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Thermal and Microstructural Evaluation of Natural-Glass Fiber Hybrid Composites: Sustainable Alternatives to Synthetic Materials

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Abstract

The scope of engineering requirements for composite materials, which mix features from several elements engaged in engineering applications to enable greater performance, cannot be adequately understood in this way. The most recent of these materials are hybrid composites, which combine synthetic and natural fibers, particularly glass fibers, and are anticipated to create new, promising materials in terms of their ties to cost, performance, and consistency. From the perspective of their qualities as reinforcements, the majority of natural fibers, including jute, banana, and sugarcane, are lightweight, biodegradable, and renewable, making them environmentally desirable. However, these materials cannot be employed on their own to strengthen high-performance conditions because of their poor mechanical strength and limited thermal stability. By enhancing overall strength, dimensional stability, and durability, their combination with glass fibers overcomes these limitations. In this work, these natural fibers—jute, banana, and sugarcane—were processed and combined with glass and epoxy resin to create hybrid composites using the traditional hand lay-up method. Thermal characterisation, including TGA, DTA, thermal conductivity, and effusivity studies, is employed for the produced composites. In contrast, the microstructure characterization was done at the SEM and AFM levels. The findings of the experiment showed that pure glass fiber composites had the best stability and thermal conductivity, indicating that they had comparatively greater heat resistance. Conversely, the performance of hybrid composites varies based on the type of reinforcement provided by natural fibers. With better interfacial bonding, appropriate fiber dispersion, and comparatively low heat conductivity, the banana-glass fiber hybrid composite demonstrated the best level of balanced performance among the investigated configurations. When comparing banana-glass hybrids to jute or sugarcane-glass systems, the results of scanning electron microscopy and atomic force microscopy showed that fiber-matrix adhesion is improved and microvoids formation is decreased. Overall, adding natural fibers to a glass fiber composite makes it more environmentally friendly without significantly compromising its mechanical or thermal performance.

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Keywords: Hybrid composites, natural fibers, glass fiber, thermal properties, fiber–matrix bonding

INTRODUCTION

Fiber reinforced polymer composites (FRPCs) are advanced materials consisting of high-performance fibers as reinforcement and a polymer matrix that binds them together, providing structural integrity and desired mechanical properties [1,2]. These composites are typically fabricated using multiple layers of unidirectional

(UD) tapes reimpregnated with the polymer matrix, leading to enhanced anisotropic strength and stiffness. Owing to their superior properties such as high specific stiffness, excellent strength-to-weight ratio, and corrosion resistance, FRPCs have gradually replaced metals in several industries including aerospace, automotive, marine, and defense sectors [3]. Reinforcing fibers can be broadly classified into synthetic and natural types, with glass, aramid, and carbon fibers being the most commonly used synthetic variants, while epoxy is often employed as the matrix due to its excellent adhesion and mechanical stability [4]. Among these, glass fiber remains the most widely used reinforcement, available in types like E-glass and S-glass, with E-glass being especially popular because of its low cost, easy availability, and reliable insulation properties [5]. In contrast, natural fibers such as jute, banana, bamboo, sisal, coir, wood, and sugarcane bagasse have recently gained significant research attention owing to their renewability, biodegradability, light weight, low cost, and environmental friendliness [6,7]. Jute fibers, in particular, are promising because of their high cellulose content (61–72%), moderate hemicellulose (14–20.4%), and lignin (12–13%), which contribute to their mechanical strength [8]. Bagasse fibers, derived as agricultural waste from sugar industries, also provide attractive reinforcement options due to their easy availability, low cost, and fairly good strength properties [9]. However, despite these benefits, natural fibers face critical drawbacks such as poor wetting with polymer matrices, hydrophilic behavior, dimensional instability, and low thermal resistance [10]. To address these issues, hybrid composites that combine natural and synthetic fibers are increasingly being developed, allowing the environmental and cost advantages of natural fibers to be integrated with the mechanical reliability of synthetic fibers [11,12]. This hybridization approach not only overcomes the drawbacks of single fiber systems but also results in composites with balanced mechanical, thermal, and durability properties suitable for modern engineering applications [13]. A hybrid composite is essentially a combination of two or more distinct fibers that are strategically selected so that one fiber compensates for the limitations of the other, thereby producing a material with improved overall performance [10]. The primary purpose of hybridization is to retain the advantageous properties of the constituent fibers while minimizing or eliminating their weaknesses, which makes such composites superior to single-fiber reinforced materials. In most cases, hybrid composites combine synthetic fibers, such as glass or carbon, with natural fibers like jute, bagasse, or banana, in order to achieve a balance between mechanical performance, cost-effectiveness, and environmental sustainability [11, 14–17]. Among the most popular hybrid composites are glass–jute and glass–bagasse systems, which are extensively used in industrial applications including wall partitions, automobile interiors (dashboard, inner fenders), household utilities (lamp shades, floor tiles), and packaging materials due to their adequate strength, stiffness, and durability. Research has shown that incorporation of bagasse fiber reduces the ultimate tensile strength of a composite; however, when combined with glass fiber, the tensile strength is improved significantly compared to composites made with bagasse alone, while also enhancing the modulus of elasticity. Cao et al. demonstrated that alkali treatment of bagasse fibers improves interfacial adhesion with the polymer matrix, leading to superior mechanical performance compared to untreated fibers [18]. In line with these findings, the present research aims to systematically investigate the mechanical properties of jute–glass/epoxy and bagasse–glass/epoxy hybrid composites, focusing on strength, durability, and environmental perormance under conditions such as water immersion and soil burial. Further, the study emphasizes the role of alkali treatment in enhancing fiber–matrix bonding and thereby improving the tensile strength and stiffness of hybrid composites. Previous works also provide insight into the factors influencing hybrid composite performance: Hossain et al. reported that fiber orientation significantly affects tensile properties [13], while Rahman et al. highlighted that increasing fiber loading enhances both strength and hardness in jute composites [19]. Similarly, Ramesh et al. compared hybrid glass–natural fiber composites and confirmed that glass fiber contributes positively to the strength of natural fiber systems [20], and Singh et al. experimentally evaluated bagasse–glass reinforced composites, validating the potential of these hybrids for practical applications [21]. Taken together, these studies establish a strong foundation for exploring hybrid composites as viable alternatives to traditional materials in structural and semi-structural applications.

Table 1. Specimen compositions.

Specimen	Composition (by weight %)
1	50% resin, 30% glass fibers, 20% jute fibers
2	50% resin, 30% glass fibers, 20% sugarcane fibers
3	50% resin, 30% glass fibers, 20% banana fibers
4	50% resin, 50% glass fibers
5	40% resin, 60% glass fibers

The engineering industry continues to look for new lightweight, affordable, and sustainable materials. For composite materials, the engineering industry continues to use high-strength and thermally stable synthetic composite materials, ignoring the high price, non-biodegradability, and environmental unsustainability. Jute, banana, and sugarcane, however, can provide natural and biodegradable fibers. Unfortunately, their excessive moisture absorption, poor thermal stability, and irregular strength limit their use alone. Thus, the use of hybrid composites is required, where durability, mechanical strength, and thermal performance are improved and environmental impact is reduced by natural fibers glass and resin fibers. Despite this, limited research exists on the thermal and microstructural behavior of such hybrids, specifically those combining jute, banana, and sugarcane with glass fibers. Key challenges remain in understanding property variations, including thermal conductivity, heat capacity, and degradation, as well as achieving effective fiber–matrix bonding through fabrication methods like hand lay-up. Addressing these issues is essential to optimize hybrid composites for real-world applications.

MATERIAL AND METHODOLOGY

The hybrid composites were fabricated using a combination of natural fibers (jute, banana, and sugarcane bagasse) and synthetic glass fibers, with epoxy resin (Araldite 556) and hardener (Aradur HY951) as the polymer matrix. The glass fiber (Grade E), epoxy resin, and hardener were procured from Shipping Harbor industrial material market, Visakhapatnam. The jute (Grade A), banana, and sugarcane bagasse were procured from Vijayawada agricultural fiber suppliers, India. Glass fibers, with an average diameter of 15 μm, were chosen for their high tensile strength and thermal stability, while the natural fibers were selected for their biodegradability, low density, and cost-effectiveness. Prior to fabrication, natural fibers were treated with a 5% NaOH solution for 2 hours at room temperature to remove lignin, hemicellulose, and impurities, improving fiber surface roughness and enhancing fiber–matrix adhesion. The treated fibers were washed thoroughly with distilled water to neutralize residual alkali and dried under ambient conditions for 24 hours. Five different specimens were prepared with varying proportions of resin, glass fibers, and natural fibers, maintaining consistent weight percentages for comparative analysis. The fiber diameters ranged from 10–30 μm depending on the type, and uniform cutting was carried out to ensure proper orientation during fabrication. The specimens included both hybrid and purely synthetic composites to benchmark the performance of natural–synthetic blends. The detailed specimen composition was selected from previously reported article, which provides validated composition for the resent study [22]. The composition of each specimen is presented in Table 1.

The hand lay-up technique was adopted for composite fabrication due to its simplicity and effectiveness in controlling fiber orientation and resin impregnation. A clean mold surface was prepared by spraying release gel and covering it with thin plastic sheets to achieve uniform surface finishing. The epoxy resin and hardener were mixed in a 2:1 ratio, ensuring proper stirring to minimize air bubble formation. Fiber layers were placed sequentially in the mold, with each layer thoroughly coated with resin mixture. A roller was used after every application to remove entrapped air, enhance densification, and promote uniform wetting of fibers. For hybrid specimens, layers of glass fibers and natural fibers were arranged alternately to achieve balanced reinforcement. A uniform weight of approximately 200 g was applied on the mold to ensure thickness control and better fiber–matrix bonding. The specimens were cured at room temperature for 24 hours, followed by post-curing to enhance cross-linking and

thermal stability. After curing, the composites were demolded, cut into standard dimensions, and surface-finished for characterization. Tests included mechanical (tensile, flexural, and impact), thermal (TGA, DTA, and thermal conductivity), and microstructural (SEM and AFM) evaluations, all conducted in accordance with ASTM standards to ensure accuracy and repeatability.

TGA/DTA Testing

Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) were carried out using a Simultaneous Thermal Analyzer (STA) as shown in Figure 1(a), which records mass changes and thermal transitions under identical conditions. Each specimen (10 mm × 10 mm) was cut precisely and placed in a platinum crucible, with an empty crucible as reference. The chamber was purged with nitrogen/argon for inert analysis or oxygen/air for combustion characteristic, ensuring accurate degradation profiles. A controlled heating rate of 5–20°C/min was applied, from room temperature up to 800–1000°C, depending on the requirement. TGA recorded weight changes cognate to the process of decaying of fibers, resin volatilization, or char formation, while DTA simultaneously detected exothermic and endothermic events. This dualrecording capability allowed direct correlation between weight loss and structural transitions such as glass transition (Tg), crystallization, and decomposition. The key outputs obtained were onset degradation temperature, peak degradation temperature, residual char content, and phase transitions are presented in Figure 1(b).

SEM and AFM results complemented TGA/DTA findings, confirming fiber–matrix interactions and void effects. By testing all five specimens under the same protocol, a comparative evaluation was made between hybrid and fully synthetic composites. The results highlighted how fiber type and resin-to-glass ratios influenced thermal durability, degradation pathways, and residue stability. The thermal response of the five specimens revealed clear differences in stability and decomposition patterns. Sample 5 (40% resin, 60% glass) showed the highest residual mass (4.594 mg after 575°C), proving superior resistance to high-temperature degradation due to its high synthetic content. Sample 4 (50% resin, 50% glass) ranked next, retaining 4.006 mg at 576°C, indicating excellent balance between strength and stability. Sample 3 (glass + banana fibers) stabilized at 2.590 mg after 568°C, reflecting moderate stability and improved bonding compared to other natural hybrids. Sample 2 (glass + sugarcane fibers) had weaker resistance, retaining only 0.542 mg after 573°C, with instability evident in the 300–600°C range. Sample 1 (glass + jute fibers) exhibited the lowest stability, leaving just 0.209 mg after 582°C, showing early and near-complete degradation. DTA peaks confirmed major transitions: dehydration, resin volatilization, and fiber decomposition. Especially, hybrid samples demonstrated multiple degradation stages, unlike purely synthetic composites which resisted decomposition longer. These ranking highlights that glass fiber reinforcement plays a dominant role in thermal stability, while natural fibers improve sustainability but reduce high-temperature resistance.

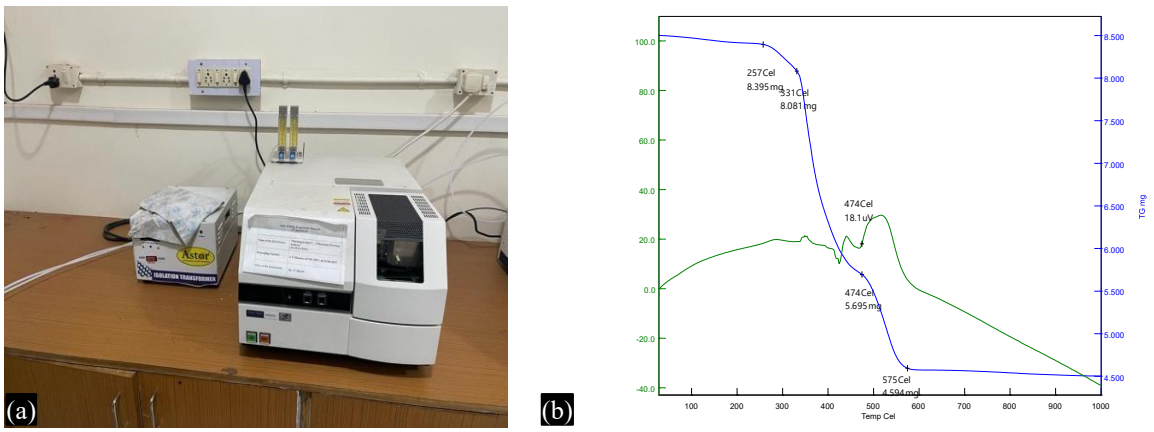
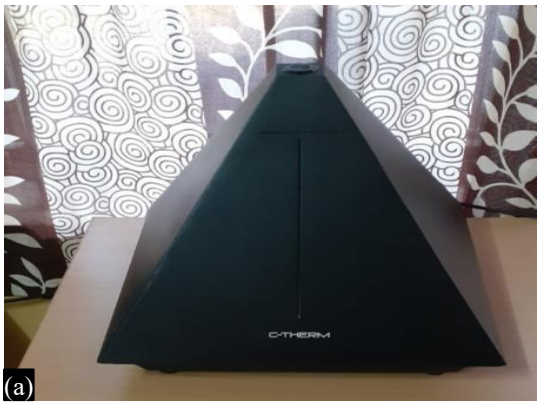


Figure 1. (a) Thermogravimetric Analyzer; (b) TGA and DTA Plot for Sample 5.



C-THERM

MTPS GUARD RING TECHNOLOGY

Test Details

Instrument:	C-ThermTrident	Test ID:	MTPS-Polymers-2025-07-26-02:08:49P
Sensor Serial:	H1032	TestDate:	2025-07-26 14:28
Calibration Name:	Polymers	Project:	POLYMER COMP.
Contact Agent:	None	Material:	POLYMERS
		SampleID:	1-5

MeasurementResult:

Measurement Data

#	k (W/mK)	Effusivity (Ws½/m²K)	R²	1/m	Temperature (°C)
1	0.5642	1111.8	0.9997	33.7	26.1
2	0.5568	1198.8	0.9997	33.6	26.1
3	0.5592	1199.0	0.9998	33.6	26.1
4	0.5673	1218.8	0.9997	33.8	26.1
5	0.5789	1285.3	0.9998	33.8	26.1

(b)

Figure 2. (a) C-Thermal Conductivity Analyzer; (b) Thermal Conductivity Results for Samples

Thermal Conductivity Testing

The thermal conductivity of the five hybrid composite specimens was assessed using the C-type Thermal Conductivity Analyzer as shown in Figure 2(a), based on the Modified Transient Plane Source (MTPS) technique. Uniform square samples of 10 mm × 10 mm were prepared, cleaned, and placed in direct contact with the MTPS sensor to ensure accurate heat transfer measurements. A low-voltage electrical current was passed through the sensor to generate a transient heat pulse, and the analyzer recorded the temperature response at the sensor–sample interface. The rate of temperature rise was inversely proportional to the material's conductivity, allowing direct calculation of thermal conductivity (W/m·K) values. Each specimen tested multiple times to minimize experimental errors, and the averaged results were used for comparison. This method proved highly effective for analyzing hybrid composites, as it captured variations due to the presence of both synthetic glass fibers and natural fibers like jute, banana, and sugarcane.

The thermal conductivity values of the composites ranged from 0.5568 to 0.5789 W/m·K, indicating moderate heat transfer capability across all samples. Sample 2 (glass + sugarcane) showed the lowest conductivity (0.5568 W/m·K), reflecting the insulating nature of natural fibers, whereas Sample 5 (40% resin, 60% glass) exhibited the highest value (0.5789 W/m·K), confirming the superior heat conduction ability of glass-rich composites. The results also showed a consistent trend of increasing conductivity from Sample 1 to Sample 5, demonstrating that fiber hybridization and proportion directly influence thermal performance. Thermal effusivity values, ranging from 1111.8 to 1285.3 Ws½/m²K, followed a similar pattern, with Sample 5 achieving the highest (1285.3 Ws½/m²K), indicating better heat absorption and dissipation potential. The high linearity of the data (R^2 = 0.9997–0.9998) confirms the reliability of the measurements as shown in Figure 2(b). These findings suggest that while natural fiber composites are better suited for insulation, glass-rich hybrid composites such as Sample 5 are more appropriate for thermal management applications in automotive, aerospace, and electronics.

Atomic Force Microscopy (AFM) Testing

AFM was USED to analyze the surface morphology and roughness of the five composite specimens at the nanoscale. Each sample of 10 mm × 10 mm was cleaned to remove impuritiess and mounted securely on the sample stage to prevent vibrations during scanning. The AFM probe, consisting of a sharp tip attached to a cantilever, was brought in close proximity to the specimen surface. Scanning was conducted in tapping mode to avoid sample damage, while the interaction forces between the tip and the surface were recorded by a laser–photodiode detection system. The data was processed by the AFM software to generate three-dimensional (3D) topographical images as shown in Figure 3, providing detailed insights into fiber dispersion, surface smoothness, and interfacial bonding. Parameters such as average roughness (Ra), root mean square roughness (Rq), and peak-to-valley height (Rz) were obtained for quantitative comparison of the specimens.

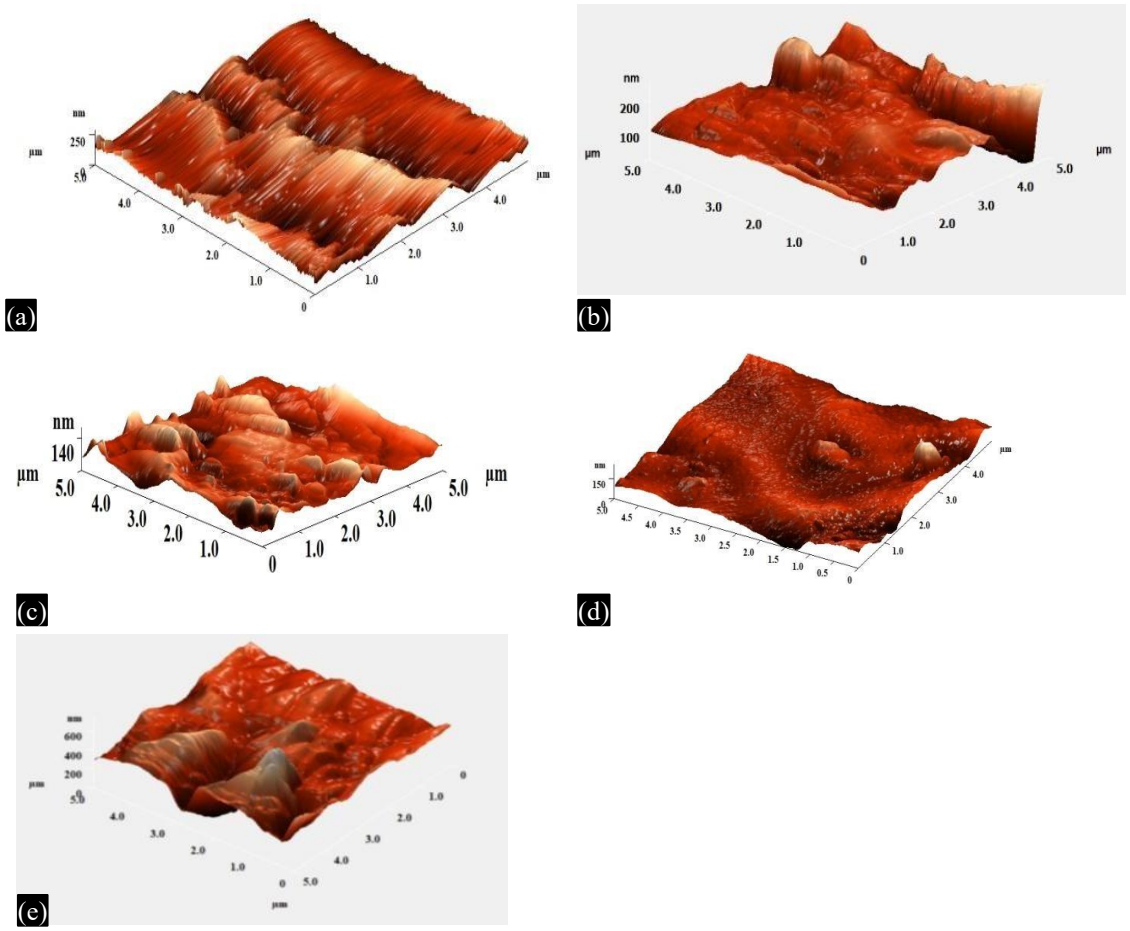


Figure 3. 3D Surface topography maps of different sample regions obtained via AFM

Scanning Electron Microscopy Analysis

Scanning Electron Microscopy (SEM) was employed to investigate the surface morphology and interfacial bonding of the five composite specimens, providing high-resolution images that reveal microstructural features such as fiber distribution, cracks, and voids. The analysis showed that hybrid composites containing natural fibers like jute, banana, and sugarcane exhibited irregular surfaces and partial fiber pull-outs, indicating weaker adhesion compared to glass rich specimens. Sample 1 (glass–jute) displayed moderate bonding with some voids, while Sample 2 (glass–sugarcane) showed poor wetting and higher porosity. Sample 3 (glass–banana) had improved interfacial bonding with fewer gaps, suggesting better compatibility between banana fibers and the resin. In contrast, Sample 4 (50% glass) and Sample 5 (60% glass) showed uniform fiber alignment, minimal voids, and strong adhesion, reflecting superior structural integrity. SEM images also confirmed the positive influence of alkali treatment on natural fibers, as treated surfaces appeared rougher and cleaner, enhancing resin impregnation. The SEM results at 1 µm magnification revealed distinct microstructural features of the hybrid composites, with the resin phase appearing smooth and continuous around the fibers. Glass fibers were observed as uniform cylindrical structures, while natural fibers like jute, banana, and sugarcane showed rough surfaces with fibrils, enhancing resin adhesion, especially after alkali treatment and a similar trend was observed in Devireddy, S. B. R., & Biswas, S [23]. Small voids and resin-rich zones were present due to hand lay-up processing, though areas of proper impregnation confirmed effective wetting. Strong bonding was seen where fibers were well-embedded in resin, while weak adhesion was marked by gaps or partial pull-outs. Glass-rich samples showed uniformity, whereas natural fiber samples exhibited higher variation due to porosity. Overall, SEM confirmed that hybrid composites achieved a balanced structure, supporting the mechanical and thermal performance results.

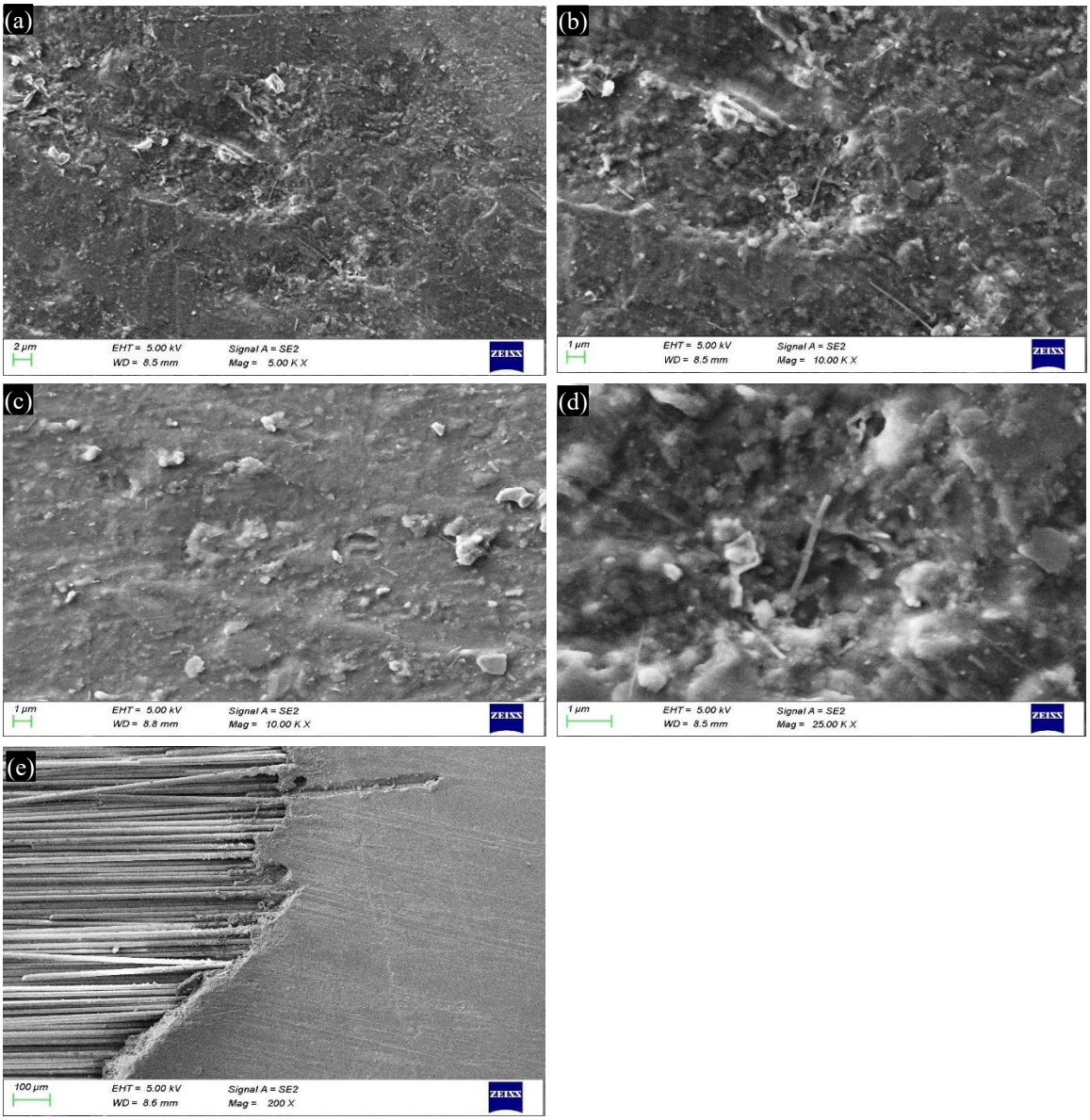


Figure 4. (a)–(d)Scanning Electron Microscopy (SEM) Images Showing the Surface Morphology of the Samples

RESULTS AND DISCUSSION

Scanning Electron Microscopy (SEM) results regarding the surface morphology and interfacial bonding of the five composite specimens is shown in Figure 4. The thermal analysis results show that Sample 5 demonstrated the highest thermal stability, retaining 4.594 mg residue (about 41.6% higher than Sample 4 and nearly 95% higher than Sample 1) within the 300–500°C decomposition range, making it best suited for high-temperature applications. Sample 4 also performed well with 4.006 mg residue, significantly higher than Sample 3 (2.59 mg) and many times greater than Samples 2 and 1.

In contrast, Sample 3 showed moderate stability, while Samples 2 (0.542 mg) and 1 (0.209 mg) were highly unstable, retaining negligible residue. Overall, Sample 5 ranked best, followed by Sample 4, whereas Samples 1 and 2 proved unsuitable for thermal resistance applications as shown in Figure 5.

The thermal conductivity results indicate a progressive improvement across the five samples, reflecting differences in fiber–resin bonding and structural composition as shown in Figure 6. Sample

5 shows the highest conductivity at 0.5789 W/mK, attributed to optimal fiber dispersion and strong resin interaction, which reduces voids and enhances heat transfer. Sample 4 follows with 0.5673 W/mK, demonstrating very good thermal performance, while Sample 1 has a mid-range value of 0.5642 W/mK. On the lower end, Sample 2 records the lowest conductivity at 0.5568 W/mK, likely due to less uniform fiber distribution, whereas Sample 3 slightly improves to 0.5592 W/mK. Overall, the thermal conductivity ranking is Sample 5 > Sample 4 > Sample 1 > Sample 3 > Sample 2, confirming that proper fiber alignment and resin integration enhance composite heat transfer efficiency.

The graph shown in Figure 7, provides the effusivity results reflect the composites' ability to absorb and release heat, with Sample 5 showing the highest value at 1285.3 Ws½/m²K, indicating superior thermal energy exchange due to optimal fiber–resin integration and reduced localized resistance. Sample 4 follows at 1218.8 Ws½/m²K, demonstrating that higher glass fiber content enhances thermal response. Lower-performing samples include Sample 1 with the lowest effusivity of 1111.8 Ws½/m²K, while Samples 2 and 3 show intermediate values of 1198.8 Ws½/m²K and 1199 Ws½/m²K, respectively. The ranking based on effusivity is Sample 5 > Sample 4 > Sample 3 > Sample 2 > Sample 1, confirming that improved fiber distribution and resin impregnation enhance thermal energy management, with Sample 5 being the most efficient hybrid composite.

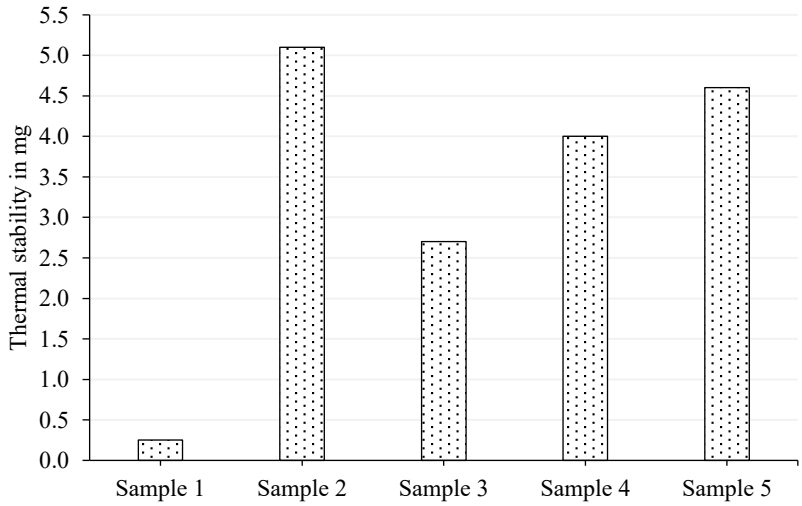


Figure 5. Thermal stability results.

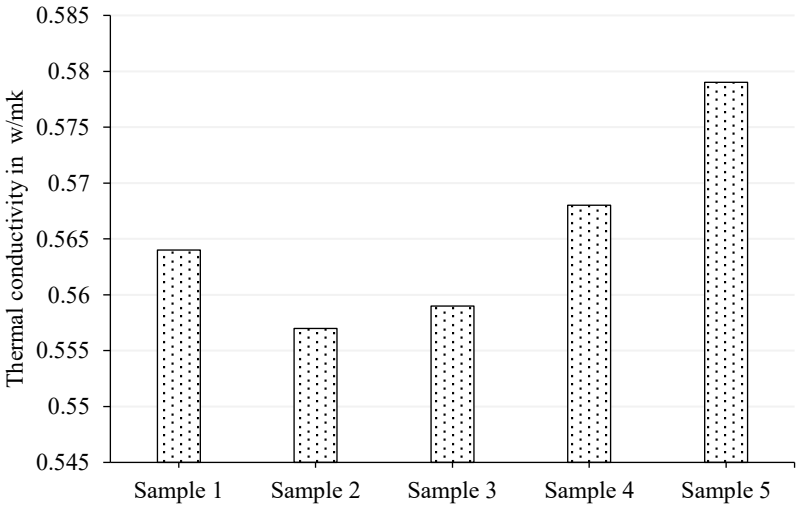


Figure 6. Thermal conductivity results.

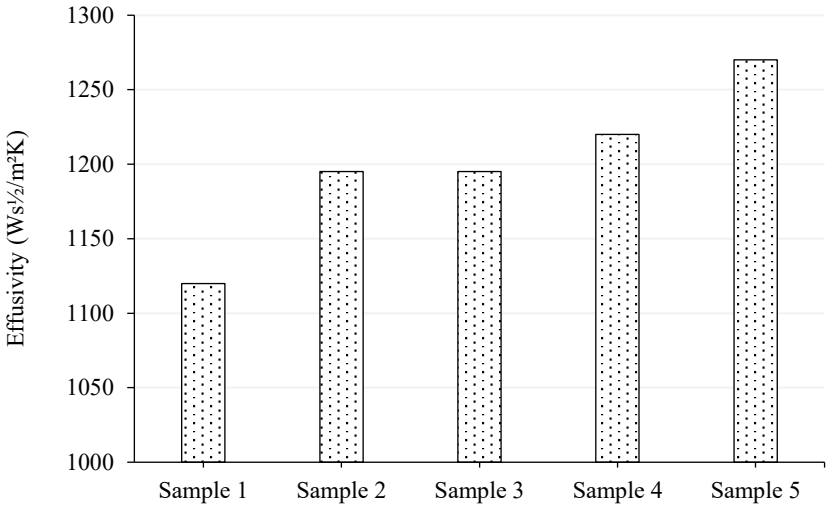


Figure 7. Effusivity Results.

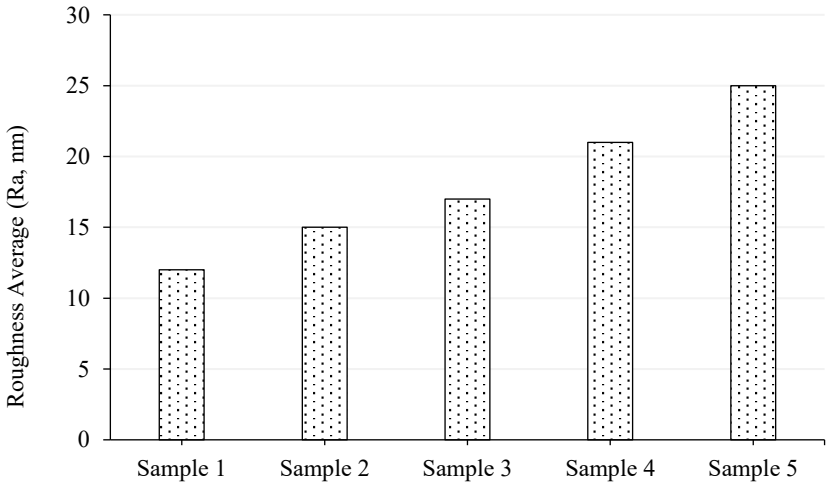


Figure 8. Roughness results for different samples.

The AFM analysis revealed variations in surface texture and bonding quality among the composite samples is presented in Figure 8. Sample 1 exhibited the smoothest surface with an Ra of 12 nm, waviness of 16 nm, and RMS of 14 nm, indicating uniform fiber–resin adhesion. Incorporation of natural fibers in Samples 2 and 3 slightly increased roughness (Ra of 15 nm and 18 nm), reflecting the uneven morphology of sugarcane and banana fibers. Samples 4 and 5, with higher glass fiber content, showed the highest roughness, with Sample 5 reaching Ra of 25 nm, waviness of 28 nm, and RMS of 27 nm, due to increased fiber volume and less uniform resin coverage. While higher roughness may affect surface aesthetics, it enhances mechanical interlocking and adhesion. Overall, natural fiber–rich composites yielded smoother surfaces, whereas glass fiber–dominant samples offered higher roughness, potentially improving structural bonding [24].

CONCLUSION

The experimental study of hybrid composites showed clear differences in thermal and structural performance based on fiber type and resin-to-glass ratios. Sample 5, with 60% glass fiber, exhibited the highest thermal stability (residue 4.594 mg) and decomposition range of 300–500°C, making it the best-performing specimen, while natural fiber hybrids (Samples 1–3) degraded earlier, with residues of 0.209–2.59 mg. Sample 4, containing 50% glass fiber, also performed well (residue 4.006 mg),

confirming that higher glass content enhances thermal resistance. Thermal conductivity and effusivity tests supported these findings, with Sample 5 achieving 0.5789 W/mK and 1285.3 Ws½/m²K, surpassing natural fiber hybrids, which showed moderate values (e.g., Sample 3: 0.5592 W/mK and 1199 Ws½/m²K). Overall, Pure glass fiber composites exhibit a higher level of thermal performance. In contrast, hybrid composites, especially those with natural fibers like banana fiber, present a more favorable integration of environmental benefits, reasonable thermal stability, and permissible heat transfer, which qualifies them for use in sustainable applications.

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