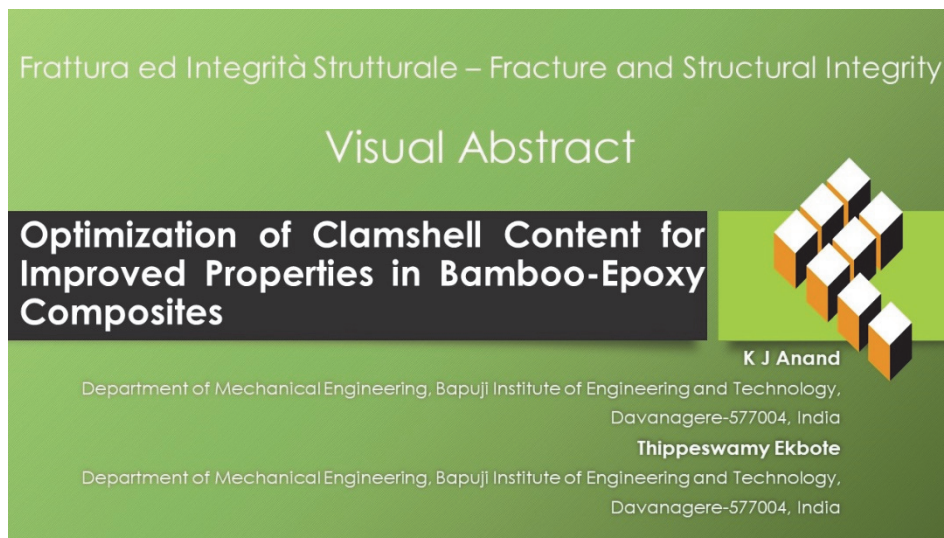# Optimization of clamshell content for improved properties in bamboo-epoxy composites

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INTRODUCTION

P olymer composites reinforced with glass and carbon fibers have been extensively utilized in many different sectors and demand for them has increased significantly in recent years. The usage volume of FRP composites in 2021 was estimated to be 12.1 million tons, with an estimated production value of USD 100 billion [1]. However, increasing demand and production of these materials have raised concerns regarding resource depletion, energy consumption, waste generation, and sustainability. The projected energy consumption and carbon dioxide emissions per kilogram of glass fiber production are roughly 48.5 MJ and 2.04 kg, respectively [2]. Furthermore, only a small portion of FRP composite wastes get recycled and the majority of the waste is either burned or deposited in landfills, thus contributing to environmental contamination and harming the ecosystem [3]. This significant adverse influence stemming from the manufacturing and disposal of polymer composites on the environment has prompted the scientific community to explore eco-friendly materials that are derived fully or partially from renewable sources. This has led to the development of eco-friendly bio-based matrices and natural fibre composites owing to their sustainability, renewability, and bio-degradability [4]. Studies have demonstrated that proteins sourced from food and polysaccharides sourced from plants can be harnessed to develop

eco-materials offering a potential substitute for synthetic polymers [5]. Biopolymers derived from agricultural and food sources such as wheat protein, wheat gluten, soy proteins, corn zein, egg, and polysaccharides including chitosan, cellulose, and starch have been extensively researched to create polymers envisioned as replacements for synthetic polymers in packaging and other applications, exhibiting exceptional biodegradability at a comparatively low cost [6]. Composite made of wheat gluten matrix with dialdehyde starch filler, and glycerol plasticizers exhibit improved tensile strength and reduced moisture absorption [7]. However, it has been noted that polymers derived from natural sources, exhibit lower elongation and induce brittleness. Further, proteins and polysaccharides-based biopolymers application is limited due to their strength and stiffness capabilities. To improve the performance and extend their applications, natural fibers are reinforced in these biopolymers. Studies showed that fiber addition has a significant positive correlation with the strength characteristics of biopolymers [8]. Wheat gluten biocomposite when reinforced with short hemp fibers increased the matrix modulus and contributed to the overall improvement of the composite properties [9]. Wheat gluten-starch-glycerol biocomposites reinforced by jute, coconut, and sisal fibers enhanced mechanical properties [10]. These plant-based natural fibers also emerged as an alternative to synthetic fibers in developing FRP composites. These composites offer several benefits, making them attractive for various applications [11]. However, natural fibre composites are also associated with challenges despite these advantages. They have poor compatibility with the matrix and tend to absorb moisture easily because of their hydrophilic nature. This can lead to weak fibre-matrix interfacial adhesion and degradation, affecting overall durability and properties. For natural fibre composites to be widely accepted, issues like weak interfacial adhesion and moisture absorption must be resolved [12]. Much research was done to address the shortcomings of the fibres to increase the capabilities and applications of these materials. Prior research on this subject demonstrated that adding filler particles to the polymeric matrix could improve fibre-matrix adhesion, thereby improving the composites' overall performance [13,14]. The majority of these earlier studies focused on the use of various types of ceramic/inorganic fillers [15,16]. However, in recent years, increasing environmental awareness has shifted focus to reusing waste materials for sustainable growth. As a consequence, emphasis on the use of waste material as filler has gained significant prominence, and extensive research work has been reported on utilizing various types of waste, residues, and by-products as reinforcement/filler for developing polymer composites [17–19].

Sumesh et al. [20] used biowaste fillers from pineapple, banana, and coconut plants to develop hybrid composites and investigated the mechanical properties. Results revealed that composite provided the best properties by adding biowaste fillers. K. C. Anil et al. [21] used industrial wastes like fly ash, red mud, and aluminium powder to create hybrid epoxy composites. The outcome demonstrates that hybrid composites containing FA, RM, and aluminium powder (6/1.5/1.5 wt%) had the highest hardness, tensile modulus, and flexural strength. Pramod V. Badyankal et al. [22] examined the effect of naturally available fillers like fly ash, sawdust, kolam, and coconut shell powder on the mechanical and wear properties of hybrid sisal, banana, and pineapple fibre-reinforced epoxy composites. Results showed that all fillers positively influence composite properties. Coconut shell filler gave the best results compared to other compositions. Vivek S, Kanthavel [23] reported that adding bagasse ash filler in hybrid plant fibres epoxy composites significantly improved thermal and mechanical properties. Velmurugan K et al. [24] used chicken feather with eggshell particles to develop a hybrid jute-epoxy composite. Composite with 10% eggshell had the highest hardness, tensile, and impact properties. Panneerdhass R et al. [25] examined groundnut content effect on the mechanical properties and moisture-absorption capabilities of luffa fibre-epoxy composites. The findings indicate that hybrid luffa fibre composites reinforced with groundnut have superior mechanical properties compared to composites reinforced only with luffa fibre. Saba N et al. [26] reported that adding palm oil nanofillers significantly improved the mechanical properties of the kenaf fibre-epoxy composite. S. Ramu et al. [27] examined the properties of bamboo fibre, and rice husk epoxy composite with and without the addition of MWCNT. Their studies revealed that adding fillers reduced voids in composites, improved interfacial bonding, and contributed to overall enhancement in properties. Panda et al. [28] utilized red mud filler with bamboo epoxy composite and reported adding red mud up to 10 wt.% enhanced its mechanical properties. However, a further addition of filler was not beneficial. As filler % increased, void content decreased, whereas the hardness of composites improved. Anu Gupta et al. [29] examined the industrial wastes cenosphere flyash, and cement by-pass dust particulate fillers' effect on water absorption and chemical behaviour of bamboo fibres composites. Composites with fillers exhibited good chemical and water resistance. The author also reported that bamboo-composite having 10 wt% cement by-pass dust filler improves the mechanical and erosion wear behaviour [30]. Sukumar. N et al. [31] studied bamboo fibre epoxy composite with bagasse as filler. They reported that bamboo fibre and bagasse filler reinforcement significantly changed the composites' water absorption and strength properties. A study by H Jena et al. [32] testified that including cenosphere in bamboo epoxy composite enhanced mechanical properties, and composites with 33 wt % bamboo fibre and 3 wt % cenosphere exhibited the highest properties. Based on the literature review, it is clear that the hybrid polymer composites created with fillers derived from agricultural residues/industrial waste has been acknowledged as a viable method to create sustainable, environmentally friendly,

affordable composites with improved properties. Despite numerous research studies on using waste fillers from various sources, relatively few studies published on utilizing marine wastes such as seashells. Seashells are considered unique biowaste produced by the marine food business, specifically from bivalves like clams, oysters, mussels, and scallops. The bivalve production process discards a significant proportion of the shell. It produces a lot of solid waste, which is disposed of on land or in coastal seas and deteriorates the surrounding ecosystem. To solve this issue, attempts have been undertaken to repurpose shell waste in various methods [33]. Recent research has indicated that sea shell wastes, which are predominantly composed of calcium carbonate (about 95%), have the potential to be used as an affordable filler material in place of commercial $CaCO_3$ filler when developing polymer composites [34,35]. Y. Mahshuri & M. A. Amalina [36] reported that the hardness and compressive strength of the unsaturated polyester matrix improved by the introduction of $CaCO_3$ bio filler derived from clamshell and finer particles exhibited better results than courser particles for the same filler loading. C.U. Atuanya et al. [37] used snailshell with recycled LDPE to develop bio composites with varying weight percentages (0-15 wt%) and particle sizes. Flexural and tensile strength increased with the increase in the wt% of snailshells. 75 µm fine particle samples exhibited better properties. Vasanthkumar P et al. [38] investigated the influence of seashell particulate (3, 6, and 9 wt%) reinforcement on the thermal & mechanical properties of nylon 66 polymer composite. Investigation showed that the seashell particles of 75 µm size enhanced the matrix properties, and the composite with 6% filler exhibited the highest elastic strength. H. Jena et al. investigated the mechanical properties of hybrid jute fibre epoxy composites with clamshell filler [39]. Studies revealed that with the increase in filler content, the hardness of the composites increased, but impact strength decreased. While enhancement in strength was observed up to 5% filler addition, further addition resulted in the reduction of strength.

Based on the preceding discussions and literature review available, it has been observed that there hasn't been much research done on natural fibre composites using sea shell filler. As per the author's knowledge, research on a hybrid bamboo-epoxy composite that includes seashells as a filler material has not yet been reported. Motivated by this observation, the authors propose this pioneering work with the primary aim of developing hybrid composites that optimize the synergies among bamboo fibres, epoxy, and seashell fillers. Hybrid composites were developed with different filler wt% and properties were evaluated by conducting tests as per ASTM standards. SEM was used to perform fractographic analysis on fractured samples to determine the failure mechanism.

MATERIALS

Bamboo and epoxy are selected as the main fibre & matrix constituents to develop base composite specimens. Bamboo-epoxy composite material is a material that combines the strength of the bamboo fibre and the durability of epoxy resin [40]. The filler material to develop hybrid composites is derived from seashell waste. Clamshell, an abundantly available sea shell, is chosen as a secondary reinforcing material. The discarded clamshells are collected from the seashores of Mangalore, coastal Karnataka, India. The collected clamshells are first cleaned thoroughly with water to remove any dust and organic matter and then kept to dry under sunlight for 3 days. Using a mechanical jaw crusher these clam sea shells are pulverized to obtain a filler particulate and are sieved to get filler of 75 µm size. Bamboo mat - Twill woven type (2/2, 150 GSM) was supplied by Sreenath weaving Industry Rajasthan, India. Fig. 1 shows CS filler and bamboo mat fibre used in this work. Epoxy L12(density = 1.15–1.20 g/cc) with hardener K6 (density = 0.95 g/cc) from Atul India Pvt Ltd was supplied by Yuji Marketing, Bengaluru.
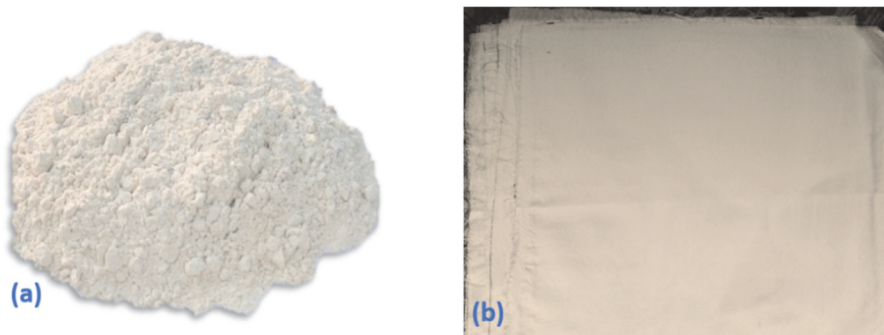

Figure 1: (a) Clamshell (CS) filler (b) Bamboo fibre mat.

PREPARATION OF COMPOSITES

Two types of composite specimens were mainly prepared to investigate the clamshell filler effect on the composite properties. The unfilled bamboo fibre-epoxy composite with 35-65 wt.% is considered for preparing base material [32] . The second type of specimens prepared was a set of hybrid composites prepared by the inclusion of clamshell filler with varying wt%. Tab. 1 shows the details of all the composites prepared.

Specimen Code	Clamshell (CS) filler (wt %)	Bamboo fibre (wt %)	Epoxy (wt %)
B-E	0	35	65
B-E/C3	3	35	62
B-E/C6	6	35	59
B-E/C9	9	35	56

Table 1: Specimens configuration details.

To develop the composites compression moulding technique was employed. Initially, the required number of bamboo mat fibre layers were cut. Then each layer of the bamboo fibre mat was impregnated with a determined amount of epoxy-hardener (10:1 ratio) mixture. A roller removes any bubbles and ensures the uniform spread of resin over the fibre surface (Fig. 2a). This process is repeated until it gets the required thickness. A similar procedure is used for the CS-filled hybrid composite preparation. First, epoxy resin was mixed with a calculated amount of CS filler particles using a mechanical stirrer for 30 minutes to obtain the homogeneity of the mixture, and then hardener was added & mixed for around 5 minutes to initiate the reaction. This epoxy-filler mixture is poured on each fabric layer and a hand roller is used to spread this uniformly over the fibre surface. Then, wetted fabrics were laid on the flat mould. The mould is then closed with a cover plate and kept in a hydraulic press, applying a pressure of 150 bar. Initially, for one hour, a temperature of 70°C is maintained. Then, it is allowed to cure at room temperature for the following 24 hours as shown in Fig. 2b. Finally, the composite plate was removed from the mould (Fig. 2c). Testing samples were cut from the developed plates for mechanical characterization testing.

Figure 2: (a-b) Fabrication process (c) Composite plate.

EXPERIMENTATION

Density and Void content of composites

Eqn. (1) is used to calculate the theoretical density, and the experimental density of composites is found using the water immersion method based on Archimedes' principle, in which the sample is first weighed in air and then in water. The void content of composites was calculated by Eqn. (2).

$$\varrho_{th} = \frac{1}{\dfrac{w_m}{\varrho_m} + \dfrac{w_f}{\varrho_f} + \dfrac{w_p}{\varrho_p}} \qquad \text{(g/cc)} \qquad\qquad (1)$$

where ρ_{th} is the theoretical density of composite in g/cc, w_m, w_f, w_p and ρ_m, ρ_f, ρ_p are weight fractions in % and densities (in g/cc) of matrix, fibre, and filler, respectively.

$$\text{Void content}\left(\%\right) = \frac{\varrho_{th} - \varrho_{exp}}{\varrho_{th}} \times 100 \qquad\qquad (2)$$

where ρ_{exp} is the experimental density of the composite in g/cc.

Hardness test

A Shore D hardness test in compliance with ASTM D2240 standards was employed to evaluate the hardness of composites. Each sample undergoes testing at five distinct surface locations. The hardness number of each sample is determined by taking the average of the five readings taken at these distinct points.

Mechanical properties

Tensile, bending, and impact tests are conducted on composites to evaluate their mechanical properties. The tensile test is conducted using a Zwick/Roell Z020 UTM (20 kN load cell capacity) at a cross-head speed of 2 mm/min as per the ASTM 3039 standard. The bending test was done on the same machine employing a 3-point bending method according to ASTM D 790 standard as depicted in Fig. 3.
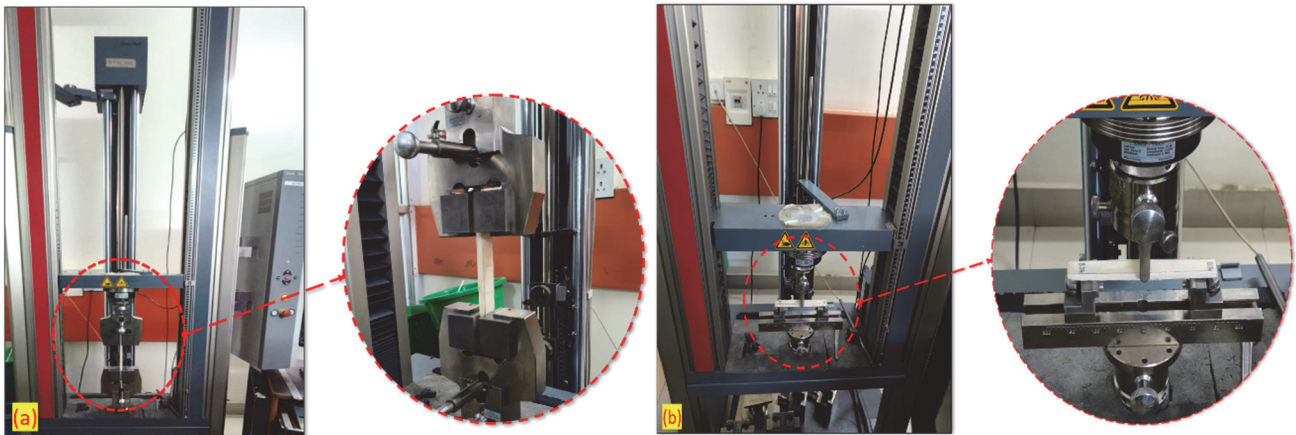

Figure 3: Testing of the composite: (a) Tensile testing (b) Bending test.
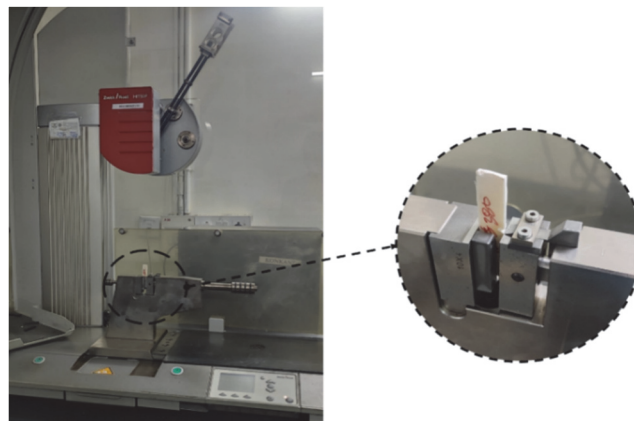

Figure 4: Impact testing of the composite.

The impact strength was determined by conducting an Izod impact test as per ASTM D 4812 standard using ZWICK /ROELL HIT 50P impact machine. Before testing, a V-notch was made on each sample. The specimen was then held as a cantilever beam in a vertical position and fractured by a single pendulum swing, as depicted in Fig. 4. Then, impact energy (J/m) readings displayed were taken, and the average impact energy calculations for each specimen were done. All the tests were repeated 5 times for each type of composite to increase the reliability of results and average data was considered to analyze the properties of each composite.

RESULTS AND DISCUSSIONS

Density and Void analysis

The density, void, and hardness of the composites determined are shown in Tab. 2. The density of hybrid composites increased proportionally with the inclusion of CS filler in the composites. This could be because the clamshell particles have a higher density than epoxy, and incorporating high-density clamshell particles embedded in the low-density epoxy matrix will increase the composite's density. As more clamshell particles are added, the overall density of the composite increases. Further, it can be observed that the addition of filler resulted in a reduction of voids due to the proper dispersion of filler particles. For uniform and homogeneous distribution of the filler within epoxy resin, adequate mixing of filler particles in the resin mixture was done carefully during the fabrication process. Better adhesion allows the filler particles to fill up the spaces, which reduces the number of voids in hybrid composites.

Specimen Code	Theoretical Density (g/cc)	Experimental Density (g/cc)	Void content (%)	Hardness (Shore D)
B-E	1.167	1.114	4.5	71.8
B-E/C3	1.188	1.148	3.4	80.5
B-E/C6	1.210	1.175	2.9	85.6
B-E/C9	1.233	1.196	3.05	84.2

Table 2: Density and Hardness results.

Hardness

Fig. 5 represents a graph obtained by recorded hardness values of various compositions of B-E composites. From the results, it is evident that the inclusion of CS filler increased the hardness. Composite with 6% clamshell records the highest hardness number 85.6 and the hardness increased by 19.20 %. This improvement in hardness can be attributed to the presence of high $CaCo_3$ content in clamshell material within the epoxy matrix.
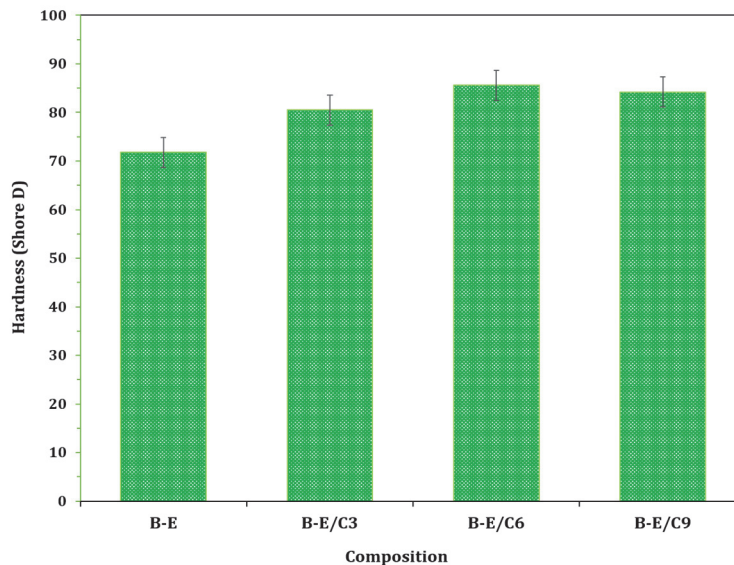

Figure 5: Hardness of the composites.

Tensile test result

Tensile strength and modulus results obtained from tensile testing of composite samples are shown in Fig. 6. It is evident that the CS-filled B-E composites have more strength than the unfilled B-E composites. The tensile strength of composites increases with an increase in filler content. Adding 3 wt% CS filler slightly improved the tensile strength of the composite from 39 MPa to 42.5 MPa. The composite attained maximum strength for 6 wt% filler inclusion, exhibiting the highest tensile strength of 47 MPa and modulus of 790 MPa. Compared to the unfilled B-E composite, an improvement of 20.5% in tensile strength and a 16.8 % increase in modulus was achieved for this filler loading in the B-E composite. With the inclusion of filler, uniform dispersion of CS particles results in lower voids in composites, leading to better wettability of the fibres. Improvement in interfacial bonding enhances the load-bearing capacity of composites by providing a better transfer of the stresses, leading to an increase in strength. Further addition of CS filler to 9 wt% resulted in a decrease of tensile strength. At higher filler concentrations, agglomeration of filler particles occurs. This results in weaker bonding, eventually causing a decrease in load transfer and interfacial stress, leading to early failure.
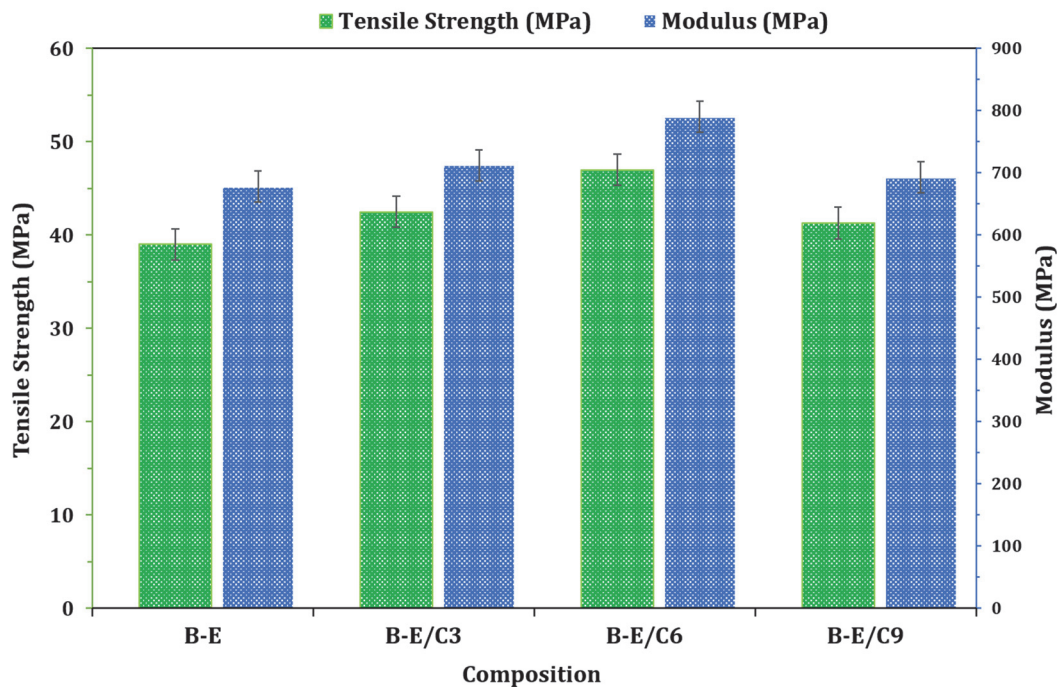

Figure 6: Tensile test results of composites.

Bending test result

The behaviour of composites for various filler loadings under bending load has shown characteristics similar to tensile loading. Fig. 7 shows the results obtained from bending tests for all the composite specimens. As shown in the figure, incorporating CS filler in B-E composites has enhanced the bending strength and modulus due to good interaction of CS particles with the matrix. This improves interfacial adhesion, leading to improved stress transfer and higher strength. Under bending load, composite with 6 wt% CS filler has also shown a maximum strength. It has a bending strength of 87.5 MPa and a modulus of 4.85 GPa compared to the unfilled B-E composite with a lowest bending strength of 70.3 MPa and modulus of 4.10 GPa. Adding filler content up to 6 wt% in composite improved bending strength by 24.4% and 18.3 % in modulus. However, at 9 wt% filler strength was slightly decreased to 82.5 MPa and modulus to 4.35 GPa, a decline of 5.7% in bending strength & 10.3 % in modulus. This decline in strength at higher CS filler concentrations can be mainly attributed to filler particle agglomeration, which weakens the material and reduces its strength.

Impact test result

Fig. 8 displays the impact strength of the composites with varying weight percentages of CS filler.

The impact strength of composites decreases with the addition of filler. At 61 J/m, the B-E composite has the highest impact strength. Impact strength decreased by 5.6% and 10%, respectively, with 3% and 6% additions of CS filler, indicating

filler has a negative effect on the impact strength of composites. The lowest impact strength of 52 J/m was recorded for 9 wt.% of CS filler. Including CS filler increased the hardness, which may have reduced the fibre-matrix interface's ability to absorb less energy under impact load, leading to the observed reduction in impact strength. Similar results were recorded by H. Jena et al. [39] when they added clamshell filler to jute epoxy composite, impact strength was decreased. They explained this decrease by pointing to the addition of filler to the neat polymer, which enhanced its hardness and decreased its crystallinity.
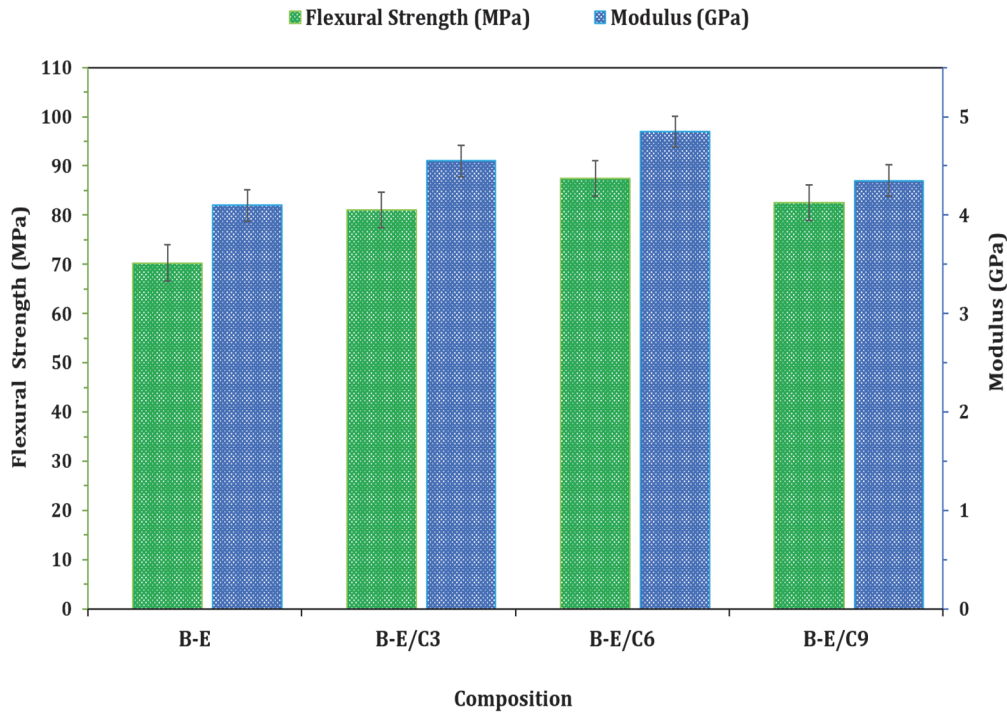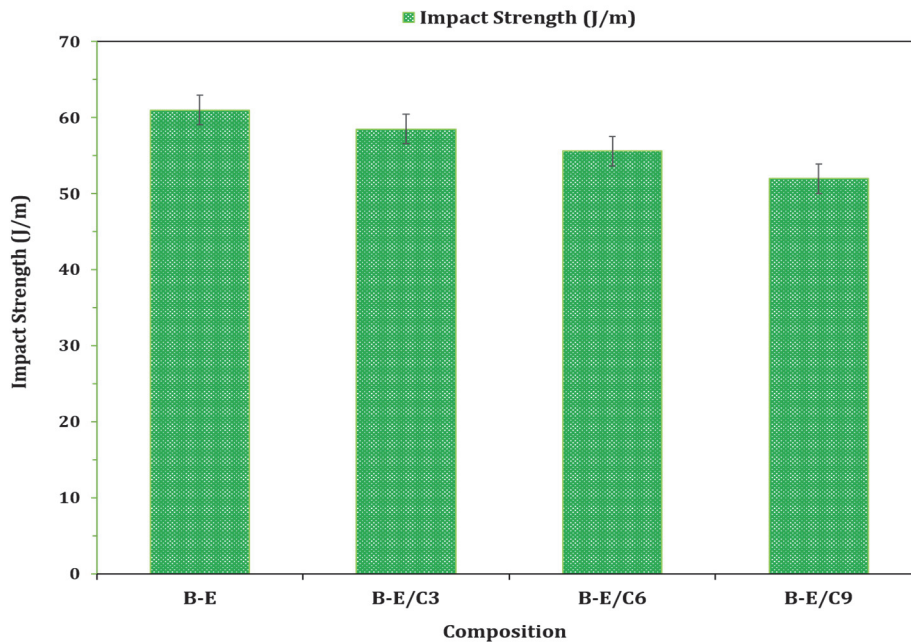

Figure 7: Bending test results of composites.

Figure 8: Impact test results of composites.

From the findings, it is evident that the enhancement of mechanical characteristics in composites, such as tensile strength, tensile modulus, flexural strength, and flexural modulus, was achieved through the incorporation of CS filler. While the introduction of CS filler resulted in an enhancement of composite properties, there is a limitation to the filler incorporation. Higher filler content negatively affected composite characteristics. In summary, it can be concluded that CS filler particles were efficiently utilized as a cost-efficient filler in hybrid composites, with the optimal filler content identified as 6%.

A similar observation was made when the clamshell filler was incorporated into the jute-epoxy composite [39]. The addition of clamshell filler improved the tensile and flexural strength up to 5 wt.%, but strength decreased at higher wt.% of filler. Tab. 3 shows a comparison of results obtained for two different hybrid composites with clamshell filler. The comparative analysis highlights significant differences in the performance of these composites. Hybrid bamboo-epoxy composite outperforms the hybrid jute-epoxy composite in both tensile and flexural strength. Bamboo hybrid composite has a tensile strength of 47 MPa and a flexural strength of 87.5 MPa. Whereas the jute hybrid composite has a tensile strength of 35.6 MPa, which is lower than that of the bamboo hybrid composite, and with a flexural strength of 43 MPa, the composite demonstrates less than half the bending resistance of the bamboo hybrid composite.

Composite Material	Optimum Clamshell Filler (wt.%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Reference
Bamboo/Epoxy/Clamshell	6	47	87.5	Present work
Jute/Epoxy/Clamshell	5	35.6	43	[39]

Table 3: Comparison of results.

In summary, the outcome of the present work suggests that bamboo fibers and clamshell filler provide a more robust reinforcement for epoxy resins than jute fibers and can be considered as a potential replacement to jute hybrid composites for applications where load-bearing capacity is essential and that require bending resistance such as panels and frames.

SEM analysis of composite fractured surface
Scanning Electron Microscopy VEGA3 TESCAN with a working voltage of 10kV was used to study the fractured surfaces. SEM Micrographs of tensile and bending fractured images taken for B-E composites are displayed in Figs. 9–12.
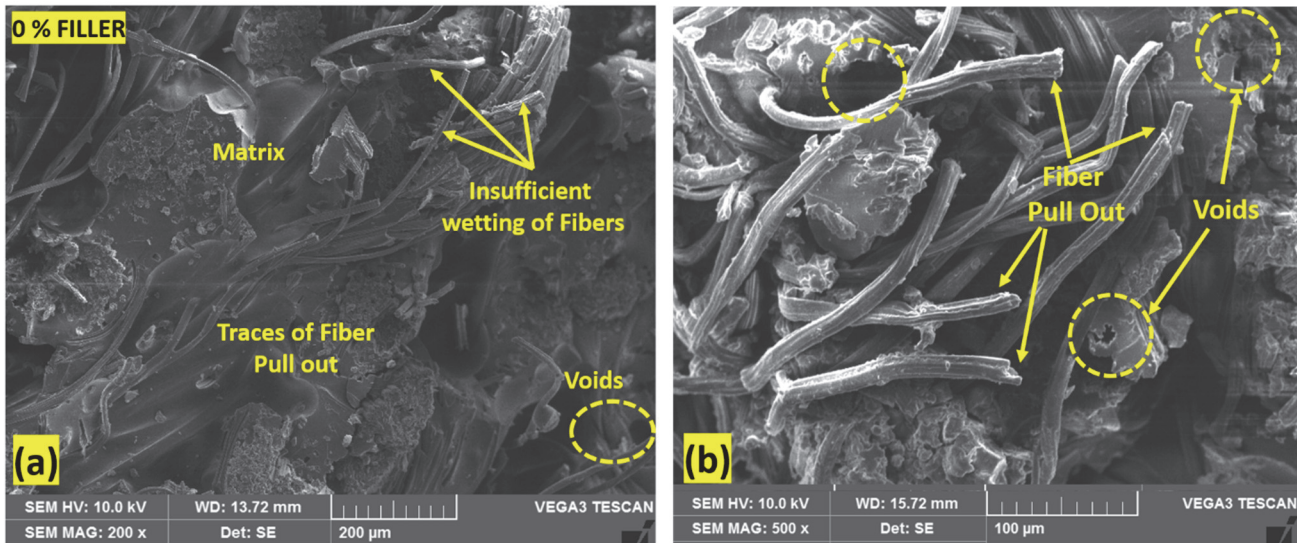

Figure 9: SEM images of a fractured tensile specimen of B-E composite (without filler).

For composite without filler, SEM images of the tensile fractured specimen are displayed in Fig. 9. The presence of voids in fairly recognizable and inefficient wetting of fibres was evident in the fractured samples. Subsequently, this influences the wettability of the fibre. Insufficient wetting of the bamboo fibre surface will cause poor interfacial bonding. This leads to significant debonding of fibres, which may hinder the effective transmission of stress and reduce tensile strength. This occurrence of fibre detachment, fibre pull-out traces, and void formation in composite without filler is evident in Fig. 9 (a).

As displayed in Fig. 9 (b) more fibre pull-out from the epoxy matrix occurred in the fractured sample. Further, initiation and propagation of cracks in these composites occur due to the high void content.

Similar observations are made in the fractured samples obtained from the bending test as shown in Fig. 10(a). A significant presence of voids and large amounts of fibre pulled out were visible. Weak bonding between fibre and matrix reduces their bending strength. Whereas for composite with 3 wt% filler shown in Fig. 10 (b), comparatively fewer voids formed. There is less fibre pull-out, and the fibre experiences bending or breakage. Better fibre-matrix adhesion is attained as more resin is seen on the fibre surface, suggesting a modest increase in composite strength.
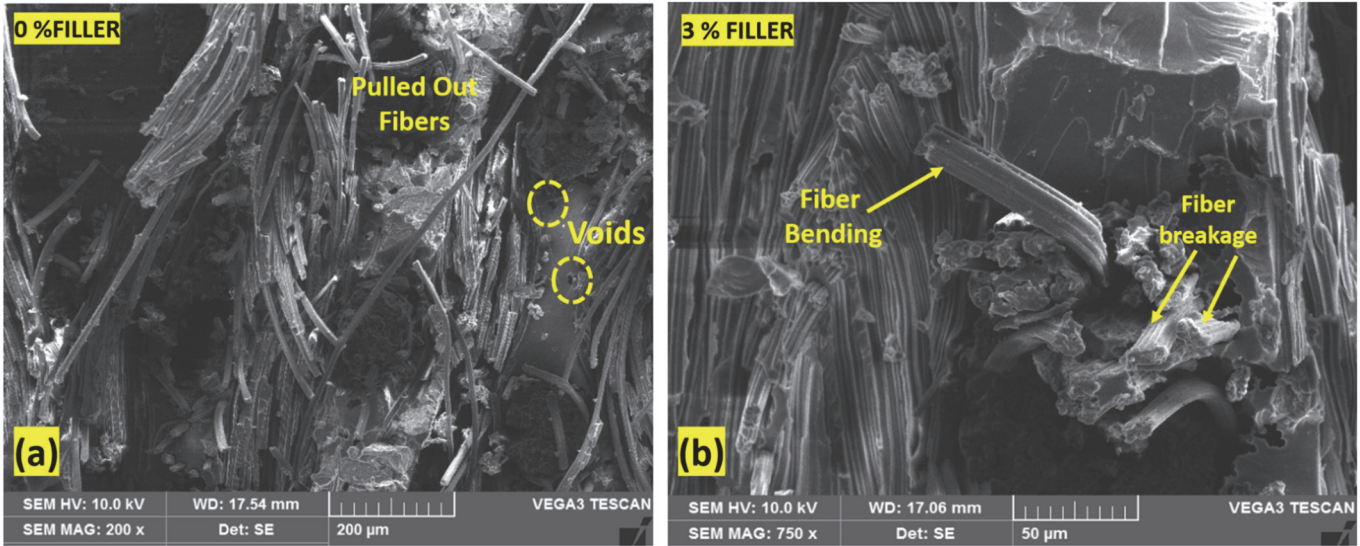

Figure 10: SEM images of a fractured bending specimen (a) B-E composite (without filler) (b) B-E/C3 composite.
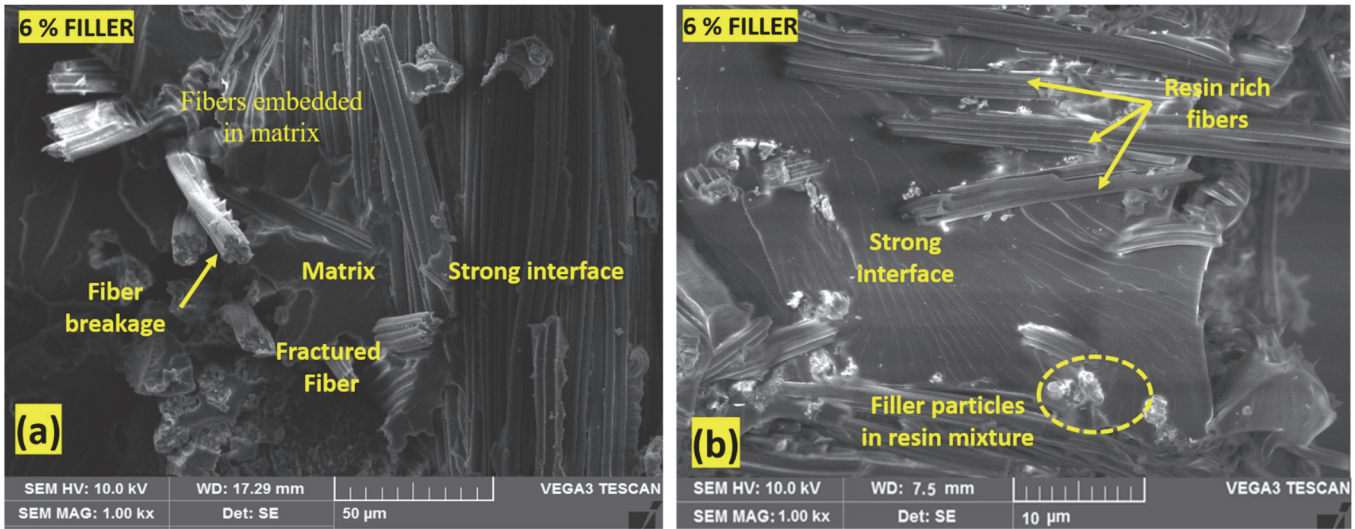

Figure 11: SEM images of fractured B-E/C6 samples (a) Tensile (b) Bending.

For composite with 6 wt% filler, Fig. 11 (a) and (b) display SEM micrographs of tensile and bending fractured specimens respectively. The morphological study of SEM reveals a uniform distribution of clamshell filler particles in the epoxy matrix, leading to fewer voids and better bonding. The fibres embedded in the matrix indicate better wetting and a strong interfacial bond between the bamboo fibre and epoxy is noticeable. This ensures efficient stress transfer, increasing the tensile strength. As evident from Fig. 11 (b) well-dispersed CS particles in the epoxy form a strong interface and an increase in the amount of epoxy on the bamboo fibre surface, ensuring enhanced wettability. As the particle loading increased to 6%, the formation of strong bonding resulted in a reduction of fibre pull-outs from the matrix and the fractured specimen showed more fibre

breakage or bending at the matrix interphase signifying the improved transfer of stresses. Hence, composite with 6 wt% filler exhibited the highest strength.

Fig. 12 (a) and (b) display SEM images of fractured surfaces of composite with 9 wt% filler under tensile and bending loading, respectively. As evident from the figure, the discontinuous phase in the matrix interface and formation of filler clusters occurs at a higher wt% of filler addition. Agglomeration of CS particles causes weak fibre wetting and a few voids around fibres. This further served as a point of failure initiation and decline in the strength of composites.
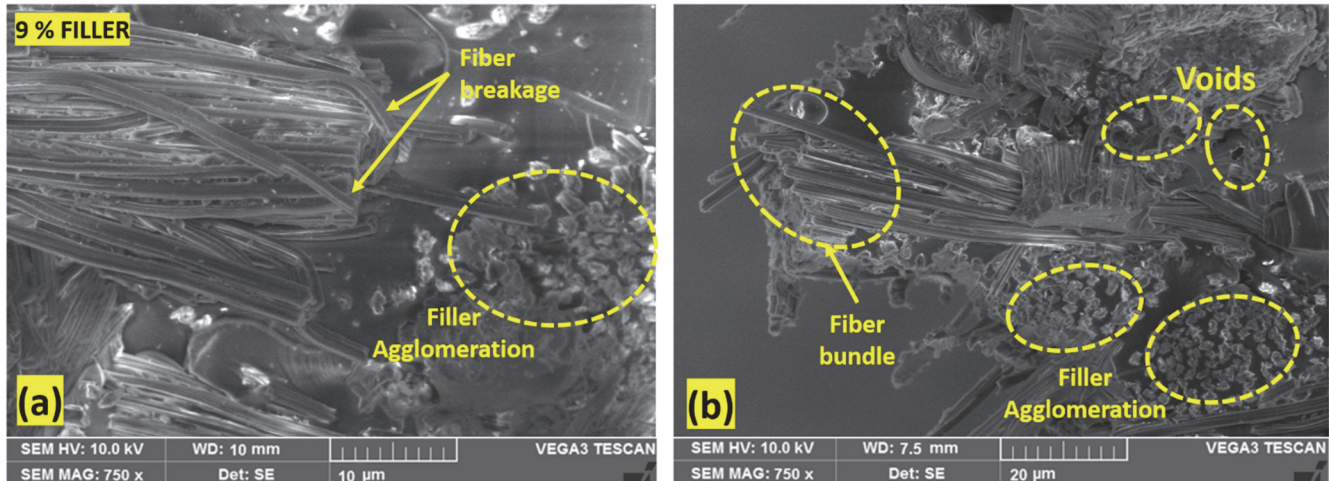

Figure 12: SEM images of fractured B-E/C9 composite samples (a) Tensile (b) Bending.

The fractographic analysis of composite with and without CS filler reveals a significant impact of CS filler inclusion on the behavior of composites. Uniform distribution of CS filler in the epoxy matrix reduced voids, ensured proper wetting of fibres as validated by the adequate presence of resin on fibers. A well-formed matrix around fibers and the formation of strong interfacial adhesion was evident which facilitated better transfer of applied stress leading to an increase in strength. Fewer fiber pullouts from the matrix were observed and the primary cause of failure was mainly by fiber breakages, indicating enhanced stress transfer. Additionally, a sufficient quantity of resin on the surfaces of pulled-out fibers was also noticeable. However, upon further increase in filler to 9% resulted in the agglomeration of fillers as confirmed by SEM image analysis. This morphological analysis explains the notable improvement in mechanical performance attained by the addition of CS filler to B-E composite and is in consistent with the results found in experimental investigations.

CONCLUSIONS

This study examined the feasibility of incorporating clamshell in developing bamboo-epoxy composite and investigated the effects of CS filler on its properties. From the present study, the main conclusions drawn are as follows:

- Composite characteristics are substantially impacted by clamshell filler. The presence of filler decreased the amount of voids in composites. With the inclusion of CS filler, the density and hardness of composites increased.
- Addition of CS filler, enhanced tensile and flexural strength, while a decrease in impact strength was observed. Composite having 6 wt% CS filler demonstrated the maximum strength with an improvement of tensile strength by 20.5% and 24.4% in flexural strength. This is explained by the strong interfacial adhesion achieved by the inclusion of CS filler, which allowed for effective load transfer.
- While composite properties are enhanced by CS filler inclusion, it has a limitation. Composite strength decreased at 9 wt% due to CS particle agglomeration. This indicates a filler addition limit, above which the strength begins to deteriorate.
- The experimental results obtained are supported by SEM analysis. The increase in composites' performance by including CS filler, as revealed by SEM, was attributed to the compatibility of CS filler with epoxy matrix and the high adhesion strength of the CS particles with the B-E composite system. A strong interfacial bonding was observed. However, mechanical properties were decreased at higher filler content. As confirmed by SEM image analysis, the addition of 9% CS filler caused agglomeration of filler particles.

- The findings of this study have set a precedent for the valorization of seashell waste and promote environmental sustainability by the creation of inexpensive, robust natural composite that may possess suitable qualities for diverse applications. Furthermore, converting otherwise worthless waste into value-added products solves a major disposal issue and contributes to a cleaner environment.
- This study has given a brief understanding of exploring biowaste filler derived from clamshell as a cost-effective alternative to traditional reinforcing fillers, without compromising much on the performance of hybrid composites. Subsequent future research could involve the integration of clamshell powder in nano-particle size or combine with other nanofillers to enhance the fiber-matrix interface and improve the impact strength. Additionally, this study opens avenues for further research into optimizing the composition and processing parameters of hybrid composites, as well as investigate their thermal and wear properties, expanding the scope of sustainable composite applications.

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