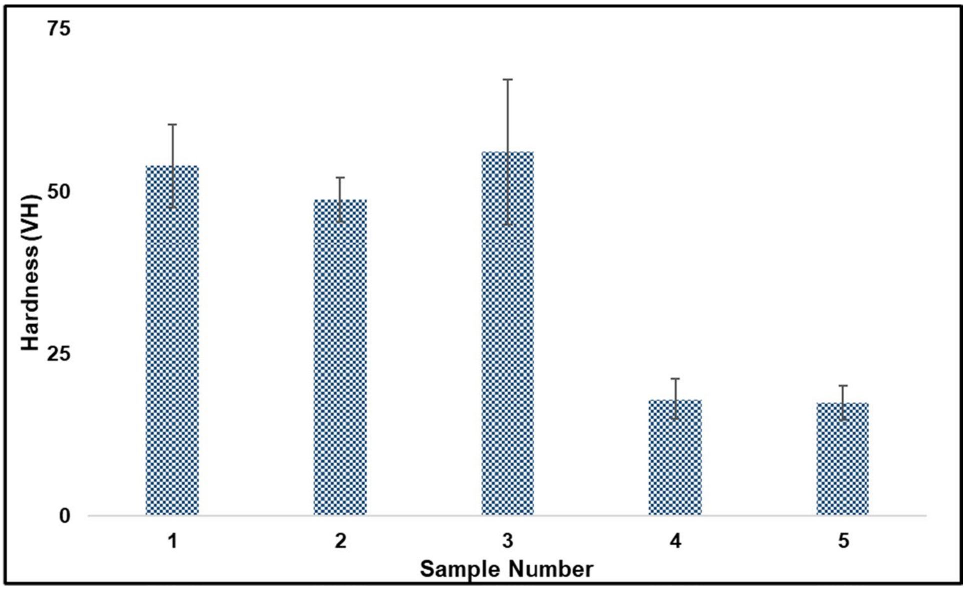

Fig. 3 Hardness values of epoxy-based laminates

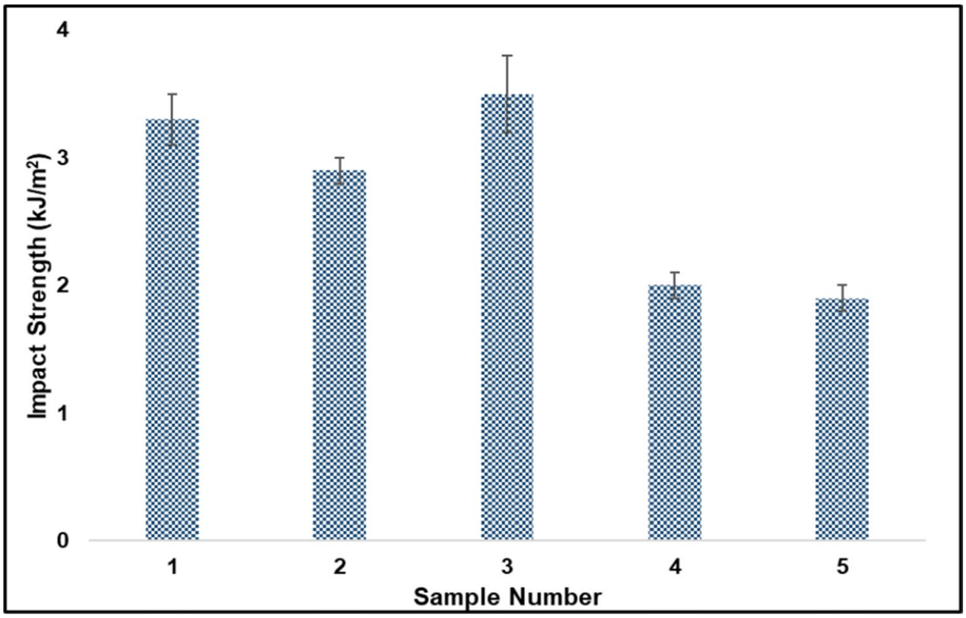

Fig. 4 Impact strength of epoxy-based laminates

glass fibers. Sample 1, which is hybrid with only banana fibers as reinforcing material, has an impact strength of about 3.3 kJ/m^2. The impact strength of the laminate starts decreasing when banana fiber layer is replaced with glass fibers, i.e., sample 2 (2.9 kJ/m^2). On the other hand, the addition of about 1 wt.% charcoal again leads to an improvement in the impact strength of the laminate, where impact strength increases from 2.9 to 3.5 kJ/m^2 for samples 2 and 3, respectively.

3.5 Thermal conductivity test

Variation of thermal conductivity values of epoxy-based laminates is tabulated in Table 3. The thermal conductivity of epoxy is about 0.3 W/mK, as reported in the work of Srinivas and Arumugaprabu [61]. Results show that with addition of banana fibers, thermal conductivity of laminates increases; but increase is not significant as shown by sample 1 that has a thermal conductivity of about 0.345 W/mK. On the other hand, addition of glass fibers result in lowering of the thermal conductivity of laminates, i.e., the samples 2 and 3 have thermal conductivity of 0.217 and 0.207 W/mK, respectively. But addition of 2 wt.% charcoal enhances the thermal conductivity of laminate to a significant level as shown in samples 4 and 5 that is about 0.501 and 0.398 W/mK, respectively. Meanwhile, the authors also conducted the flame test whose results are reported in the Table 4.

Table 3 Thermal conductivity of epoxy-based laminates

Sample No.	Mean temperature (°C)	Delta temperature (°C)	Thermal conductivity (W/m K)
1	35	10	0.345 ± 0.021
2	35	10	0.217 ± 0.018
3	35	10	0.207 ± 0.012
4	35	10	0.501 ± 0.047
5	35	10	0.398 ± 0.031

3.6 SEM analysis

Figure 5 shows different SEM morphology of fracture surface (in tensile test) of epoxy-based laminate composites. SEM morphology shows uniform dispersion of banana and glass fibers without making agglomeration in the composite domain. Moreover, fibers are uniformly dispersed in epoxy matrix in preferred direction as shown in the samples 1, 2, and 3. Fracture surface of banana and glass fiber reinforced laminates show the pulling out, dislocation of fiber, and fiber fracture in the specimen. SEM image of sample 3 shows that adhesion between fibers and epoxy matrix is more as compared to samples 1 and 2; due to which sample 3 possess the highest tensile strength, as compared to other two samples. For sample 4, i.e., when 2 wt.% of charcoal particles is added in the epoxy matrix, brittle nature is observed.

Table 4 Flame test results

Sample No.	Dripping	Ignition	UL 94 rating
1	Yes	Yes	V2
2	No	No	V1
3	No	No	V1
4	Yes	Yes	V2
5	Yes	Yes	V2

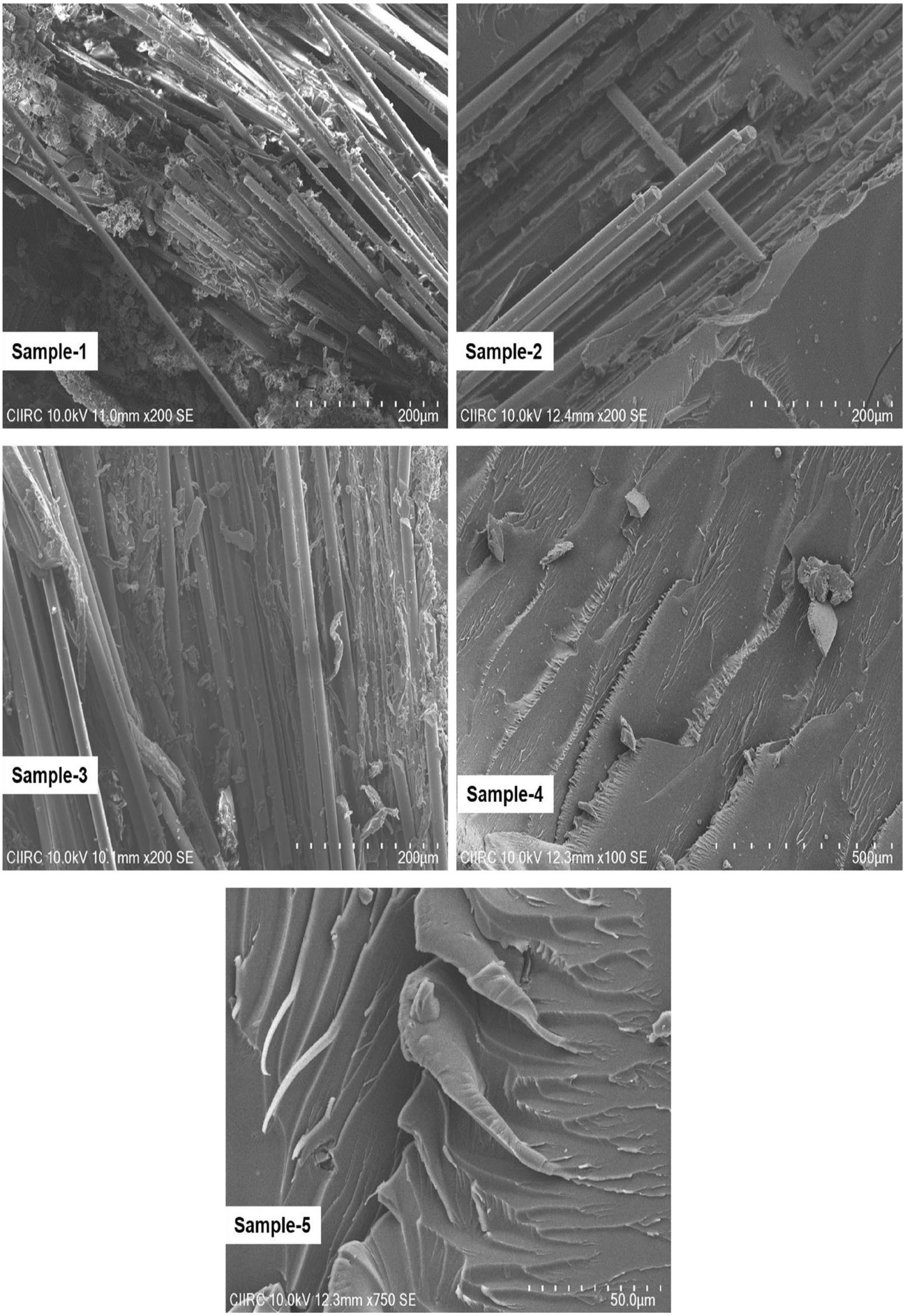

Fig. 5 SEM morphology of epoxy-based laminates

Moreover, no agglomeration of the charcoal powder is seen in the SEM morphology of samples 4 and 5. This means that a good interfacial adhesion between the charcoal particles and epoxy matrix existed.

4 Conclusions

The main focus of the present work is the preparation of a hybrid composition by reinforcing epoxy matrix with biodegradable banana and strong glass fibers. With aim to address the problems of agricultural waste disposal and environmental pollution, this investigation provides effective measures for waste disposal and improve the tensile, flexural, and impact strengths of the epoxy-based composites to increase their applications in daily life. Our results showcase that the composite reinforced with banana fiber has better mechanical properties when compared with the glass fiber composite, and can be used as a substitute for relatively expensive glass fiber. Various samples having different sequences of banana and glass fiber layers were put to mechanical and thermal tests. The maximum tensile, flexural, impact strengths, and hardness of the composite were measured to be 80.9 N/mm^2, 145.4 N/mm^2, 3.5 kJ/m^2, and 56 VH, respectively in the sample 3 (a hybrid of banana and glass fibers with 1 wt.% charcoal powder). To add on, the addition of banana fibers also increased the thermal conductivity of laminates.

Author contribution All the authors equally contributed to conceptualization, methodology, writing, reviewing, and editing.

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Data availability Not applicable.

Declarations

Ethical approval The authors hereby state that the present work is in compliance with the ethical standards.

Competing interests The authors declare no competing interests.

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