Research Article

Journal of Environmental Nanotechnology

Influence of SiC/$BaSO_4$/Graphite Nano Fillers on the Properties of Flax Fiber-reinforced Epoxy Biocomposites

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Received: 18.07.2025 Accepted: 01.09.2025 Published: 30.09.2025
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ABSTRACT

The fabrication and characterization of eleven distinct flax fiber-reinforced epoxy biocomposites (S_1–S_{11}) using varied weight percentages (wt%) of silane-treated silicon carbide (SiC), barium sulfate ($BaSO_4$) and graphite as nano fillers are the main objectives of this work. The primary objective was to evaluate the impact of these reinforcements on density, compressive strength, chemical composition using Fourier Transform Infrared Spectroscopy and Thermogravimetric Analysis. The produced biocomposites included 10 reinforced composites with three-layer flax fiber mats (15 wt%) and a control sample (S_1) with simply an epoxy matrix. The nano fillers of 3, 5 and 7 wt% in relation to the matrix were incorporated in the biocomposites. The sample S_4 (flax fiber with 5 wt% SiC) had the best mechanical performance in the density and compressive strength tests, making it the most viable option for load-bearing applications. Thermal analysis showed that S_{11} (flax fiber with 7 wt% graphite) had the highest thermal stability, suggesting enhanced heat resistance. These results demonstrate the potential of flax fiber-based biocomposites with optimal nano filler content for applications requiring enhanced thermal stability and mechanical strength. The study offers insightful information about environmentally friendly composite materials for industrial and structural applications.

Keywords: Biocomposites; Epoxy resin; Graphite nano filler; Flax fiber; Silicon carbide; Barium sulphate.

1. INTRODUCTION

Biocomposites are composite materials made of synthetic or biodegradable matrices combined with natural fibers/particles/mats or bio-based resins. Compared to conventional composites, they are ecologically friendly while providing sustainability, low weight and high mechanical strength. Bio-based resins can be made from soy, corn, palm, or lignin, whereas common natural fibers used in biocomposites are banana, flax, sisal, hemp, bagasse, jute and bamboo (Pokharel *et al.* 2022; Rouilly and Vaca-Garcia, 2015). These materials are widely employed in the packaging, automotive, construction, and aerospace sectors due to their lower environmental impact and biodegradability, (Akter *et al.* 2022; Balaji *et al.* 2015).

Continuous fibers give optimal strength and flexibility, while particles mostly provide stiffness without significantly improving tensile properties (Lakshmaiya *et al.* 2025). Mats facilitate stability. Although matting provides uniform reinforcement, fibers can be oriented for directional strength. The distribution of particles is arbitrary. Fibers need exact alignment, whereas particles are typically employed for bulk reinforcement in polymer matrices. Mats are more manageable for bigger projects (Dejene, 2024; Bernaoui *et al.* 2022).

To improve the mechanical, thermal and physical characteristics of biocomposites, nano fillers are incorporated into natural fibers, particles, or mats (Das *et al.* 2024). Strength, durability and other useful qualities are enhanced by these nanoscale additions. By bridging the gap between synthetic reinforcements and natural fibers, nano fillers improve sustainability, lifespan, and performance (Faruk *et al.* 2012). The ideal nano filler may vary depending on the desired properties, but in general, it should be strong, fireproof, durable and water resistant. Nano fillers in natural fiber composites reduce moisture absorption, preventing swelling and deterioration, while increasing thermal stability and mechanical strength (tensile, flexural, and impact resistance), making the composites more heat-resistant and durable. Durability is improved by reducing fiber pull-out and increasing the fiber-matrix adhesion, eliminating voids in the natural fiber mat composite. Nano fillers improve thermal insulation, strengthen weak interfaces between fiber particles and resin, increase toughness. They preserve lightweight characteristics and improve particle dispersion in fiber particle composites by decreasing agglomeration. They also enhance surface smoothness, finish quality and stiffness without adding excessive weight. Furthermore, they improve chemical and water resistance (Yusuf and Haji, 2023; Mokhothu and John, 2015).

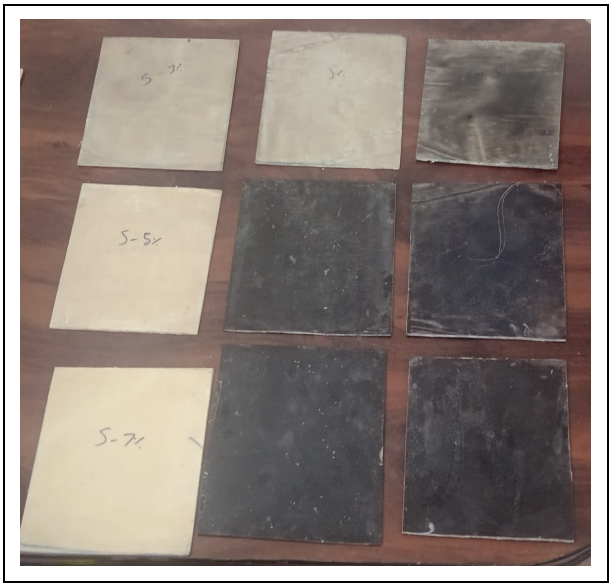


Fig. 1: Images of nano filler and epoxy-reinforced flax fiber mat biocomposites

Commonly utilized nano fillers in biocomposites include carbon-based nano fillers, carbon nanotubes, graphene, graphene oxide, and carbon black (Yibowei *et al.* 2021). Montmorillonite nanoclay, kaolinite nanoclay, and halloysite nanotubes are examples of clay-based nano fillers (Ashori and Nourbakhsh, 2009). Ceramic-based nano fillers include nano-silica, barium sulfate, titanium dioxide, alumina nanoparticles, and zinc oxide nanoparticles (Sharma *et al.* 2022). Bio-based and natural nano fillers include nano-cellulose, chitosan nanoparticles, starch nanoparticles, and lignin nanoparticles (Kumar *et al.* 2022). Metal and metal-oxide nano fillers include silver nanoparticles, copper oxide nanoparticles, and magnesium oxide nanoparticles (Wawrzyńczak *et al.* 2024).

Many studies have been conducted on natural fiber mat-reinforced biocomposites, with a focus on improving their physical, mechanical and thermal properties through resin optimization, fiber surface modification and fiber hybridization. Nano filler-reinforced polymer composites incorporating fillers like SiC, $BaSO_4$ and graphite have been extensively studied for their improved physical, mechanical strength and thermal stability. However, there is only limited research on the synergistic effects of combining natural fiber mat matting with nano fillers in epoxy composites. The mechanical, thermal and chemical properties of composites may be further enhanced by the addition of nano fillers, even though natural fiber matting boosts their sustainability and durability. This work aims to bridge these gaps by developing and analyzing flax fiber mat and silane-treated SiC, $BaSO_4$ and graphite nano filler-reinforced epoxy biocomposites. In order to ascertain the potential of these biocomposites for structural and industrial applications, they are evaluated for their mechanical, thermal, and chemical properties.

2. MATERIALS AND METHODS

2.1 Materials

The epoxy resin and curing agent Araldite (HY951) were obtained from Janki Enterprises in Thiruvananthapuram. The silane-treated SiC, $BaSO_4$, and graphite nano fillers were procured from Sigma-Aldrich Chemicals Private Limited, Bangalore. Metro Composites (P) Ltd. in Chennai, Tamil Nadu, India, supplied the natural flax fiber mat.

2.2 Silane Chemical Treatment of Flax Fiber Mats

Using silane to activate the surface of the flax fiber mat makes it stick better and spread out more evenly. In the present work, 3 wt% of silane was used to make a homogeneous ethanol-water (aqueous) mixture. Each flax fiber mat was put in a silane solution for 30 minutes. Hydrolysis of silane forms Si–OH structure. The fiber mat was then dried in an oven set to 120 to 130 °C to make a condensed Si–O–Si structure (Kalia *et al.* 2009; Kabir *et al.* 2012).

2.3 Fabrication of the Flax Fiber Mat and Nano Filler Biocomposites

The flax fiber mat biocomposite was fabricated using the traditional lay-up technique. Each of the biocomposite laminates was made using three layers of flax mats (15 wt%) and different wt% of filler nano silane-treated silicon carbide (SiC) at 3%, 5% and 7% of the total combination. Additionally, the epoxy matrix was stirred to incorporate nano-silane treated silicon carbide filler. A 300 × 300 × 3 mm manual lay-up mold was used to fabricate the flax fiber mat biocomposites. A silica polymer mold served as the molding substrate in this work. In order to facilitate the removal of the composites once they had solidified, a coarse layer of wax was primarily applied to the molding plane. Three layers of flax fiber mat (15 wt%) were applied after the trapped air pockets were removed using a cotton roller. The composites were post-cured for 48 hours at 110°C following a 24-hour curing session at ambient temperature (Dinesh *et al.* 2020; JinQiu *et al.* 2015). Until the biocomposite laminate has the proper amounts of $BaSO_4$ and graphite nano fillers at different weight percentages (3, 5 and 7), as well as nano silane-treated silicon carbide filler at 5 and 7 wt%, the process was repeated. Table 1 lists the composition and labelling of the biocomposites. Fig. 1 shows the images of nano filler and epoxy-reinforced flax fiber mat biocomposites.

Table 1. Composition of flax fiber mat nano SiC, $BaSO_4$ and graphite filler-reinforced biocomposites

S. No.	Sample Code	Matrix (Epoxy)	Flax mat	Nano filler
1	S_1	100% matrix (Control)	-	-
2	S_2	85% matrix	3 Layer (15 wt%)	-
3	S_3	82% matrix	3 Layer (15 wt%)	3 wt% of matrix SiC (silane treated silicon carbide)
4	S_4	79% matrix	3 Layer (15 wt%)	5 wt% of matrix SiC (silane treated silicon carbide)
5	S_5	76% matrix	3 Layer (15 wt%)	7 wt% of matrix SiC (Silane treated silicon carbide)
6	S_6	82% matrix	3 Layer (15 wt%)	3 wt% of matrix $BaSO_4$
7	S_7	79% matrix	3 Layer (15 wt%)	5 wt% of matrix $BaSO_4$
8	S_8	76% matrix	3 Layer (15 wt%)	7 wt% of matrix $BaSO_4$
9	S_9	82% matrix	3 Layer (15 wt%)	3 wt% of matrix Graphite
10	S_{10}	79% matrix	3 Layer (15 wt%)	5 wt% of matrix Graphite
11	S_{11}	76% matrix	3 Layer (15 wt%)	7 wt% of matrix Graphite

2.4 Flax Fiber Mat and Nano Filler Epoxy Biocomposites Characterizations

A scanning electron microscope (JEOL JSM 6610 LV) was employed to examine the tensile cracked surfaces of flax fiber mat nano biocomposites to determine their morphologies. The composites were air-dried, cleaned, then coated with platinum to enhance their conductivity. They were subsequently recorded at 15 kV using SEM.

The water displacement method was used to calculate the densities of the epoxy biocomposites reinforced with flax fiber mats and nano filler particles. The density value was determined by reference to the weight-to-volume ratio.

The compressive strength of the specimens was evaluated with the Unitek 94100 machine, with precise control over the crosshead speed and load range. The specimen was prepared for analysis following ASTM D3410 guidelines.

The hardness values of the flax fiber and nano fillers epoxy biocomposites were determined using a 1.56 mm steel ball indenter, a minor load of 10 N, and a major load of 100 N on a Rockwell hardness machine RAB 250 SCNO: SN 7078. Five replicates were evaluated for every sample in order to determine the average value of all measurements.

The thermal analysis of the biocomposites was conducted using the NETZSCH STA 449F3 thermal analyzer at the Department of Physics, Annamalai University, Tamil Nadu. This analysis was performed to assess the thermal stability and degradation behavior of the samples under controlled conditions. Each biocomposite sample, weighing 10 g, was placed in a platinum pan and subjected to a gradual heating process. The heating was carried out in an inert nitrogen atmosphere to prevent accidental oxidation, ensuring accurate thermal characterization. The temperature was increased at a controlled rate of 5°C per minute, beginning from an ambient temperature of 27°C and reaching a maximum of 603°C. This systematic approach allowed for the precise determination of key thermal properties, such as decomposition temperature and weight loss, which are crucial for evaluating the material's suitability for high-temperature applications.

A Bruker IFS 66 infrared spectrophotometer was used to perform FT-IR measurements using the KBr pellet technique (Department of Chemistry, Annamalai University, Tamil Nadu, India). Each spectrum was recorded with a resolution of 4 cm^{-1}, covering the range from 4000 to 400 cm^{-1}.

The biodegradability of the samples was assessed through an experiential method by monitoring weight loss over time in a controlled soil environment. Initially, the samples were weighed prior to burying. After sixty days, the specimens were retrieved from the

soil. Upon removal, they were cleaned with tissue paper and subsequently weighed to determine the extent of weight loss.

$$W(\%) = \{(W_{In} - W_{Fi}) / W_{In}\} \times 100\ \% \quad \ldots (1)$$

where, W_{In} and W_{Fi} were initial and final day weight of specimens respectively.

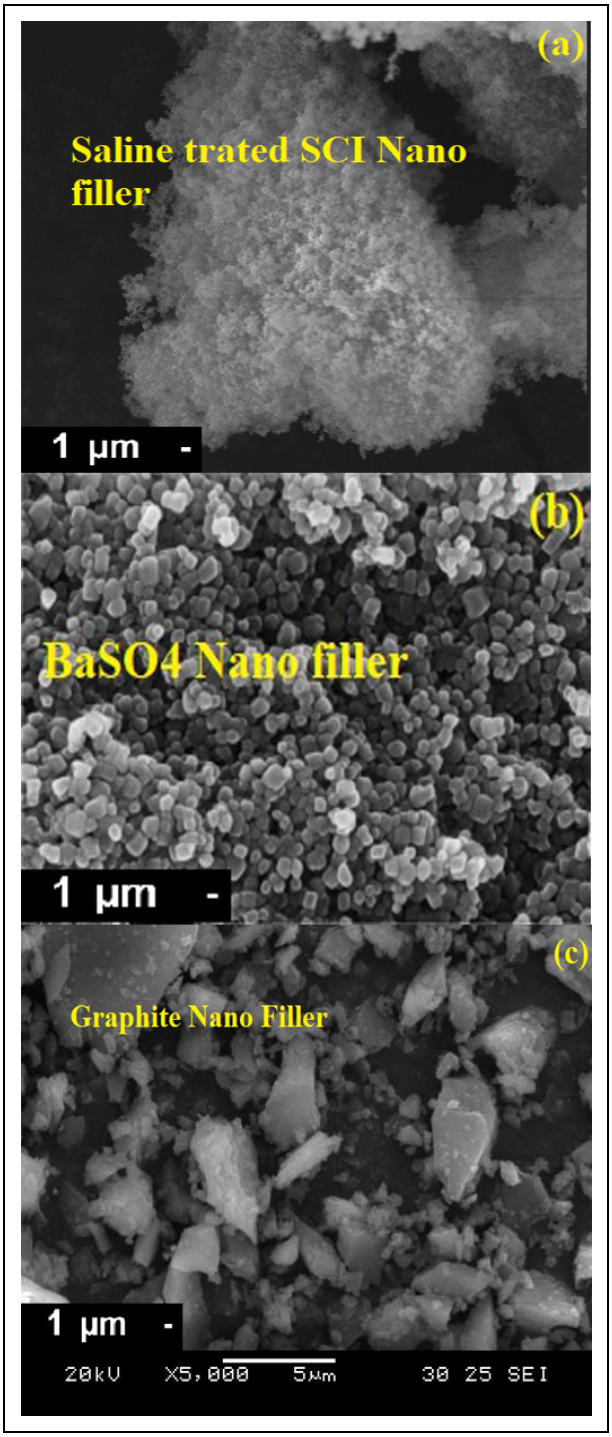


Fig. 2: SEM pictures of (a) SCI, (b) $BaSO_4$ and (c) graphite nano fillers

3. RESULTS AND DISCUSSION

3.1 Morphologies For SiC, $BaSO_4$ and Graphite Nano Fillers

Fig. 2 (a, b, c) presents SEM images of several nano fillers: silane-treated SiC, $BaSO_4$, and graphite. In Fig. 2(a) shows that the SiC nano filler is porous with loosely aggregated particles of approximately homogeneous sizes. Notwithstanding minor aggregation, the higher surface area and porous structure can enhance interaction with matrix materials and provide superior mechanical interlocking. The silane treatment may improve compatibility with polymers by incorporating functional groups. Fig. 2(b) shows uniformly sized, well-dispersed, almost spherical particles of $BaSO_4$ nano filler. This indicates increased crystallinity and regulated synthesis, rendering $BaSO_4$ appropriate for applications requiring mechanical strength or radiopacity, where consistent filler distribution is crucial. Fig. 2(c) illustrates graphite nano filler characterized by uneven, flaky, and layered particles. This characteristic graphite shape enhances electrical conductivity and mechanical characteristics in composites. Despite the particles being non-uniform and irregularly distributed, the layered structure facilitates efficient reinforcing in particular applications. Each filler possesses unique properties that provide benefits based on the intended features of the final biocomposite material (Dias *et al.* 2019).

3.2 Density of Flax Fiber Mat and Nano Biocomposites

Fig. 3 depicts the density analysis of the flax fiber mat and three distinct nano filler biocomposite structures for the various specimens (S_1 to S_{11}). It is noticed that the density rises from 1.10 g/cm^3 in the absence of flax fiber mat and nano filler (S_1) to a peak of 1.43 g/cm^3 for the three-layered flax fiber mat and 5 wt% Silane treated SiC biocomposites (S_4). S_1 (pure epoxy sample) comprises of 100% epoxy, devoid of flax fiber and nano fillers with a minimal density of 1.10 g/cm^3. The lack of high-density fillers and fiber reinforcement, together with the low inherent density of epoxy resin, leads to S_1 exhibiting the lowest density. Sample S_2 (flax fiber alone) showed enhanced density (1.19 g/cm^3) relative to pure epoxy. In the samples S_3-S_5, the SiC nano filler content was increased from 3 wt% to 7 wt%. Sample S_4 attains the maximum density (1.43 g/cm^3) within this category. For samples S_6 to S_8, the density increases from 1.35 g/cm^3 to 1.43 g/cm^3 with an increase in $BaSO_4$ concentration. For S_9-S_{11}, the density rises from 1.23 g/cm^3 to 1.26 g/cm^3, followed by a minor decline to 1.25 g/cm^3. It is noted that SiC nano filler reinforced composites have the maximum density in comparison to $BaSO_4$ and graphite-reinforced composites. The SiC nano filler significantly increases density owing to the elevated intrinsic density of SiC (3.2 g/cm^3). Its hardness

and compactness enable it to densely pack within the flax fiber mat and epoxy matrix, while fine particle distribution of SiC minimizes voids, thereby enhancing the final composite density (Essabir *et al.* 2016). $BaSO_4$ and graphite particles may agglomerate or form micro-voids, resulting in marginally reduced densities. The density of all three nano fillers (SiC, $BaSO_4$, and graphite) rose linearly up to 5 wt% concentration. Increased filler content often elevates density; nevertheless, an excessive filler concentration (7 wt%) may marginally decrease density, maybe due to material agglomeration or porosity effects (Amjad *et al.* 2022).

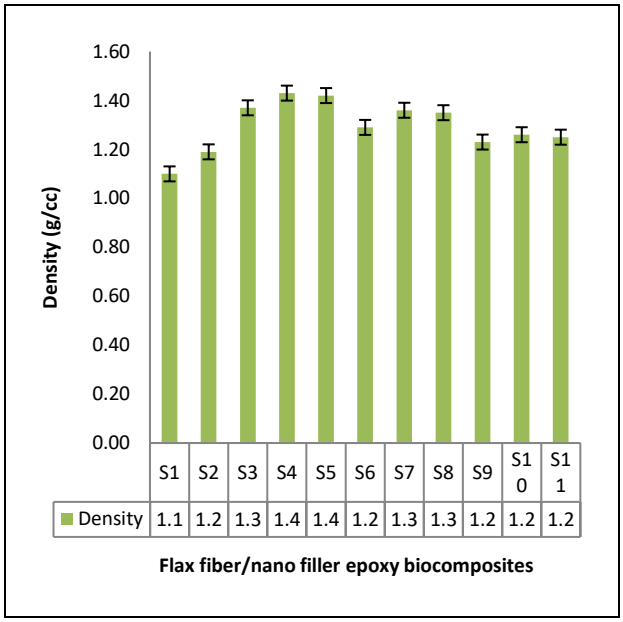


Fig. 3: Density for flax fiber mat and silane-treated SiC / $BaSO_4$ / and graphite nano fillers biocomposites

3.3 Hardness

Fig. 4 illustrates the hardness of flax fiber/nano filler epoxy biocomposites (S_1 to S_{11}). Sample S1 made of unreinforced epoxy exhibits the lowest hardness value of 56 RHN. The use of flax fiber in S_2 elevates hardness from 56 RHN (S_1) to 67 RHN (S_2) owing to its superior stiffness and inherent toughness. Flax fiber serves as a reinforcing agent, enhancing the mechanical properties of the epoxy matrix. The hardness of samples (flax + SiC nano filler at 3 wt%, 5 wt% and 7 wt%) rises from 75 RHN (S_3) to 81 RHN (S_4). It was observed that with the addition of SiC nano filler up to 5 wt%, the hardness rises but experiences a little decline at 7 wt%. This is perhaps attributable to agglomeration or inadequate dispersion. The hardness values for S_6 to S_8 samples (flax + $BaSO_4$ nano filler at 3 wt%, 5 wt% and 7 wt%) are 72 RHN (S_6), 79 RHN (S_7) and 76 RHN (S_8). The $BaSO_4$ nano filler enhances hardness, reaching a maximum at 5 wt%, followed by a slight reduction at 7 wt%. The influence of graphite as a nano filler (S_9-S_{11}) yields hardness values of 68 RHN (S_9), 72 RHN (S_{10}) and 71 RHN (S_{11}). Graphite exerts a minimal influence in comparison to SiC and $BaSO_4$. The incorporation of flax fiber enhances hardness. Nano fillers significantly improve hardness, with SiC demonstrating the highest efficacy (81 RHN at 5 wt%). The ideal concentration of nano filler across all kinds is 5 wt%. Nano fillers serve as reinforcements by occupying voids between polymer chains or inside the matrix material, hence augmenting mechanical strength and hardness (Shen *et al.* 2001; Ramesh, 2016). It limits chain motion, resulting in increased stiffness and hardness of the material. This phenomenon is particularly evident in elastomers and thermosetting polymers. SiC features a very hard crystalline structure that interlaces with the epoxy matrix, forming a densely packed network. The intricate network of robust interfacial adhesion limits molecular mobility, leading to increased hardness. $BaSO_4$ increases density but does not possess sufficient hardness to substantially strengthen the composite. Graphite, recognized for its lubricating characteristics, helps to diminish friction, potentially resulting in a marginal decrease in hardness rating. Thus, SiC is among the most resilient ceramic materials, exceeding the inherent hardness of $BaSO_4$ and graphite.

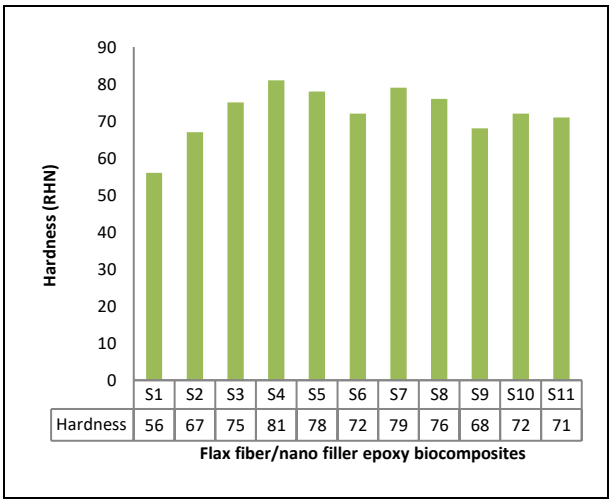


Fig. 4: Hardness for flax fiber mat and silane-treated SiC / $BaSO_4$ / graphite nano fillers biocomposites

3.4 Compressive Strength

The compressive strength of flax fiber/nano filler epoxy biocomposites is shown in Fig. 5. S_1 has the lowest compressive strength (84.2 N/mm^2) due to its 100% epoxy content and lack of reinforcement. Compressive strength is greatly increased to 93.8 N/mm^2 by adding three layers of flax mat in S_2 sample (15 wt%), demonstrating that flax fibers improve mechanical characteristics. By serving as reinforcement, flax fibers stop cracks from spreading. Compared to pure epoxy, the fiber-matrix interaction distributes the load more effectively. The compressive strength is further enhanced by the reinforcement with nano fillers. The most efficient material is SiC, which has the maximum strength at 111

N/mm^2 (S_4). With a value of 109 N/mm^2, graphite (S_{10}) outperforms $BaSO_4$. Of the three fillers, $BaSO_4$ is the least effective, although it increases strength. SiC is an ultra-hard ceramic substance with superior stiffness and compressive strength. Because of its extremely high hardness (Mohs scale ~9.5), it is frequently utilized in applications that require extraordinary strength. SiC greatly increases the load-bearing capacity and resistance to deformation under compression when added to an epoxy matrix. Because graphite is layered, stress may not be distributed as well. Because $BaSO_4$ is denser, it may settle and lessen the reinforcing effect (Callister and Rethwisch, 2020). The ideal concentration of nano filler is 5 wt%. Particle agglomeration caused by a higher nano filler concentration (>5 wt%) might decrease efficacy (Tong *et al.* 2022).

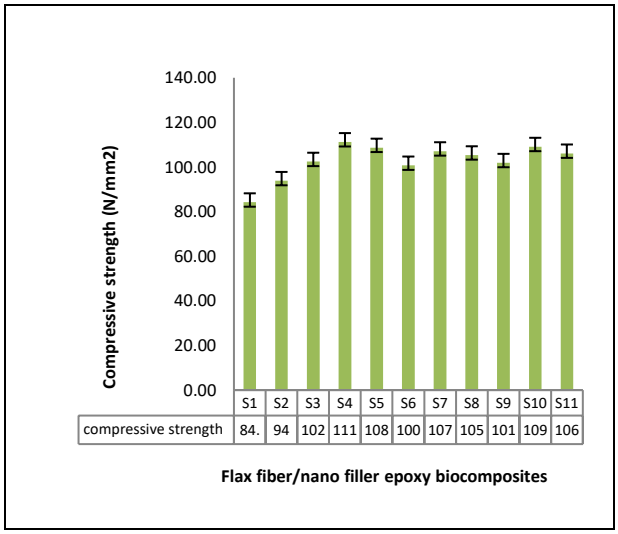


Fig. 5: Compressive strength for flax fiber mat and silane-treated SiC / $BaSO_4$ / graphite nano fillers biocomposites

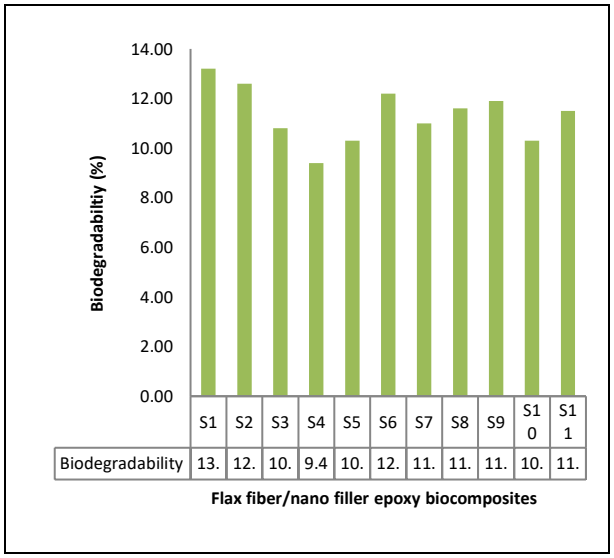


Fig. 6: Biodegradability for flax fiber mat and silane-treated SiC/$BaSO_4$/graphite nano fillers biocomposites

3.5 Biodegradability

Fig. 6 illustrates the biodegradability of flax fiber/nano filler epoxy biocomposites. The highest biodegradability (13.2%) is found in S_1. The sample has higher biodegradability since it absorbs more water as it doesn't contain any fiber or nano filler. All other samples are relatively less biodegradable. Nano fillers and flax fiber reinforcement enhance cross-linking, which lowers water absorption and biodegradability. The least biodegradable material is S_4 (5 wt% SiC) (9.4%). By improving bonding and decreasing voids, SiC nano filler increases the durability and water resistance of the composites. Samples containing graphite/$BaSO_4$ exhibit moderate biodegradability (10.3%–12.2%). Although graphite and $BaSO_4$ are more hydrophobic than SiC, they do not form bonds with the matrix as strong as those formed by SiC. The high density of $BaSO_4$ may also influence uniform dispersion, resulting in marginal increase in water absorption (Vimalanathan *et al.* 2016; Jawaid *et al.* 2022). The ideal concentration is 5 wt% since higher concentrations might cause agglomeration (as seen in S_5).

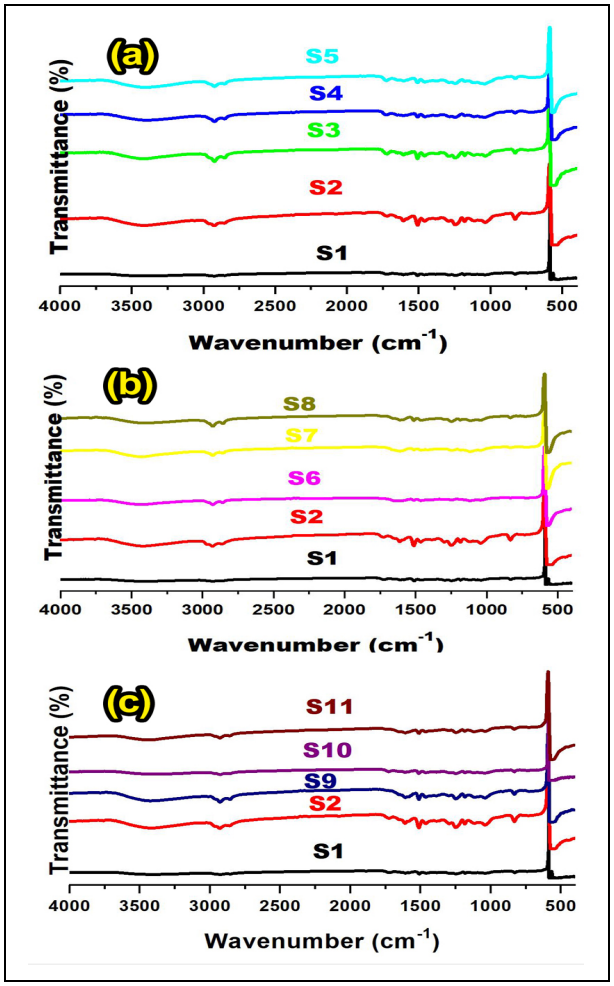


Fig. 6: FT-IR for flax fiber mat and SiC/ BaSO4/ Graphite nano filler biocomposites

3.6 FT-IR Analyses of Flax Fiber Mat and Nano Filler Biocomposites

Table 2 lists the chemical groups of the flax fiber mat SiC/$BaSO_4$/graphite nano biocomposites. The samples with different wt% of nano fillers were subjected to a thorough comparative FT-IR investigation (Fig. 7(a–c)). The spectra of all the biocomposites showed a strong correlation, and the chemical group identities are shown in Table 2. The FT-IR spectrum changes when flax matting and nano fillers are added, indicating that the epoxy, flax and nano filler reinforcements interact chemically. Absorption increases with filler quantity, suggesting structural changes in the composite. The information aids in the analysis of possible interactions, material composition and chemical bonding in the biocomposites.

The presence of hydroxyl groups is indicated by a broad peak in the high-wavenumber range (3300–3500 cm^{-1}), which corresponds to O–H stretching. This increases the possibility that the flax fiber or any remaining hydroxyl groups in the epoxy matrix are absorbing moisture. Aliphatic-CH bonds found in both the flax fiber and epoxy resin are responsible for the C-H stretching vibrations that are seen in the range 2900–2950 cm^{-1}. The carbonyl groups of the epoxy matrix are highlighted by the presence of C=O stretching vibrations at around 1720–1750 cm^{-1}. The composite structure may be impacted by interactions between the nano filler and the carbonyl group. Furthermore, aromatic C=C stretching, a characteristic of the epoxy resin backbone, is visible in the 1500–1600 cm^{-1} region, indicating the structural integrity of the polymer. The C–O–C asymmetric stretching is shown by a prominent absorption band in the range 1250–1300 cm^{-1}. This suggests that even with reinforcement, the molecular structure of epoxy resin is maintained. The C–H out-of-plane bending vibrations, which correlate to aromatic epoxy ring vibrations, are found in the 800–900 cm^{-1} range. These peaks, which are most prevalent in Fig. 6 (a, b, and c), are linked to the structural stability of the polymer and show that the composite contains aromatic groups (Swaminathan *et al.* 2009; Guo *et al.* 2019). The existence of silicon carbide (SiC) nano fillers in the composite samples is confirmed by the peaks found in the range 1000–1100 cm^{-1}, which correlate to Si–O stretching vibrations (Fig. 7(a)). The presence of barium sulfate nano fillers in the modified composite samples is confirmed by S–O stretching vibrations in the 1100–1150 cm^{-1} region (Fig. 7(b)). Aromatic C=C stretching vibrations, which are mostly connected to the epoxy resin backbone, are represented by peaks found in the region 1500–1600 cm^{-1}. This peak attests to the epoxy polymer's structural integrity. Furthermore, because graphite has conjugated carbon-carbon (C=C) bonds (Fig. 7(c)), this absorption band is more noticeable in samples that include graphite nano fillers (Liyanage *et al.* 2015).

Table 2. Identities of the chemical groups for flax fiber mat and SiC/$BaSO_4$/graphite nano filler biocomposites

S. No.	FT-IR frequency											Vibrational Assignment
	Nano filler											
	Epoxy	Epoxy and Flax Fiber	SiC			$BaSO_4$			Graphite			
			3%	5%	7%	3%	5%	7%	3%	5%	7%	
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	
1	3452 br s	3460 br s	3484 br s	3486 br s	3490 br s	3402 br s	3424 br s	3422 br s	3322 br s	3332br s	3326br s	O-H Stretching
2	2942 s	2946 s	2932 s	2930s	2934 s	2932 s	2936 s	2932 s	2938 s	2932 s	2930 s	CH Stretching
3	2752 w	2751 w	2754 w	2754 w	2751 w	2758 w	2760 w	2757 w	2766 w	2764w	2768 w	CH_2 Stretching
4	1732 m	1742 m	1735 m	1737 m	1736 m	1748m	1742 m	1745 m	1747 m	1741m	1744 m	C=O Stretching
5	1555 m	1568 m	1566 m	1578 m	1562 m	1528 m	1522 m	1535 m	1542 m	1545m	1545 m	C=C Stretching
6	1511 vs	1509 vs	1510 vs	1511 vs	1510 vs	1511 vs	1512 vs	1509 vs	1516 vs	1514 vs	1513 vs	C=C Stretching
7	1351 s	1359 s	1360 m	1361 m	1361 m	1361 m	1364 m	1368 m	1372 m	1374m	1375 m	C-C Stretching
8	1224 w	1190 w	1190 w	1188 w	1186 w	1188 w	1192 w	1172 w	1196 w	1202w	1201 w	C-O-C Stretching
9	-	-	1054 br	1052 br	1055 br	-	-	-	-	-	-	Si–O stretching
10	-	-	-	-	-	1122 br	1128 br	1129 br	-	-	-	S–O stretching $BaSO_4$ presence
11	-	-	-	-	-	-	-	-	1555 br	1554 br	1552 br	Aromatic C=C stretching & Graphite presence
12	852 s	854 s	872 s	875 s	876 s	851 s	854 s	858 s	862 s	865 s	864 s	Ar. C-H Scissoring
13	784 vs	789 vs	809 s	809 s	809 s	802 s	804 s	803 s	802 s	803 s	804 s	C-C-C In-plane Bending

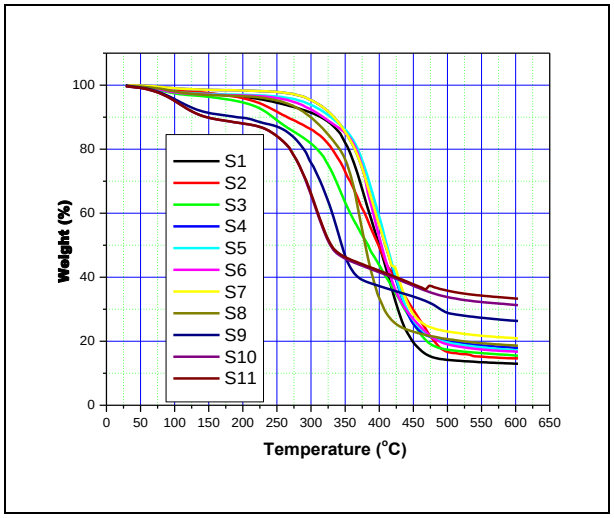


Fig. 8: TGA for flax fiber mat and SiC/$BaSO_4$/graphite nano filler biocomposites

3.7 Thermogravimetric Analysis (TGA) of Flax Fiber Mat and SiC/$BaSO_4$/Graphite Nano Filler Biocomposites

The TGA curves in Fig. 8 represent several composite samples with varied epoxy matrix compositions, flax mat reinforcement and different nano fillers (SiC, $BaSO_4$ and graphite) with changing wt%. Early weight loss (~100–200°C) was seen in all samples (S_1–S_{11}) as a result of moisture and volatile chemicals. The main decomposition was found around 250–450°C. This is the temperature range when flax and epoxy polymer break down. Compared to samples S_1 and S_2, samples containing fillers (S_3–S_{11}) exhibit decreased rate of weight loss. Since pure epoxy degrades at a certain temperature range without reinforcement, the sample S_1 is predicted to have the lowest thermal stability. Compared to other samples, it most likely exhibits an earlier and more noticeable weight loss. The presence of natural flax fibers in the S_2 sample (85% epoxy + 15% flax mat, no filler) increases thermal resistance. But the organic component may breakdown at lower temperatures. It has a weight loss pattern that differs from S_1, although it still degrades noticeably between 250 and 450°C (Chollakup *et al.* 2011). Thermal stability is increased in S_3–S_{11} by the inclusion of nano fillers. By acting as thermal barriers, nano fillers increase residual content at higher temperatures and slow down degradation. The heat resistance increases with the proportion of nano filler (3, 5, and 7 wt%). SiC nano fillers (S_3, S_4 and S_5) are renowned for their ability to withstand high temperatures (Balaji *et al.* 2025). The degradation temperature are higher in samples with SiC. Although $BaSO_4$ stabilizes the biocomposites (S6, S7 and S8), it might not be a good heat resistant like SiC. Graphite (S_9, S_{10} and S_{11}) increases heat conductivity and may result in a larger post-decomposition residual mass. Graphite outperforms SiC and $BaSO_4$ as far as heat resistance is concerned. The highest stability is achieved with a higher filler wt% (7 wt%); nevertheless, too much filler may degrade mechanical properties.

4. CONCLUSION

Epoxy resin biocomposites reinforced with flax fiber mat and three distinct SiC/$BaSO_4$/graphite nano fillers with three different wt% (3, 5 and 7 wt%) were investigated in this study for their density, compressive strength, hardness, biodegradability, FT-IR and thermal stability. Out of the eleven biocomposites.

- The three-layer flax fiber mat and 5 wt% SiC nano filler biocomposite (S_4) had the greatest density, measuring 1.43 g/cm^3. And the lowest density is 5wt% of graphite nano filler composite (S_{11}) which is of 1.43 g/cm^3. Compared to Epoxy composite (S_1) the percentage raise is 30% for S_4 and 13.66% for S_{11} respectively.

- The sample (S_4) exhibited the best mechanical properties. These properties include higher compressive strength (111 N/mm^2) and hardness (81 RHN) compared to the wt% of graphite and $BaSO_4$ nano filler biocomposites. And also compared to base composite S_1 the percentage raise is 75.71% in compressive strength, 69% in Hardness.

- The sample (S_1) exhibited the best biodegradability which is 13.20% and lowest biodegradability is S_4 which is 9.40%.

- Thermal analysis revealed that the sample S_{11} was more resistant to thermal degradation and had greater thermal strength than the other nano filler-reinforced biocomposites.

- The results of this study suggest that these biocomposites can be used in the manufacturing of lightweight home applications.

FUNDING

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

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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