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Study on Physical, Chemical and Thermal Properties of Bamboo Fiber Mat/Nano Silica Reinforced Epoxy/Palm Oil Bio Composites

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Abstract

Objectives: This study investigates the interface interactions, thermal properties, and chemical bonding of bamboo fiber mat layers with epoxy resin and nano-silica concentrations with palm oil-based bio-resins. **Methods:** Thirteen composite compositions (C1 to C13) were fabricated, by varying the bamboo fiber mat layers (0, 2, 3, and 4) and nano-silica content (0, 3, 5, and 7 Wt%). **Findings:** Fourier-Transform Infrared Spectroscopy (FTIR) analysis revealed highly correlated spectra across all samples. Thermogravimetric Analysis (TGA) of Sample C9 (3-layered bamboo fiber mat & 5 wt% nano-silica) demonstrated superior thermal stability, exhibiting 67% less weight loss compared to other compositions. The study also examined density and biodegradability characteristics of the biocomposites. Biodegradability tests on two-layer mat composites showed improved performance relative to other layer configurations. **Novelty:** Results indicate that combining natural bamboo fibers with nano silica particles and a palm oil-based epoxy matrix yields a composite material with enhanced physical, chemical, and thermal properties. This green and sustainable approach improves material performance and reduces environmental impact compared to conventional petroleum-based resins, offering a promising alternative for various applications.

Keywords: Biocomposites; Palm oil; Bamboo fiber mat; Nano silica; TGA; FTIR

1 Introduction

The growing environmental concerns and the need for sustainable materials have led to increased interest in bio-composites across various industries. These materials, typically composed of natural fibers and bio-based resins, offer a promising alternative to conventional composites that rely heavily on synthetic fibers and petroleum-based polymers. The potential of bio-composites derived from renewable resources to reduce environmental impacts, such as waste generation and carbon footprint, has garnered significant attention from researchers and industry alike [1,2].

Among the various natural fibers available, bamboo has emerged as an attractive option due to its remarkable mechanical properties, rapid growth, and widespread availability. Concurrently, the incorporation of nano-reinforcements, particularly nano-silica particles, has proven to be an effective strategy in enhancing the properties of composite materials. Nano-silica's large surface area and superior interaction capabilities with polymer matrices can significantly improve the mechanical, chemical, and thermal resistance of composite materials [3,4].

Epoxy resin, a widely used thermoset polymer, is known for its excellent thermal stability and resistance to contaminants. Recent years have seen successful attempts to incorporate various plant-based oils, such as soybean oil [5], castor oil [6], and annona squamosa oil [7], as compounding components in epoxy resin. In this context, palm oil presents an interesting opportunity due to its sustainable supply and abundance, particularly in countries like India. The development of epoxidized palm oil (EPO) as a novel derivative product could establish new market opportunities for value-added palm oil products [8–10].

However, research on epoxy composites reinforced with varying numbers of bamboo fiber mat layers and different weight percentages of nano-silica, especially in combination with palm oil-derived biomaterials, remains relatively scarce. While epoxy-based composites have been extensively studied, there is limited knowledge on how the incorporation of bio-resins from palm oil can optimize their physical, chemical, and thermal properties.

Many studies focus on either synthetic resin with fiber mats or natural oil with fiber mats, but not all three components together. This study aims to bridge this knowledge gap by developing and characterizing a novel bio-composite consisting of bamboo fiber mats and nano-silica reinforced with a palm oil-based epoxy matrix. The objective of this research is to fabricate and investigate the density, Fourier-Transform Infrared Spectroscopy (FT-IR), thermal gravimetric analysis (TGA), and biodegradability characteristics of the palm oil/epoxy and bamboo fiber mat/nano-silica biocomposites.

By combining natural and nanoscale reinforcements, this study aims to develop a high-performing, environmentally friendly composite material suitable for various industrial applications. The results of this research will contribute to the growing knowledge of green materials and help bridge the gap between performance and sustainability in composite materials. The physical and mechanical characteristics of bamboo fiber are listed here in Table 1 [11].

Table 1. Physical and mechanical characteristics of bamboo fiber

Characteristics	Value	Unit
Solid density	0.91–1.4	g/cm^3
Tensile strength	270–615	MPa
Young's modulus	17–36	MPa

2 Methodology

2.1 Materials

Palm oil was sourced from Shree Western G & C Industries and Saj International Exports. The epoxy matrix (Araldite HY 951) and hardener (Aradur 22962) were obtained from M/s Seenivasa Solutions, Pondicherry, India. Sodium hydroxide (NaOH) was procured from Indian Scientific Solution, India. Bamboo fiber mats with an area density of 240 GSM and a thickness of 0.34 mm were supplied by Metro Composites, Pvt. Ltd., Tamil Nadu, India.

2.2 Alkaline treatment in bamboo fibers mat

The bamboo fiber mats were subjected to a comprehensive treatment process. The mats were cleaned using pressurized water for one hour to eliminate organic materials and fine particles. Following this, they were sun-dried for a period of two days. The cleaned and dried mats were immersed in distilled water at room temperature, after which they were oven-dried at 110°C for 24 hours. Subsequently, the mats were soaked in a 5 wt% NaOH solution, with the solution weight calculated relative to the bamboo fiber mat weight, for a duration of 24 hours. The treatment process concluded with a final oven-drying step at 110°C for 24 hours. These multi-step procedures were designed to thoroughly clean and prepare the bamboo fiber mats, potentially enhancing their properties for subsequent use or analysis.

This treatment increases the surface area of fiber and reduces hydrophilic groups, thereby improving compatibility with the hydrophobic polymer matrix and enhancing fiber mat/matrix interface adhesion [12,13].

2.3 Fabrication of Biocomposites

Thirteen biocomposite samples were fabricated with varying compositions of nano-silica and bamboo fiber mats. The process began with the uniform dispersion of nano-silica particles in the epoxy-palm oil matrix. Biocomposites were prepared using a hand lay-up mould (300 x 300 x 3 mm). For multi-layered composites, NaOH-treated fiber mats (10.5 wt%) were applied sequentially. The samples underwent curing at room temperature for 24 hours, followed by post-curing at 120°C for 48 hours, as per previous studies[14,15]. This process was repeated to produce biocomposite laminates with different nano-silica concentrations (0, 3, 5, and 7 wt%) and bamboo fiber mat layers (0, 2, 3, and 4). Consistency in the hand lay-up moulding process was likely maintained through careful weighing of materials, Using molds of the same size, following a standardized layering process, and applying consistent pressure during molding.

The designation and composition of the resulting nano-biocomposites are detailed in Table 2. This systematic approach allowed for the creation of a range of samples with varying reinforcement levels, enabling a comprehensive investigation of the effects of nano-silica content and bamboo fiber mat layers on the biocomposite properties. Figure 1 illustrates biocomposites composed of nano-silica particles and bamboo fiber mats reinforced with palm oil and epoxy.

Table 2. Composition of bamboo fiber mat nano biocomposites

S.No	Composite designation	Epoxy & Palm oil wt%	Bamboo fiber mat (0, 2, 3 & 4 layer)	Nano silica (wt%) (0 %, 3%, 5% & 7%)
1	C1	70 % + 30 %	0 (0 wt %)	0
2	C2	59.5 % + 30 %	2 (10.5 wt %)	0
3	C3	59.5 % + 27 %	2 (10.5 wt %)	3
4	C4	59.5 % + 25 %	2 (10.5 wt %)	5
5	C5	59.5 % +23 %	2 (10.5 wt %)	7
6	C6	54.25 % + 30 %	3 (15.75 wt %)	0
7	C7	54.25 % + 27 %	3 (15.75 wt %)	3
8	C8	54.25 % + 25 %	3 (15.75 wt %)	5
9	C9	54.25 % + 23 %	3 (15.75 wt %)	7
10	C10	49 % + 30 %	4 (21 wt %)	0
11	C11	49 % + 27 %	4 (21 wt %)	3
12	C12	49 % + 25 %	4 (21 wt %)	5
13	C13	49 % + 23 %	4 (21 wt %)	7

Fig 1. Bamboo fiber mats/nano-silica particles reinforced with palm oil and epoxy biocomposites

Characterization Techniques

2.4.1 Density Measurement

The densities of the biocomposites were determined using the water displacement method. Samples were fully immersed in water, and their volumetric displacement was measured. Density was calculated as the ratio of weight to volume.

2.4.2 Fourier Transform Infrared Spectroscopy (FT-IR)

FT-IR analysis helps identify chemical groups by showing which types of bonds are present in the material. This information helps us understand how the bamboo fibers, nano-silica, and bio-oil interact. FT-IR measurements were conducted using a Bruker IFS 66 infrared spectrophotometer at the Department of Chemistry, Annamalai University. The KBr pellet technique was employed, and spectra were recorded with a resolution of 4 cm—1 over the range of 4000 to 400 cm—1. Background spectra were obtained before each sample, and KBr was oven-dried to minimize water interference.

2.4.3 Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) is to assess the thermal stability and composition of biocomposites. It measures the weight loss of a material as it is heated, determining the decomposition temperature of biocomposites. Thermal analysis of the biocomposites was performed using a NETZSCH STA 449F3 at the Department of Physics, Annamalai University. Samples (10 g) were heated in a platinum pan under a nitrogen atmosphere from 27°C to 597°C at a rate of 5°C/min to assess thermal stability and degradation.

2.4.4 Biodegradability Test

The biodegradability of samples prepared according to ASTM D570 standard were assessed through a soil burial test. Samples were weighed, then buried in soil for 60 days. After this period, they were retrieved, cleaned with tissue paper, and weighed again. The weight loss, calculated as the difference between initial and final weights, served as an indicator of biodegradation. This method provided a practical means of evaluating the samples' susceptibility to natural decomposition over time.

The percentage weight loss was calculated using the following equation:

$$W\ (\%) = \{(W_{in} - W_{fi})\,/\,W_{in}\} \times 100\% \tag{1}$$

Where W_{in} and W_{fi} are the initial and final weights of specimens, respectively.

3 Results and Discussions

3.1 Density Analysis of Bamboo Fiber Mat Nano Biocomposites

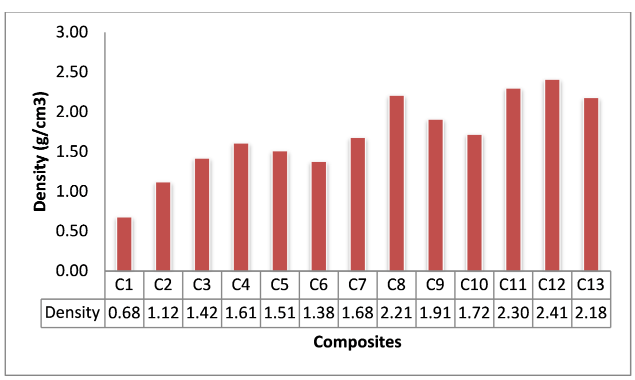

Fig 2. Density obtained for bamboo fiber mat nano biocomposites

Figure 2 illustrates the density analysis of the bamboo fiber mat nano biocomposite structures for specimens C1 to C13. The density increased from 0.6 g/cm^3 for the sample without bamboo fiber mat layers and nano-silica (C1) to a maximum of 2.4 g/cm^3 for the four-layer bamboo fiber mat with 5 wt% nano-silica biocomposite (C12).

For all layer configurations (2, 3, and 4), the density increased linearly up to 5 wt% of nano-silica content. However, beyond this point, the density began to decrease despite the continued increase in nano-silica reinforcement. The optimum density of 2.4 g/cm^3 was achieved by the four-layer bamboo fiber mat with 5 wt% nano-silica particles (C12).

These results align with the general trend of natural fiber composites having lower densities compared to synthetic fiber composites such as carbon or glass. The specific density within this range is influenced by factors including fiber content, nano-particle content, orientation, and the degree of compaction during manufacturing. Typically, composites with higher natural fiber and nano-particle content exhibit increased density, which often correlates with enhanced mechanical and thermal properties[16].

The observed decrease in density for nano-silica concentrations exceeding 5 wt% can be attributed to the combined effects of lower-density fillers, potential increases in porosity, and changes in the composite's structural arrangement[17].

The density increases up to 5 wt% nano-silica is likely due to the silica filling gaps in the material. The decrease beyond 5 wt% might be caused by the silica particles clumping together, creating larger spaces in the composite. Nano-silica helps reduce weight loss by filling small spaces in the material and creating stronger bonds. This makes the composite more resistant to breaking down when exposed to heat.

3.2 FT-IR analyses of bamboo fiber mat nano biocomposites

resents the chemical groups identified in the bamboo fiber mat nano biocomposites. A comprehensive comparative FT-IR analysis was conducted for 2-, 3-, and 4-layer bamboo fiber composites with varying nano-silica content (0, 3, 5, and 7 wt%), as shown in Figure 3 (**a–c**).

The FT-IR analyses of these nano biocomposites revealed that all spectra were highly correlated. The identities of the chemical groups are displayed in Table 3, indicating consistency in the chemical composition across the different samples[18–20].

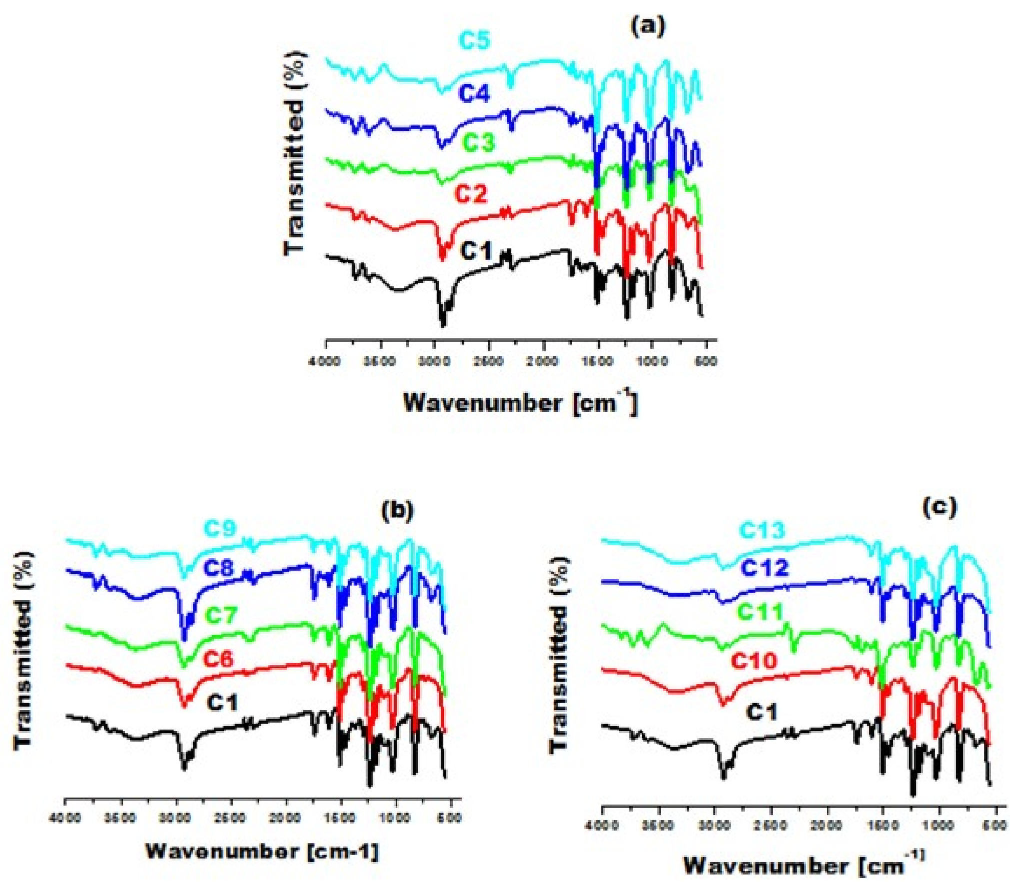

Fig 3. FT-IR for bamboo fiber mat nano biocomposites

Table 3. The identities of the chemical groups for bamboo fiber mat nano biocomposites

S.No	FT-IR frequency													Vibrational assignment
	Bamboo fiber mat													
	0 layer	2 layer				3 layer				4 layer				
	Nano slica (wt%)													
	0%	0%	3%	5%	7%	0%	3%	5%	7%	0%	3%	5%	7%	
	Sample Name													
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	
1	3322 br s	3382 br s	3392 br s	3402 br s	3404 br s	3396 br s	3384 br s	3399 br s	3402 br s	3384 br s	3394 br s	3388 br s	3406 br s	O-H Stretching
2	2986 s	2965 s	2968 s	2962s	2974 s	2981 s	2966 s	2982 s	2972 s	2964 s	2972 s	2984 s	2968 s	CH_2 Stretching
3	2762 w	2756 w	2754 w	2758 w	2751 w	2754 w	2756 w	2762 w	2766 w	2744 w	2758 w	2758 w	2766 w	CH_2 Stretching
4	1742 m	1744 m	1745 m	1745 m	1746 m	1751 m	1750 m	1748m	1742 m	1754 m	1756 m	1748m	1747 m	C=O Stretching
5	1598 m	1592 m	1596 m	1598 m	1602 m	1606 m	1607 m	1608 m	1602 m	1602 m	1604m	1608 m	1602 m	C=C Stretching
6	1509 vs	1509 vs	1510 vs	1510 vs	1510 vs	1509 vs	1509 vs	1510 vs	1512 vs	1512 vs	1509 vs	1514 vs	1516 vs	C=C Stretching
7	1359 s	1360 m	1360 m	1361 m	1361 m	1359 m	1361 m	1361 m	1364 m	1376 m	1368 m	1369 m	1372 m	C-C Stretching
8	1190 w	1190 w	1190 w	1188 w	1186 w	1186 w	1186 w	1188 w	1192 w	1186 w	1172 w	1198 w	1196 w	C-O Stretching
9	1146 s	1147 s	1148 s	1148 s	1148 s	1247 s	1147 s	1148 s	1144 s	1148 s	1145s	1152 s	1148 s	C-O Stretching
10	1082 s	1081 s	1081 s	1081 s	1081 s	1081 s	1081 s	1081 s	1071 s	1074 s	1078 s	1079 s	1181 s	Ar. C-H Scissoring
11	1038 m	1038 m	1040 m	1040 m	1042 m	1039 m	1039 m	1040 m	1040 m	1040 m	1042 m	1039 m	1042 m	Ar. C-H Inplane Bending
13	789 vs	802 s	809 s	809 s	809 s	809 s	804 s	802 s	804 s	805 s	803 s	802 s	803 s	C-C-C Inplane Bending

3.3 Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) of C1-C13 bamboo fiber mat nano biocomposites revealed varying thermal stability profiles (Figure 4). The C9 sample, a three-layer bamboo fiber mat with 7 wt% nano-silica, exhibited the highest thermal stability. All composites showed good thermal resistance, with 2.5-8% weight loss at 230°C. Initial degradation occurred between 290-350°C, resulting in a 22% weight loss due to moisture departure and cellulose/hemicellulose decomposition. A significant weight loss from 350-482°C was attributed to the breakdown of hemicelluloses, cellulose, and lignin[21]. Complete decomposition of combustible components and char formation occurred at 510°C. Total weight losses for C1-C13 composites ranged from 79.4 to 88.2 wt%, with C9 exhibiting the lowest weight loss (79.4%). These findings highlight the thermal behavior and stability of bamboo fiber mat nano biocomposites, providing valuable insights for potential applications in thermal environments[22]. The C9 sample showed the highest thermal stability because it had a good balance of bamboo fiber mats (three layers) and the highest amount of nano-silica (7 wt%). Together, these factors create a strong, heat-resistant structure.

3.4 Biodegradability Testing

Figure 5 illustrates the biodegradability of the bamboo fiber mat nano biocomposites. The results show that biodegradability decreased as the number of bamboo fiber mat layers and the weight percentage of nano-silica reinforcement increased.

Composites reinforced with two fiber mat layers exhibited greater biodegradability compared to those with three and four mat layers. The decrease in biodegradability can be attributed to the increased number of bamboo fiber mat layers and

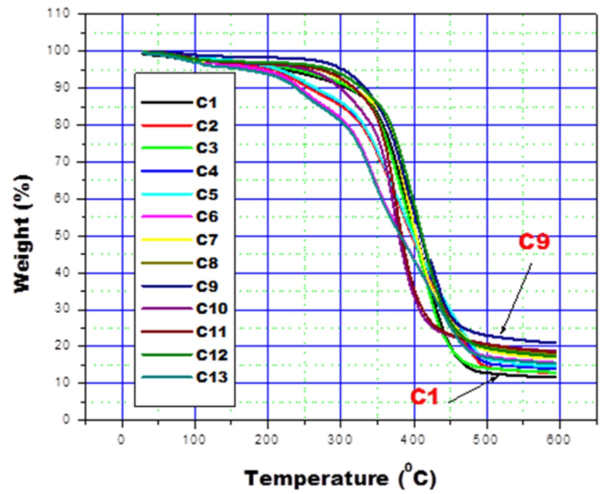

Fig 4. TGA for bamboo fiber mat nano biocomposites

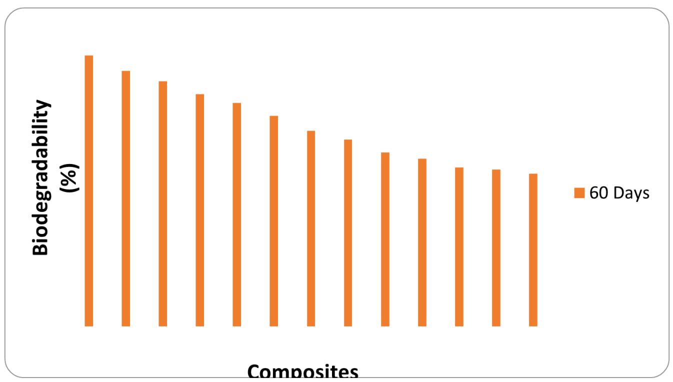

Fig 5. Biodegradability for bamboo fiber mat nano biocomposites

higher weight percentage of nano-silica reinforcement, which contribute to a more compact, less porous, and chemically stable composite material. These factors collectively reduce the composite material's biodegradability by limiting the interface between micro and macro organisms and the composite samples over an extended period[23,24]. Biodegradability decreases with more bamboo layers and nano-silica because more layers create a denser, more complex structure and Nano-silica fills gaps, making it harder for microorganisms to break down the material. The stronger bonds in the material resist decomposition. The study suggests that composites with more bamboo fiber layers and higher nano-silica content were less biodegradable. This impacts environmental sustainability by increasing the material's lifespan, which could be good or bad depending on the intended use.

3.5 Comparative Analysis

Table 4 represents a comparative investigation of the current epoxy composites with various previously reported composites[24–30]. This comparison reveals that while many researchers have blended synthetic resin with natural oil, and others have reinforced composites using natural fiber mats and nano fillers, very few studies have combined bio-oil, nano fillers, and natural fiber mats in a single composite system.

This unique combination in the present study offers potential advantages in terms of sustainability and performance, positioning this composite as a promising material for various applications.

Table 4. Comparative analysis of Epoxy composite with some composites reported [25–31]

Matrix	Natural Oil	Fiber mat	Fiber mat wt % (or) layers of mats	Filler	Filler (wt%)	Tests	Reference
Epoxy		Areca natural fiber mat	0 – 4 layer	-	-	Mechanical, Thermal, & Morphological Properties	[25]
Epoxy	-	Bamboo fiber mat	1 to 3 layer	SiO_2	0 to 4 wt%	Mechanical Test	[26]
Epoxy	-	Flax Fiber	40 wt%	Palm nano filler	2 - 6 wt%	Mechanical Test & Thermal Test	[27]
Polyester & Anogeissus latifolia	-	Abaca/Hemp/Kenaf Natural Fiber Mats	40 wt%	Fly ash	0 – 5 wt%	Mechanical Test & Thermal Test	[28]
Epoxy	Soybean Oil	Sisal Fiber	0 – 20 wt%	-	-	Mechanical & Dynamic Analysis	[29]
Epoxy	Bio Resin	Sisal Fiber Mat	0 – 30 wt%	-	-	Mechanical	[30]
Epoxy	Pam Oil	Kenaf Fiber Mat	0 – 30 wt%	Basalt Particulate	0- 3 wt%	Mechanical Properties	[31]

4 Conclusion

This study examined the properties of palm oil-blend epoxy resin biocomposites reinforced with bamboo fiber mats and nano-silica. The three-layer bamboo fiber mat with 5 wt% nano-silica (C8) exhibited the highest density (2.4 g/cm^3), indicating enhanced material compactness. FT-IR analysis confirmed the presence of cellulose and lignin, suggesting strong bonding between components. Thermogravimetric analysis revealed superior thermal stability in the C9 nano-silica biocomposite, with only 20.6% weight loss. A weight loss of only 20.6% in the TGA for the C9 sample suggests very good thermal stability. It means that even at high temperatures, most of the material remains intact, indicating strong heat resistance.

These findings indicate potential applications in lightweight domestic products. The combination of natural bamboo fibers, nanoscale silica particles, and a bio-based epoxy matrix derived from palm oil resulted in a composite with enhanced physical, chemical, and thermal properties, offering an environmentally friendly alternative to conventional petroleum-based resins. This study demonstrates the successful development of a novel biocomposite balancing performance with sustainability. The synergistic effect of the components has produced a material with promising characteristics for various applications. Future research should focus on optimizing processing parameters, exploring additional natural fiber and bio-resin combinations, and conducting long-term durability studies, Fiber treatment methods, Nano-silica dispersion techniques, Bio-oil composition, Curing conditions (time, temperature, pressure), and Fiber mat arrangement to expand the potential of these eco-friendly composites in industrial applications.

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