

## Research Article

# Banana Fiber-Reinforced Epoxy Composites: Mechanical Properties and Fire Retardancy

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Currently, the growing field of technology has paved the way for using environmental friendly resources; in particular, plant origin holds ecological concern and renewable aspects. Currently, natural fiber composites have widening attention, thanks to their eco-friendly properties. In the present work, the composite material is reinforced with natural fibers from the bark of banana trees (banana fibers), a material available in Vietnam. Banana fibers are extracted from banana peels, pretreated with NaOH 5%, and then cut to an average length of 30 mm. Banana fiber is reinforced for epoxy resin Epikote 240 with mass percents: 10 wt.%, 15 wt.%, 20 wt.%, and 25 wt.%. The results were evaluated through structural morphology (SEM), mechanical properties, fire resistance, and thermal properties. Experimental results show that the tensile, compressive, and impact strengths of biosynthetic materials up to 20% by weight have increased compared to epoxy neat. Flame retardant and thermal properties are kept stable; 20 wt.% banana fiber gives a limiting oxygen index of 20.8% and satisfactory thermal stability.

## 1. Introduction

Natural fibers are in abundant supply, are biodegradable, and pose no danger to human and animal health. Furthermore, natural fiber-reinforced fibers are considered to have good potential in the future as an alternative to fibers of petroleum and fossil origin. Natural fibers are extracted from various plants parts and classified accordingly. It is interesting to note that natural fibers, such as jute, coir, banana, and sisal, are available a lot in developing countries such as Vietnam, Thailand, and India [1]. In recent decades, engineering applications related to polymer composites reinforced with natural fibers have increased significantly due to the advantages not only of favorable composite properties but also of fiber and environmental strength friendly nature. In recent years, more and more researchers pay their attention to environmental pollution and limited petroleum resources. The use of fibers of natural origin in research works is increasing day by day. Different plant fibers are used on different plastic substrates.

Balaj et al. studied the application of banana fibers at concentrations of 0, 5, 10, 15, and 20 wt.% into epoxy resin. The results show that when the banana fiber content is at 15 wt.%, the mechanical properties increase; when it exceeds 15 wt.%, the mechanical properties tend to decrease [2]. Karthick et al. also studied banana fiber content at different values such as 10, 15, and 20 wt.%. The results showed that with 20 wt.% banana fiber combined with glass fiber-reinforced epoxy resin, higher mechanical properties were achieved compared to the remaining samples [3].

Besides the research on putting natural fibers (banana fibers) into epoxy resin base to make green composite materials, some other works use banana fiber reinforcement for other plastics, typically polylactic acid (PLA), with different contents: 10%, 20%, and 30% weight [4]; 20, 40, and 60 weight% [5]; and 10, 20, 30, and 40% by weight [6]. Jandas et al. again researched and fabricated banana fiber biomaterial-poly-lactic acid (PLA) using a melt-blending technique followed by compression molding banana fiber (BF) surface treated with NaOH and different silanes [7].

In order to improve the mechanical properties of banana fiber-reinforced composites, some researches have sought to hybridize them with other nanoadditives such as nanoclay [8] and nanosilicon [9]. The results showed that the combination of banana fiber and nanoadditives increased the mechanical strength of the material forming hydrogen bonds of nanoclay between fiber-matrix interfaces [9]. Plant fibers of natural origin are very abundant; recently, there have been many research works on these fibers. The goal is to create a high-value biocomposite material. In addition to banana fibers, other fibers have been studied, such as coir fibers [8], sisal fibers [10], lemon and lime peels [11], cellulose and silk [12], and various fillers obtained from the outermost skin of onions, potatoes, and carrots [13]. Banana fiber and eggshell powder are used as biomaterial fillers to reinforce concrete, obtained from agricultural and post-consumer waste [14] and also from chicken waste (femur and beak) and fish bones and used as adsorbent to reduce  $\text{Cd}^{2+}$  from the aquatic environment [15].

Ramesh et al. have fabricated a 50% banana fiber and 50% epoxy resin composite material that can withstand higher loads when compared with other combinations and is used as an alternative to conventional fiber-reinforced polymer composites [16]. Bhoopathi et al. fabricated banana-hemp-glass-reinforced hybrid composites, hemp, and glass fiber-reinforced banana fibers and evaluated the mechanic properties such as tensile strength, flexural strength, and impact strength interest in using plant fibers for the preparation of polymer composites increasing significantly in recent times. The study concluded that this hemp-glass fiber-reinforced composite epoxy composite can be used as an alternative to synthetic fiber-reinforced composites [17]. Manickam Ramesh and colleagues also initially studied the hybrid between carbon fabric and banana fiber to make composites. The carbon and banana fiber-reinforced composites can withstand a maximum tensile strength of 277.06 MPa, a flexural strength of 3.07 kN, an impact strength of 4.36 J, and a water absorption rate of 70% [18]. In addition to the study of using fibers of natural origin as reinforcement for polymer composite materials, unidirectional woven fabrics and plain woven fabrics have also been studied by Mostafa et al. [19, 20]. In order to improve the mechanical and fireproof properties of composite materials, in addition to using plant fibers, artificial fibers, etc., many works have also used typical environmentally friendly additives such as fly ash [21, 22], nanoclay [23], multiwalled carbon nanotubes and especially the hybrid between those admixtures: nanoclay/multiwalled carbon nanotubes (MWCNTs) [24–26] and MWCNTs/fly ash [27], and nanoclay/fly ash [28].

The source of banana fiber is the banana stem (banana tree skin); waste is abundant in many parts of the world. Therefore, banana fiber-reinforced polymer composites from the banana stem (banana skin) with high strength and good flame retardant properties can be used in many applications. The objective of this present research work was to develop banana fiber-reinforced hybrid epoxy composites

with different concentrations: 10 wt.%, 15 wt.%, 20 wt.%, and 25 wt.%. Mechanical properties and fire retardants are evaluated. The morphological structure was investigated by the SEM method and thermal properties by TGA.

## 2. Materials and Methods

### 2.1. Materials

- (i) Epikote 240 epoxy (E 240) from bisphenol F, of Shell Chemicals (USA) with 24.6% epoxy content, equivalent to epoxy group 185–196, with viscosity at 250°C:  $0,7 \div 1,1 \text{ Pa}\cdot\text{s}$
- (ii) Curing agent used was diethylenetriamine (DETA), from Sigma-Aldrich, chemical formula of DETA:  $\text{H}_2\text{N}(\text{CH}_2)\text{NH}(\text{CH}_2)_2\text{NH}_2$ , MW:  $103 \text{ g}\cdot\text{mol}^{-1}$ , and specific gravity at 25°C:  $0.95 \text{ g}/\text{cm}^3$
- (iii) NaOH (Sigma-Aldrich Vietnam)
- (iv) Banana fiber (BF) length: 30 mm; average diameter:  $30 \mu\text{m}$  (Vietnam)

**2.2. Sample Fabrication.** Banana fiber is extracted from the sheath (banana peel) of the banana tree. Banana peels (banana skins) are cut to a length of 30 mm, extruded and naturally dried to remove water. Banana fibers are cleaned with NaOH 5% solution for 3 h and then washed several times with distilled water until the pH reached 7 [21]. Banana fibers were then air-dried for 1 day and then dried in a vacuum oven at 80°C for 8 h. Epikote 240 epoxy resin and diethylenetriamine (DETA) curing agent (10 : 1 weight ratio) were mixed together using a mechanical agitator (agitator speed 300 rpm for 5–7 minutes). Banana fibers at the ratio of 10%, 15%, 20%, and 25% by weight were mixed with epoxy resin (banana fiber length of 10 mm). The matrix material is poured into the mold. The process continues until reaching the required thickness and weight percentage of yarn to be investigated. The mold is fed onto a hydraulic press maintained at 100°C for 45 min. The samples were then allowed to dry at room temperature for 3 h. Samples should be preserved and measured for properties [2] (see Figure 1).

### 2.3. Characterization and Testing

#### 2.3.1. Fire Retardant Evaluation Method

- (i) Limiting Oxygen Index (LOI) according to JIS K720 standard (Japan): the sample bars used for the test were  $150 \times 6.5 \times 3 \text{ mm}^3$
- (ii) The Horizontal Burning tests (UL-94HB): standard bar specimens are to be  $125 \pm 5 \text{ mm}$  long by  $13.0 \pm 0.5 \text{ mm}$  wide and provided in the minimum thickness and  $3.0 (-0.0 + 0.2) \text{ mm}$  thick (ASTM D635-12) [29]

The UL 94 flame retardant and oxygen limit tests are conducted at the Polymer Materials Research Center, Hanoi University of Technology, Vietnam.

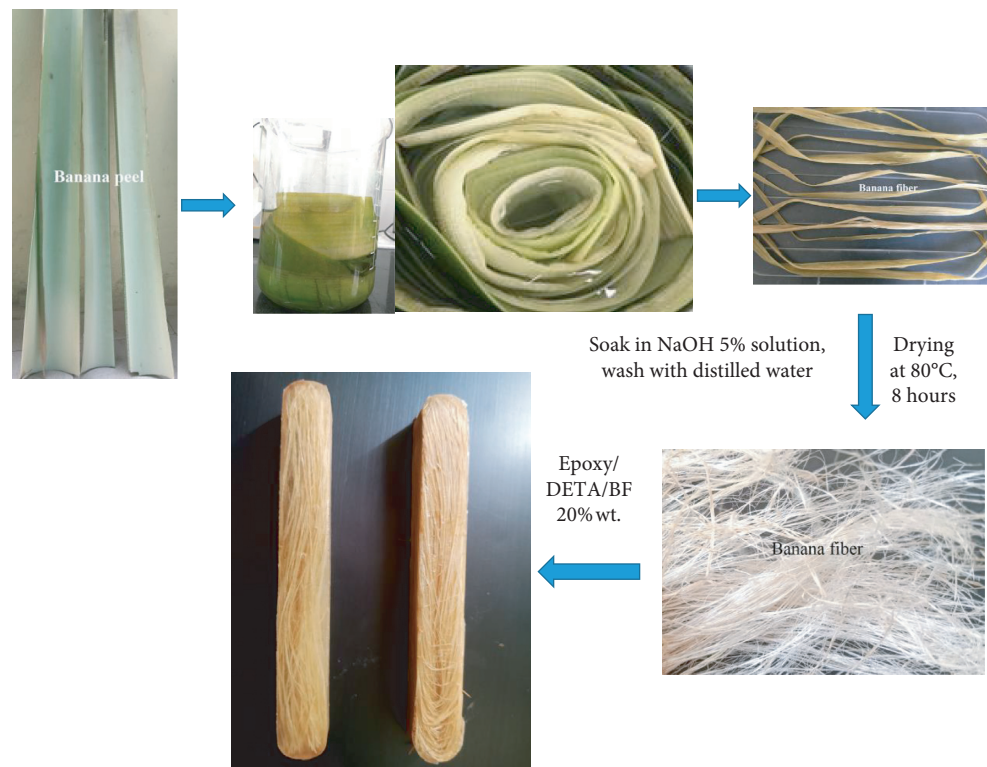


FIGURE 1: Retreatment process of banana fiber (BF).

### 2.3.2. Measurements of Mechanical Properties

- (i) Tensile strength was determined according to ISO 527–1993 standard on INSTRON 5582–100 kN machine (USA) with a tensile speed of 5 mm/min, temperature of 25°C, and humidity of 75%
- (ii) The flexural strength was determined according to ISO 178–1993 on an INSTRON 5582–100 kN machine (USA) with a bending speed of 5 mm/min, a temperature of 25°C, and a humidity of 75%. Compressive strength was determined according to the ISO 604–1993 standard on INSTRON 5582–100 kN machine (USA), compression speed of 5 mm/min, and temperature of 25°C
- (iii) Izod impact strength was determined according to the ASTM D265 standard on the Tinius Olsen machine (USA) and measured at the Research Center for Polymer Materials, Hanoi University of Science and Technology

2.3.3. *Scanning Electron Microscopy (SEM)*. The morphology of the samples was carried out by scanning electron microscope (SEM, SU3800, HITACHI, Japan) and measured at Materials Room 1, Faculty of Mechanical Engineering Technology, Hanoi University of Industry, Vietnam.

2.3.4. *TGA*. Thermal mass analysis (TGA) was performed on a DTG-60H, Shimadzu (Japan) using a heating rate of 10 C/min, under air with a flow rate of 20 cm<sup>3</sup>/min

performed at the Department Physical Chemistry, Faculty of Chemistry, Hanoi National University of Education.

## 3. Results and Discussion

3.1. *Morphology Analysis*. The dispersion state of banana fiber into epoxy resin matrix plays an important role in mechanical properties, flame retardant properties, and thermal properties. SEM method is used to evaluate the banana fiber dispersion in composite materials. The SEM results of epoxy composite materials when reinforced with banana fiber at different weight percentages (10 wt.%, 15 wt.%, 20 wt.%, and 25 wt.% banana fiber) are presented in Figure 2.

From the SEM image results in Figures 2(a)–2(d), good dispersion of banana fibers in epoxy resin matrix was observed at different incorporation ratios. From the SEM image of the fabricated material at the mixing ratio of 20 wt.% banana fiber (BF) shown in Figure 2(c), it is observed that the BFs are well dispersed in the epoxy resin matrix in the preferred direction. The absence of any gaps around the fibers indicates good adhesion between the fibers and the epoxy substrate.

From Figures 2(a)–2(d), it can be concluded that the longitudinal fracture part of the SEM image of the banana fiber composite is well connected, as the image clearly shows that there is no tension in the fibers; rather, the fibers are uniformly broken. From the above data, it is also shown that there is no chemical reaction between the fibers and epoxy resin [16, 17, 30].

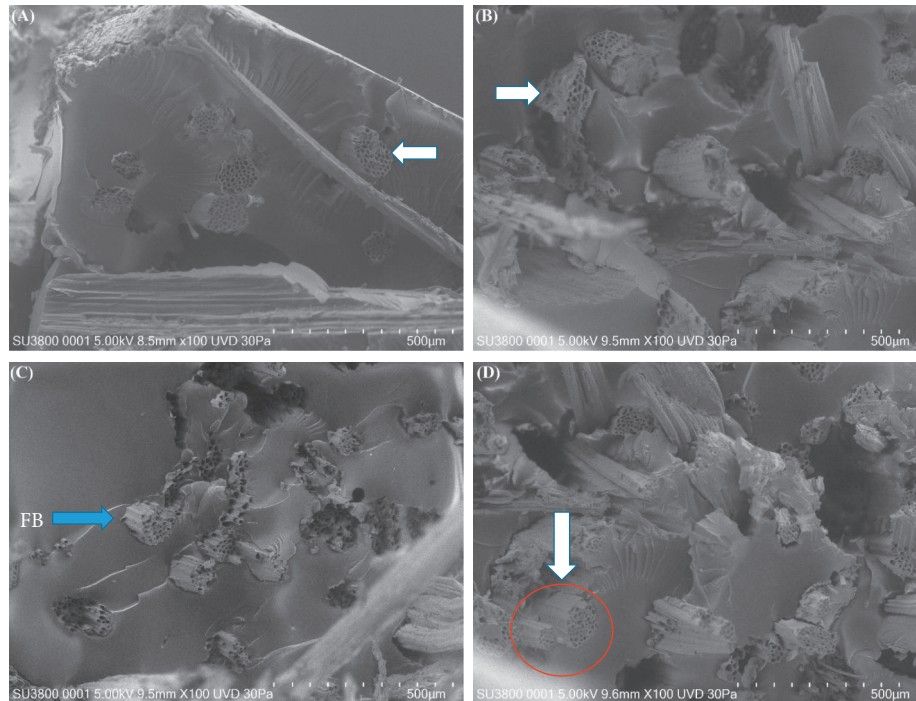


FIGURE 2: SEM image of fracture surface of epoxy composite/banana fiber (BF) materials: (a) 10 wt.% BF, (b) 15 wt.% BF, (c) 20 wt.% BF, and (d) 25 wt.% BF.

Figures 3(a), 3(b), 4(a), and 4(b) show the fracture tensile region where the distribution of fibers in the matrix, broken fibers in the matrix, and the pulled fibers have been characterized for the fracture mechanism. Cracks (green arrows) and small gaps between the matrix and fibers are observed in Figures 3(a) and 4(b).

From Figure 3, it is clear that the interfacial adhesion between the fiber and the substrate is fully enhanced in the composite material having 20 wt.% banana fiber.

From Figures 3(a) and 4(a), it can be seen very clearly that the banana fiber was pulled out of the epoxy substrate and fractured with a rough surface (red sample circle). The epoxy resin E 240 in the middle of the banana fibers was partially peeled off due to the brittle epoxy (Figure 4(a)). Figures 3(a) and 3(b) show that the amount of resin remaining on the rough fracture surface is observed and the crack (red arrow) on the interface between banana fiber and epoxy resin is observed; however, it is small.

**3.2. Mechanical Properties.** From the results of the mechanical properties of Figure 5, we see that the tensile strength, flexural strength, and impact strength Izod tend to increase when the banana fiber content increases to 20% by mass, at 25% by weight signs of a decrease. This trend is complete [2, 16, 17, 30]. It was observed that in the end, at 20 wt.% banana fiber, tensile strength increased by 37.31%, flexural strength by 10.13%, Izod impact strength by 80.99%, and compressive strength by 21.50% compared to the original epoxy material. Banana fiber is covered with the entire surface area by epoxy resin, agglomeration, and compatibility, and wetting on the epoxy-banana fiber

interface is high, especially at 20 wt.% (see Figures 2(c) and 3(b)). Therefore, the mechanical properties are improved, especially the most outstanding Izod impact resistance. At 25% by weight of banana fiber, the mechanical properties tend to decrease. 25 wt.% banana fiber, because more fiber is added, can lead to poor fiber wetting and reduced compatibility. Thus, 20% of the weight of a 30 mm long banana fiber is considered to be the optimal filler loading level [2]. Higher impact strength compared to other strengths indicates energy absorption of composites. This is because the fiber and epoxy have a strong surface bond on the epoxy fiber banana interface. Also, it depends on the nature of fibers and polymers.

It can be seen that the values of impact strength, tensile strength, and flexural strength all increase to a high degree. Therefore, the banana fiber-reinforced epoxy composite material has toughness properties, improving the embrittlement of epoxy primary materials [31].

From experimental research, it can be suggested that a mixture of 20% banana fiber and 80% epoxy resin plastic material can withstand higher loads when compared to other combinations and is used as an alternative material for conventional fiber-reinforced polymer composites [16].

**3.3. Flame Retardant Properties.** Flame retardant properties of epoxy composites reinforced with natural fibers (banana fibers) are presented in Figure 6.

From Figure 6, it can be seen that natural fibers (banana fibers) also affect the fire retardancy of epoxy composites more or less. In general, banana fiber is derived from nature, so the flame retardant properties have not been studied

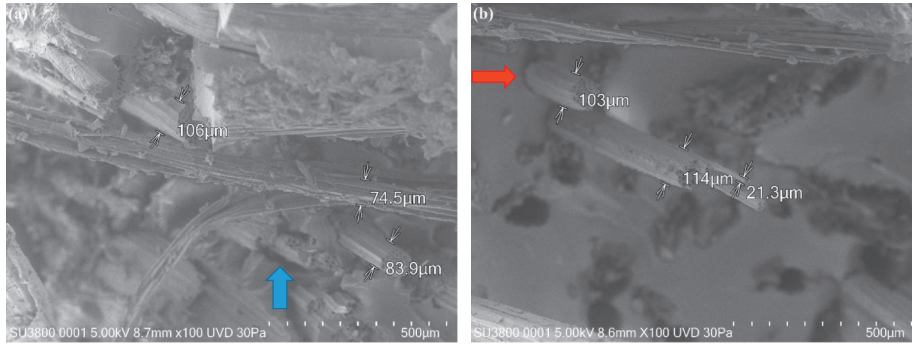


FIGURE 3: SEM image of the fracture surface of 20 wt.% banana fiber-reinforced epoxy composite material.

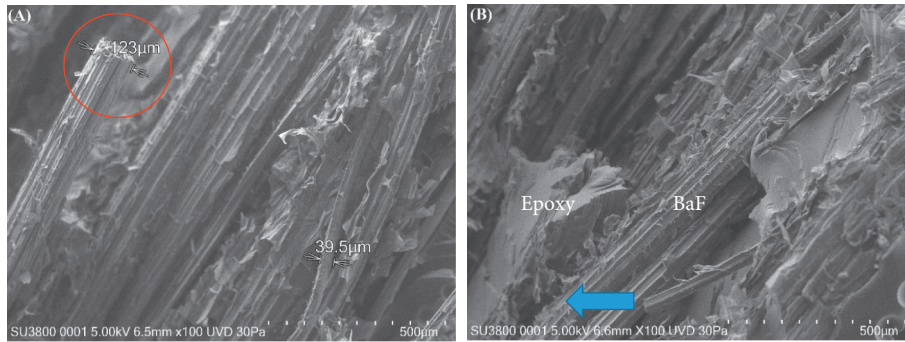
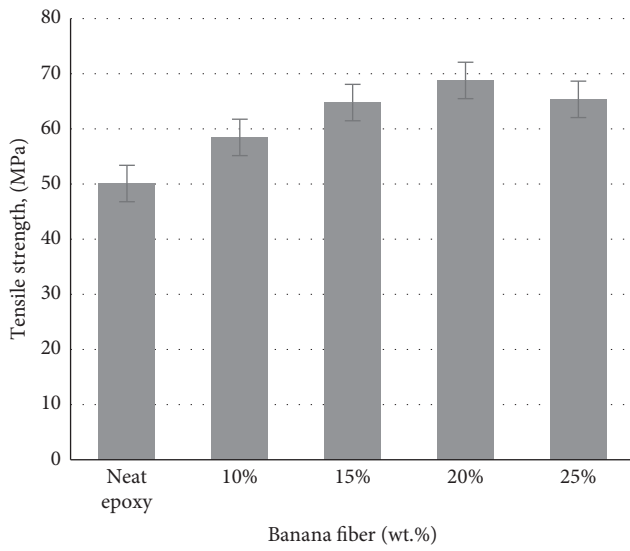
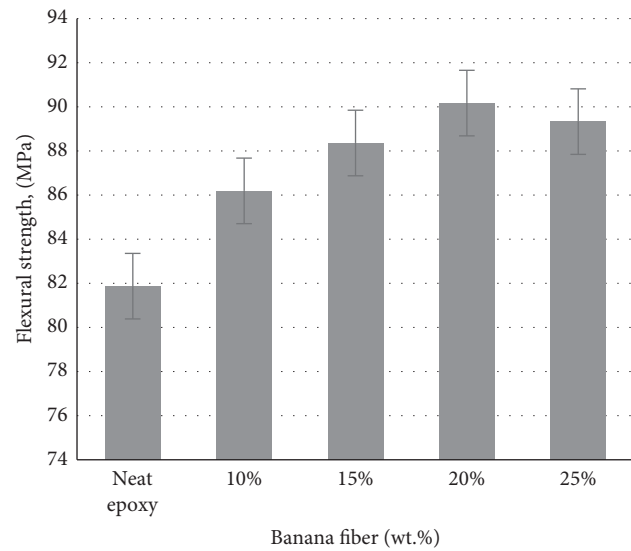


FIGURE 4: SEM image of the fracture surface of 25 wt.% banana fiber-reinforced epoxy composite material, banana fiber.



(a)



(b)

FIGURE 5: Continued.

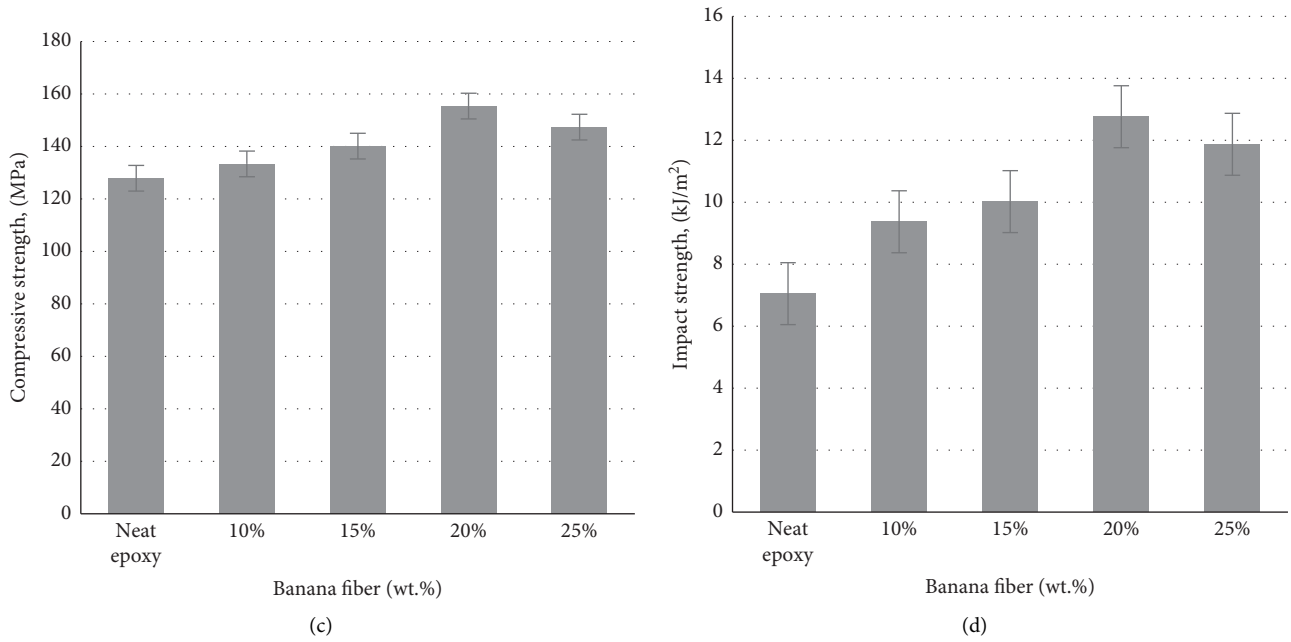


FIGURE 5: Mechanical properties of banana fiber-reinforced epoxy composites at different weight percentages: 10 wt.%, 15 wt.%, 20 wt.%, and 25 wt.%.

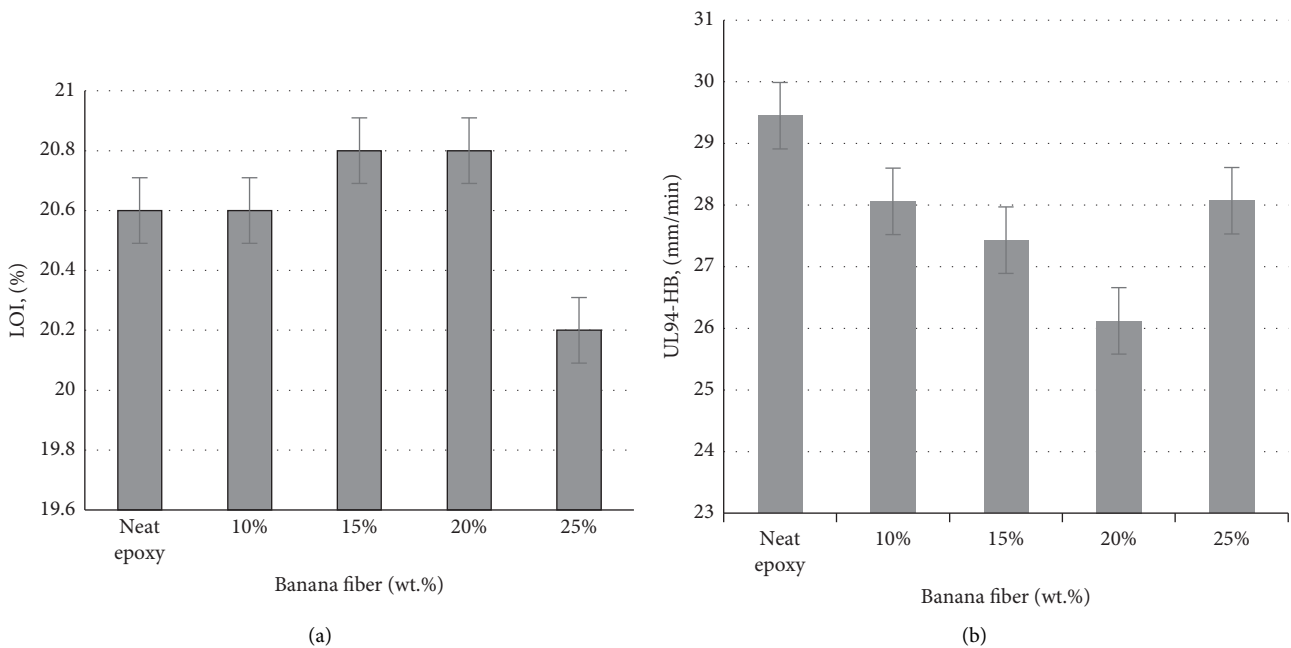


FIGURE 6: Flame retardant properties of banana fiber-reinforced epoxy materials at different mass percentages: 10 wt.%, 15 wt.%, 20 wt.%, and 25 wt.% banana fiber.

much, mainly about the mechanical properties. In this work, an initial assessment of fire retardant properties was carried out based on the limiting oxygen index and the UL 94HB method (horizontal combustion) determined through the burning speed (mm/min). In the compacted structure into a solid block, no holes were observed (see Figure 7(b)). Air-filled holes will cause fire resistance (see Figure 7(a)).

The results of the final fire resistance assessment showed that, in the presence of banana fiber, the material showed no sign of a decrease in its flame retardant properties compared to the original epoxy material. According to the combined ratio of 20% by mass of banana fiber, the degree of fire resistance is the most stable. This result is consistent with the morphological analysis in the previous section.

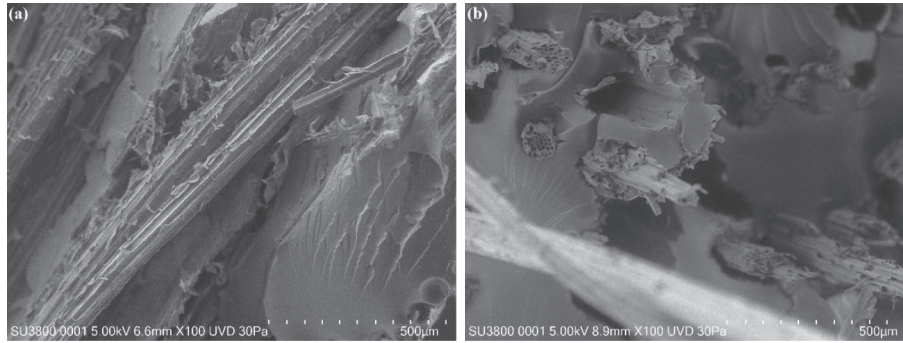


FIGURE 7: SEM image of fracture surface of epoxy composite/banana fiber (BF) materials: (a) 25 wt.% BF and (b) 20 wt.% BF.

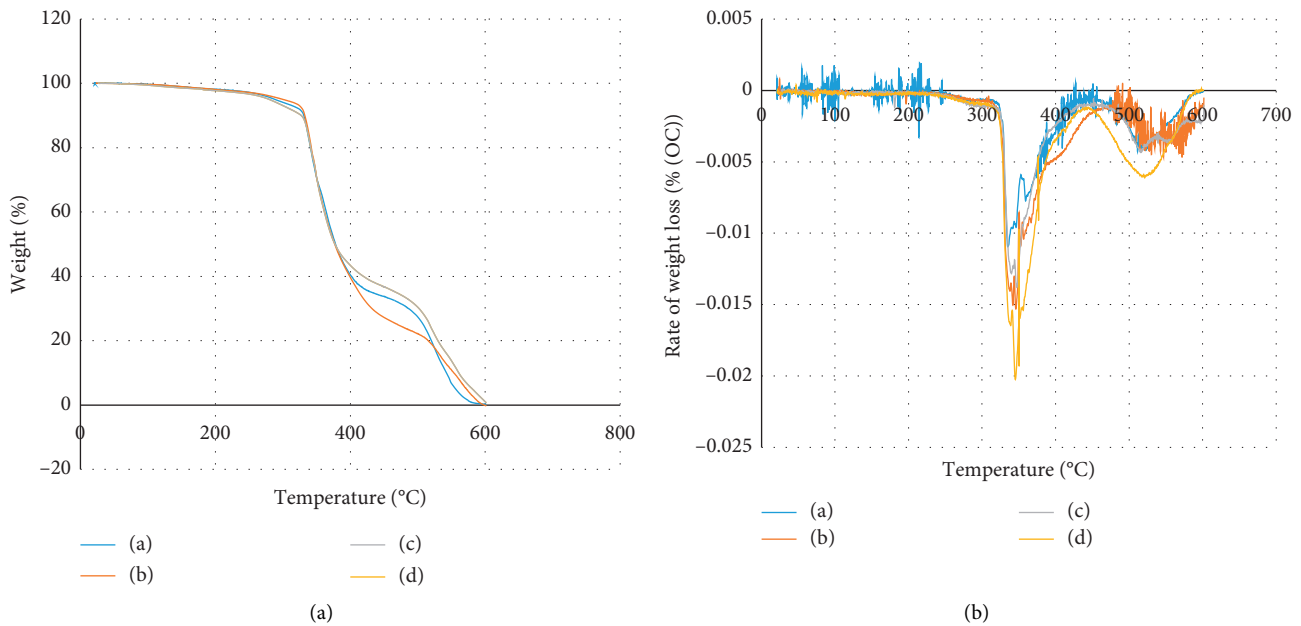


FIGURE 8: TGA and DTGA diagrams of epoxy composite reinforced with banana fiber: (a) 20 wt.%, (b) 25 wt.%, (c) 15 wt.%, and (d) 10 wt.%.

From the SEM image (Figure 7), it is clear that the banana fibers have been wetted quite well, no holes appear, the banana fibers have adhered well to epoxy, and the broken surface of the material is smooth. Forming a compact, defect-free block, the flame retardant properties are at a stable threshold, and the mechanical properties are improved.

**3.4. Thermogravimetric Analysis (TGA).** The thermal properties of epoxy/BF composite materials are presented in Figure 8.

Thermal degradation of epoxy/BF composites includes degradation, dehydration, and degradation of the main components: cellulose, hemicelluloses, and lignin (see Figure 8). Subsequent oxidation leads to the formation of burnt deposits. The TG curve shows that the decomposition initiation temperature ( $T_d$ ) corresponds to about a 10% weight loss.

The temperature at which cellulose degradation occurs, the maximum decomposition temperature ( $T_{dmax}$ ), determined from the DTG curves, is the same for all samples.

The  $T_{dmax}$  value was observed at about 359.21 C (Figure 8(a)), 345.88 C (Figure 8(b)), 347.14 C (Figure 8(c)), and 345.26 C (Figure 8(d)). These results are consistent with the results reported by Balaji et al. [2]. Among the five samples shown in Figure 8, the 20% banana fiber sample lost the least weight and the  $T_{max}$  temperature was the largest (359.21 degrees Celsius). The material achieves high compatibility, and the structure is dense so that the thermal properties are kept at the specified level, in accordance with the above fireproof and mechanical properties.

## 4. Conclusions

In this work, the influence of banana fiber mass percentage on structural morphology, mechanical properties, flame retardancy, and thermal properties was studied. The following conclusions are taken from the findings and discussion above:

- (i) This study found that banana fiber-reinforced epoxy composite, 20% by weight with a fiber length of

30 mm, displayed the highest mechanical strength, and flame retardant properties are kept stable

- (ii) In particular, the impact strength increased dramatically (80.99% compared to pure epoxy). This is because the fiber and epoxy have a strong surface bond on the epoxy fiber banana interface. However, with increasing the weight % of banana fiber to 25 wt.%, the mechanical strength tends to decrease
- (iii) TGA and DrTGA report that 20 wt.% fiber composites have higher thermal strength and temperature degradation than other %wt composites
- (iv) In general, 20% by weight is the most suitable banana fiber reinforcement to reinforce the lower epoxy matrix current research conditions

### Data Availability

The experimental data used to support the findings of this study are included within the article.

### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

### Acknowledgments

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