Received: 21 January 2025 | Revised: 26 April 2025 | Accepted: 28 April 2025

DOI: 10.1002/pc.30030

RESEARCH ARTICLE

INSPIRING PLASTICS PROFESSIONALS Polymer COMPOSITES WILEY

Synergistic enhancement of mechanical and water resistance properties in snake grass/luffa cylindrica fiber composites integrated with silicon carbide additive

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Funding information
Researchers Supporting Project, Grant/Award Number: RSPD2025R956; King Saud University, Riyadh, Saudi Arabia

Abstract

The growing awareness regarding environmental issues is prompting a transition from synthetic fibers to plant fiber-reinforced composites for eco-friendly applications across the automotive, aerospace, and marine sectors. In this study, we evaluated the impact of the silicon carbide (SiC) additive on the mechanical and water absorption (WA) characteristics of hybrid composites (HC) made of snake grass (SG) and luffa cylindrica (LC) fibers. Tensile analysis showed that the presence of 7.5 wt% SiC raised the tensile strength (TS) to 59.22 MPa with an increase of 38.91%. However, the increase of SiC to 10.0 wt % resulted in a reduction of strength to 53.21 MPa, with a 24.82% improvement, due to weakened adhesion between the fiber and matrix. The neat composites (SG/LC) exhibited a flexural strength (FS) of 61.27 MPa. The maximum FS was 78.63 MPa at 7.5 wt% SiC; however, increasing SiC content to 10.0 wt% led to a reduction in strength to 72.36 MPa because of particle aggregation. Impact testing results confirmed that adding SiC enhanced the fiber-matrix interface, thereby improving load transfer and enhancing the HC's ability to absorb and dissipate impact energy. The WA behavior of the SG/LC-SiC composites showed improvement with increasing SiC content, achieving a minimum of 14.89% at 7.5 wt% SiC, which is due to improved interfacial bonding and reduced voids. This research underscores the benefits of HC materials prepared from SG and LC fibers for applications in vehicle interiors and construction, such as wall panels and separators.

Highlights

- Incorporating 7.5 wt% SiC increases tensile strength by 38.91%.
- Flexural strength reaches a peak of 78.63 MPa with the inclusion of 7.5 wt% SiC.
- Water absorption decreases to 14.89% at 7.5 wt% SiC inclusion.

KEYWORDS

luffa cylindrica fiber, mechanical properties, silicon carbide, snake grass

1 | INTRODUCTION

The increasing interest in using plant fibers as reinforcements in composite materials is because of their outstanding strength-to-weight ratio, obtainability, and ability to be recovered and biodegraded after use.[1–3] Natural fiber-reinforced composites, made from materials such as snake grass, flax, kenaf, jute, madar, bamboo, ramie, and luffa cylindrica, have gained popularity in lightweight applications, mostly in the automotive and construction areas.[4–8] Snake grass fibers are lightweight and possess a low density, enhancing the overall strength-to-weight ratio of composites. Meanwhile, they are also renewable, making them an eco-friendly substitute for synthetic fibers.[9,10] Luffa cylindrica, generally known as sponge gourd, has promising potential in composite material applications because of its being lightweight, biodegradable, and having a high aspect ratio, making it suitable for reinforcing composites.[11–14]

However, a significant limitation of composites prepared from natural fibers is their comparatively lower mechanical properties and higher WA.[15–17] Hybridizing natural fibers is an effective strategy to address their inherent limitations in composite applications, enhancing mechanical performance while maintaining sustainability. Moreover, optimizing the stacking sequence further improves load distribution and helps reduce WA. To fully overcome the drawbacks of natural fibers, additional innovations such as barrier coatings, fiber surface treatments, filler integration, and advanced matrix systems are essential.[18–22] Natural fiber hybridization, therefore, broadens the application range of eco-friendly composites, allowing for stronger, more resilient materials that align with sustainable practices and environmental goals.[23–25] Consequently, there is an increased interest in research on HC composed of two or more types of natural material reinforcement. These HC include a blend of multiple fibers within a polymer matrix.[26–30]

The mechanical characteristics of HC are affected by several important factors, such as the volume or weight percentage of the fibers, the configuration of the fiber layers, the treatment methods used on the fibers, and the surrounding environmental conditions.[31–34] Consequently, examining the mechanical properties of HC that utilize natural fibers is of great importance. Nanofillers such as silica carbide, graphene, and CNTs can enhance these HCs.[35–39]

Many research studies have reported the fabrication process and properties of composites reinforced with natural fibers for a range of engineering applications. For instance, Radhakrishnan et al. (2023) compared untreated and treated date palm fiber with kenaf fiber in epoxy HC. They found that alkali-treated composites exhibited superior TS, reduced WA, and improved impact resistance due to enhanced fiber-polymer interactions from the treatment.[40] Praveenkumara Jagadeesh et al. (2023) studied the impact of stacking sequence and hybridization on vinyl ester composites. Results indicated that HC reinforced with kevlar fiber displayed enhanced tensile, flexural, and impact characteristics, in addition to a lower void content and better interfacial bonding.[41] Malik et al. (2022) examined epoxy HC reinforced with kenaf and flax fibers, which were prepared using vacuum-assisted resin infusion. The HC FK2 had the maximum TS (59.8 MPa), while FK3 had higher interlaminar shear strength (12.5 MPa) and fracture toughness (3302.3 J/m^2).[31] Praveena Bindiganavile Anand et al. (2023) fabricated HC by incorporating kenaf and hemp fibers along with MWCNT reinforcement in epoxy. Results revealed that the sample containing 1% MWCNT exhibited the highest TS (43.24 MPa). Meanwhile, the sample with 0.5% MWCNT demonstrated superior FS (55.63 MPa) and had maximum impact strength.[42]

Dhilipkumar et al. (2024a) fabricated HC using areca and ramie fibers reinforced with graphene nanoparticles (0.5% to 2.0% by weight) through compression molding. The specimen with 1.5% graphene showed significant improvements, with increases of 187.88% in TS, 143.17% in FS, and 159.66% in impact energy.[43] Ganesan et al. (2023) evaluated the performance of epoxy composites made from bamboo fiber and olive tree leaf powder under cryogenic exposure for different durations (15, 30, and 60 min). Their findings revealed that a 30-minute treatment produced better results, with enhanced tensile, flexural, and impact strength by 11.34%, 21.76%, and 26.52%, respectively.[44] Ben Hamou et al. (2023) found that HC combining hemp fibers and wood flour exhibited a synergistic effect, with a modulus 166% greater than neat composites.[45] Sarmin et al. (2022) reported that HC of olive and bamboo fibers at 40% total filler loading (density 1.2 g/cm^3) exhibited better mechanical properties, with a TS of 31.28–37.09 MPa, the FS of 56.70–65.64 MPa, and impact strength of 9.87–11.76 J/m.[46]

The literature review indicates that while many efforts have been made to improve HC there is a lack of research on the impact of combining different fibers and nanofillers. Specifically, although studies have highlighted the potential of using snake grass and luffa cylindrica fibers,[47,48] there has been no evaluation of composites that combine these fibers with silicon carbide nanoparticles. Luffa cylindrica (sponge gourd) and snake grass fibers are low-weight, biodegradable, and possess high TS, making them ideal for reinforcement. Luffa fibers enhance bonding due to their porous structure, while snake grass fibers provide flexibility and durability. This research explores the effect of combining snake grass and luffa cylindrica with silicon carbide integration on the tensile, flexural, impact, and WA behavior of HC.

2 | EXPERIMENTAL DETAILS

2.1 | Materials

For fabricating the HC, the snake grass and luffa cylindrica fiber were brought from local sources in Tamil Nadu, India. The epoxy (LY556) and hardener (HY951) were acquired from Covai Seenu Company, Coimbatore, India. The silicon carbide powder was purchased from Nano Research Elements, India.

2.2 | Synthesis of epoxy/silicon carbide adhesive

The sonication process lasted for 1 h at a frequency of 50 kHz, utilizing an ultrasonic liquid processor, as depicted in Figure 1. SiC's particles were blended with acetone at four distinct weight concentrations (2.5%, 5.0%, 7.5%, and 10.0%). To create a uniform mixture of the SiC particles, a suitable quantity of epoxy resin was added, and sonication continued for the specified

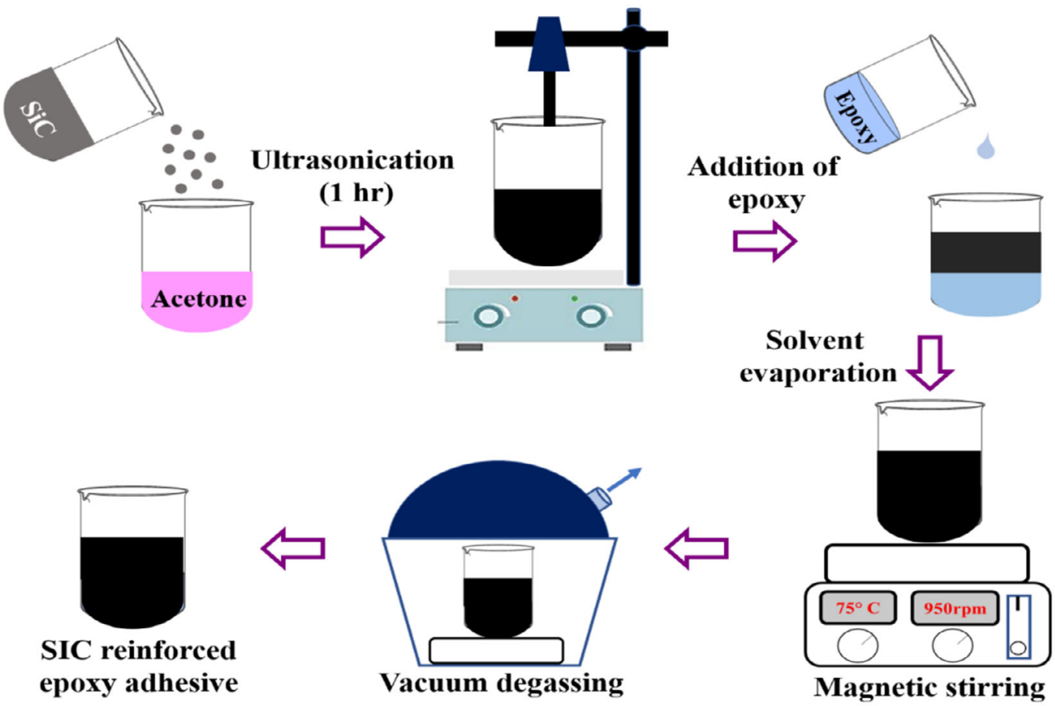

FIGURE 1 Preparation of epoxy/SiC-modified adhesive.

duration. To avoid temperature increases during the sonication, the mixture was paused every 10 min and placed in an ice bath for 3 min, during which it was stirred manually with a rod. After sonication, the mixture was maintained on a magnetic stirrer at 75 °C and 950 rpm for 1 h to facilitate the evaporation of the acetone. Subsequently, the mixture was transferred to a controlled environment set at 30 °C inside a vacuum oven at 0.25 bar for 30 min to eliminate any trapped air bubbles.

2.3 | Alkaline treatment

For the alkaline treatment, the fibers of luffa cylindrica and snake grass were cut into 30 mm segments to ensure uniform processing. These segments are kept in a 5% sodium hydroxide (NaOH) solution at atmospheric temperature. The treatment lasted between 2 and 4 h, allowing the alkali to penetrate the fibers effectively and facilitate the exclusion of impurities and lignin.

After the designated treatment period, the fibers were washed with distilled water. This washing step was crucial for eliminating any residual sodium hydroxide. The cleaned fibers were dried in a hot air oven at 70 °C for 24 h.

2.4 | Fabrication of snake grass/luffa cylindrica hybrid composites

Compression molding is a widely used technique for manufacturing composite laminates. In this study, hybrid laminates were prepared using luffa cylindrica and snake grass fibers, mixed in specific weight percentages (wt%) as detailed in Table 1. The fibers were chopped to the required sizes and blended with an epoxy resin mixture to form a uniform hybrid material. As outlined in Table 1, the epoxy resin and hardener were combined in a weight ratio of 10:1, along with specified amounts of SiC particulate filler. This mixture was mechanically stirred to ensure a homogeneous distribution of all components. The prepared hybrid material was then placed into a preheated mold.

The molding process involved maintaining the material in the mold at 130 °C for 1 h. During this time, a pressure of 35 kg/cm^2 was applied for an additional hour to confirm proper compaction and curing. After curing, the laminate was carefully detached from the mold, which was designed to produce samples measuring 300 mm × 300 mm × 5 mm.

To further enhance the curing process, the composite samples underwent a post-curing stage. Initially, the material was cured at room temperature for 24 h. Following this, it was subjected to an additional curing process at 80 °C for 3 h. After gradually cooling to room temperature, the cured laminates were removed from the mold and sliced into test samples following ASTM standards. The sample preparation process of luffa cylindrica and snake grass fibers composite is illustrated in Figure 2.

2.5 | Mechanical testing of snake grass/luffa cylindrica hybrid composites

Tensile, flexural, and impact tests were conducted as per ASTM guidelines to assess the effect of SiC integration on the mechanical behavior of SG and LC fiber-based composites. The tensile and flexural tests were executed using a YAMA UTM-E-60 universal testing machine, with a strain rate set at 1 mm/min.

For the tensile test, the samples were prepared with dimensions of 165 mm × 19 mm × 5 mm and evaluated as per ASTM D 638 standards. In the flexural test, the specimens were sized at 125 mm × 25 mm × 5 mm, and a three-point bending test was executed according to ASTM D 790 guidelines (Table 2). The impact test was performed by following the ASTM D256 standard, utilizing an Izod Impact Tester. For each test, five samples were taken, and their average values were reported in the present study.

2.6 | Water absorption properties of snake grass/luffa cylindrica hybrid composites

The analysis of WA was carried out on a composite made from luffa cylindrica and snake grass fibers in accordance

TABLE 1 Composition of snake grass, luffa cylindrica, epoxy resin, and silicon carbide additive.

Specimen code	Epoxy resin (wt%)	Snake grass fiber (wt%)	Luffa cylindrica fiber (wt%)	SiC (wt%)
SG/LC	70	15	15	0.0
SG/LC-2.5	70	13.75	13.75	2.5
SG/LC-5.0	70	12.5	12.5	5.0
SG/LC-7.5	70	11.25	11.25	7.5
SG/LC-10	70	10	10	10.0

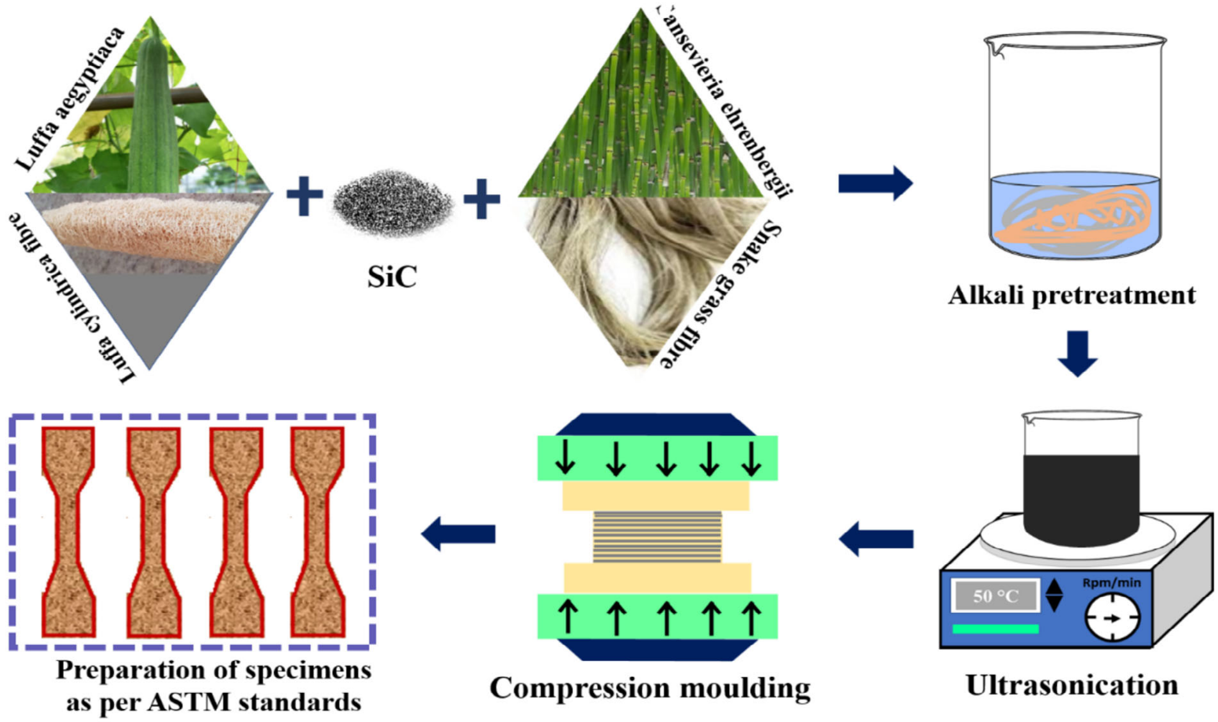

FIGURE 2 Preparation process of snake grass and luffa cylindrica fiber-based hybrid composites.

TABLE 2 Test methods and dimensions of snake grass/luffa cylindrica samples.

Test	Standard	Length of the composite (mm)	Width of the composite (mm)	Thickness of the composite (mm)
Tensile	ASTM D 638	165 ± 0.45	19 ± 0.25	5 ± 0.3
Flexural	ASTM D 790	125 ± 0.32	25 ± 0.44	5 ± 0.3
Impact	ASTM D 256	63 ± 0.28	10 ± 0.28	5 ± 0.3

with ASTM Standard D 570-98. Initially, the weight (W_b) of the specimens was measured after they had been dried in an oven at 55 °C. Subsequently, to find the weight of the wet specimens (W_a), the dried samples were submerged in ordinary water at designated time intervals. The weight measurements were conducted using an AUW220 Shimadzu weighing machine from Japan, and the percentage of WA for all composites was calculated using Equation (1).

$$\text{Water absorption, M}\,(\%) = \frac{W_a - W_b}{W_b} \times 100 \qquad (1)$$

W_a denotes the weight of the composite after soaking it in water, and W_b represents the weight before soaking it.

2.7 | Morphological study of snake grass/luffa cylindrica hybrid composites

The failed samples were analyzed using a scanning electron microscope to inspect the impact of SiC addition on the microstructural changes in snake grass/luffa cylindrica HC. The composite was coated with gold to increase conductivity. Each sample, measuring 10 mm × 10 mm × 5 mm, was used for the examination.

3 | RESULTS AND DISCUSSIONS

3.1 | Tensile behavior of snake grass/luffa cylindrica hybrid composites

Figure 3 shows the TS of snake grass and luffa cylindrica fiber-based composites with varying silicon carbide content. The tensile analysis results indicate that incorporating SiC into these natural fiber composites significantly enhances their TS compared to neat composites.

The adding of SiC improved the fiber-matrix interaction, promoting better load transfer and reducing micro-voids in the composite structure. As SiC is eminent for its better mechanical strength and thermal stability, its inclusion contributes to reinforcing the matrix and

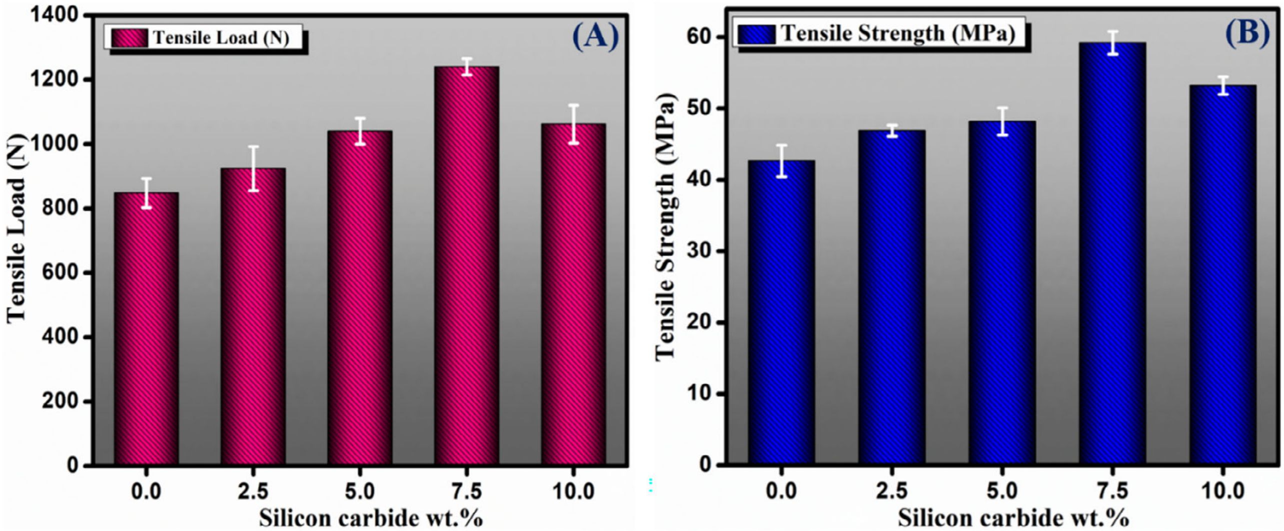

FIGURE 3 Tensile properties of snake grass/luffa cylindrica fiber-based hybrid composites (A) Tensile load versus silicon carbide wt% (B) Tensile strength versus silicon carbide wt%.

TABLE 3 Tensile behavior of snake grass/luffa cylindrica samples.

S. No	Specimen code	Silicon carbide wt%	Tensile strength (MPa)	Tensile load (N)	% Increment
1	SG/LC	0.0	42.63 ± 4.4	848 ± 45.2	–
2	SG/LC-2.5	2.5	46.89 ± 1.1	924 ± 68.4	9.99
3	SG/LC-5.0	5.0	48.17 ± 3.05	1040 ± 40.2	12.99
4	SG/LC-7.5	7.5	59.22 ± 3.9	1240 ± 25.1	38.91
5	SG/LC-10	10.0	53.21 ± 2.2	1062 ± 59.3	24.818

preventing crack initiation and propagation. Consequently, composites containing SiC demonstrate superior tensile performance, as the enhanced bonding minimizes fiber pull-out and ensures efficient stress distribution.

From the results (Table 3), it is clear that neat composite (SG/LC) has the minimum TS of 42.63 MPa. With the inclusion of 2.5 wt% SiC, the TS increases to 46.89 MPa, showing an improvement of 9.99%. Moreover, the addition of 5.0 wt% SiC increases the TS to 48.17 MPa, reflecting a 12.99% enhancement in strength. A notable increase is observed at 7.5 wt% SiC, where the TS reaches 59.22 MPa, a significant enhancement of 38.91%. However, when the SiC content increases to 10.0 wt%, the TS slightly drops to 53.21 MPa, showing a reduced improvement of 24.82%.

The observed reduction in TS at higher SiC concentrations, particularly beyond 7.5 wt%, can be attributed to inefficient stress distribution caused by particle agglomeration. Excess SiC tends to form clusters that disrupt the uniform flow of stress, creating stress concentration points that weaken the composite's structural integrity. Additionally, poor dispersion at elevated concentrations limits effective bonding between the fibers and the matrix, leading to inadequate load transfer, localized stress accumulation, and premature failure.

Overall, the findings suggest that optimizing the SiC content is crucial for maximizing the tensile properties of snake grass and luffa cylindrica-based composites. The incorporation of up to 7.5 wt% SiC significantly enhances the composite's mechanical performance, making it a suitable choice for applications demanding lightweight and high-strength materials.

Figure 4A–D illustrates the failure mechanisms observed in composites reinforced with snake grass and luffa cylindrica fibers. The SEM image reveals that neat composites fabricated from these fibers predominantly fail along the warp direction under longitudinal tensile stress. This failure mode is marked by the presence of multiple pores, matrix cracking, and noticeable fiber pull-out (Figure 4A), all of which contribute to a reduced load-bearing capacity. Incorporating 7.5 wt% silicon carbide (SiC) into the composite results in significant improvements in the bonding between the fibers and the matrix (Figure 4B). This enhancement leads to increased TS and modulus, as well as an improved ability to bear loads. The uniform dispersion of SiC particles all over the

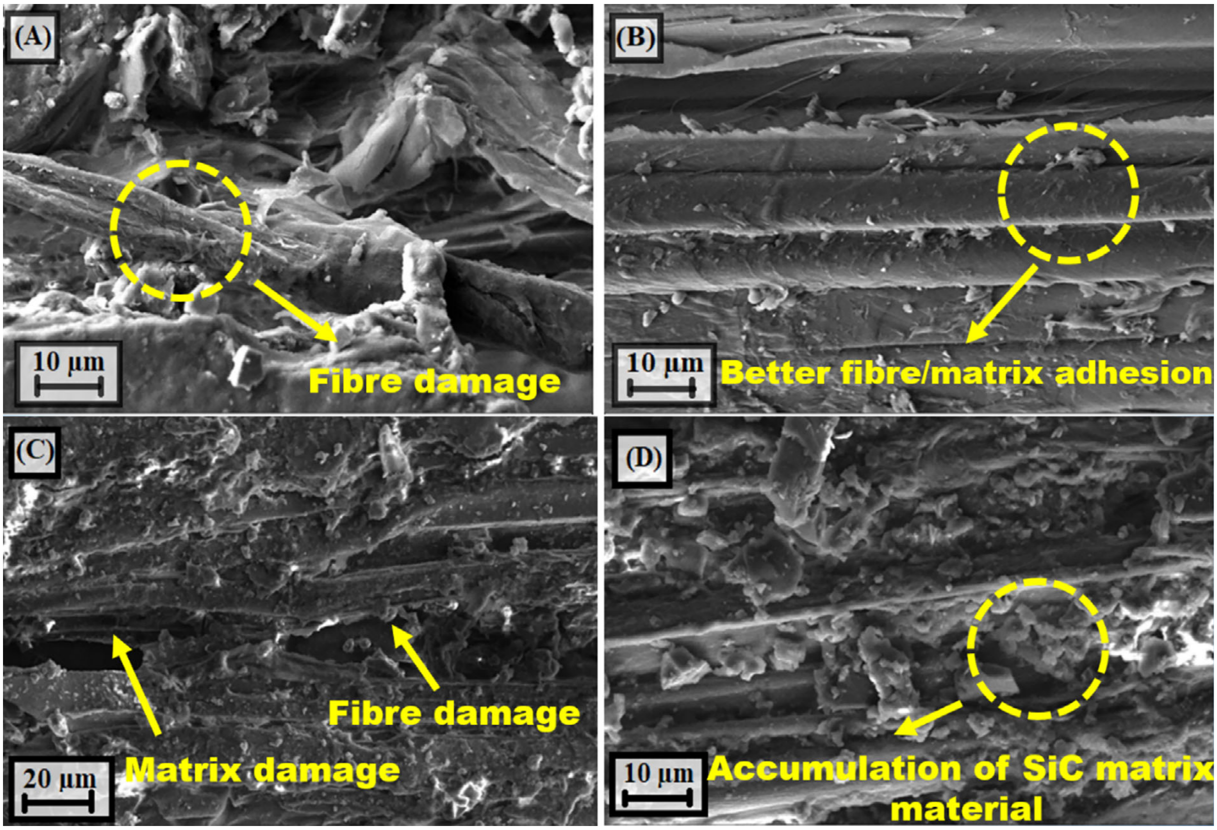

FIGURE 4 SEM images of tensile-tested snake grass/luffa cylindrica fiber-based hybrid composites: (A) Neat composite, (B) SG/LC 7.5, (C) SG/LC 10, and (D) SG/LC 10.

composite allows it to withstand higher stresses under longitudinal tensile loads.

However, when the SiC content exceeds 7.5 wt%, the sample has fiber breakage, matrix damage (Figure 4C), and also problems such as particle aggregation; clustering can occur (Figure 4D). Composites with 10.0 wt% SiC show uneven stress distribution due to the formation of SiC clusters. These clusters serve as stress concentrators, reducing the composite's structural integrity. Additionally, poor dispersion of SiC at higher concentrations reduces the effectiveness of fiber-matrix bonding, hindering proper load transfer. This results in increased localized stress and premature material failure during tensile loading.

3.2 | Flexural behavior of snake grass/luffa cylindrica hybrid composites

Figure 5A,B displays the flexural properties of snake grass/luffa cylindrica fiber-based composites with varying SiC content. The failure behavior of these composites was evaluated using three-point bending tests. Composites incorporated with 7.5 wt% SiC exhibited superior FS compared to other combinations, demonstrating the significant reinforcing effect of SiC particles.

The improvement in FS is due to greater bonding between the SG/LC fibers and the matrix due to SiC's presence. SiC particles distribute stress more uniformly during bending, increase load transfer efficiency, and help fill voids within the composite structure. As a result, composites with 7.5 wt% SiC effectively resist bending forces compared to neat composites, which lack these reinforcing benefits and have weaker fiber-matrix adhesion.

Incorporating SiC significantly increases the FS, as shown in Table 4. The neat composite (SG/LC) shows the lowest FS of 61.27 MPa. With the addition of 2.5 wt% and 5.0 wt% SiC, the FS improves to 67.05 MPa (9.43% increment) and 67.32 MPa (9.87% increment), respectively. The maximum FS of 78.63 MPa (28.33% increment) is attained with 7.5 wt% SiC, indicating optimal performance. However, increasing the SiC content to 10 wt% results in a slight decline in FS to 72.36 MPa (18.10% increment) due to particle aggregation. Excessive SiC content can cause uneven dispersion, creating stress concentrators that disrupt the effective bonding between the fibers and the matrix, reducing load transfer efficiency

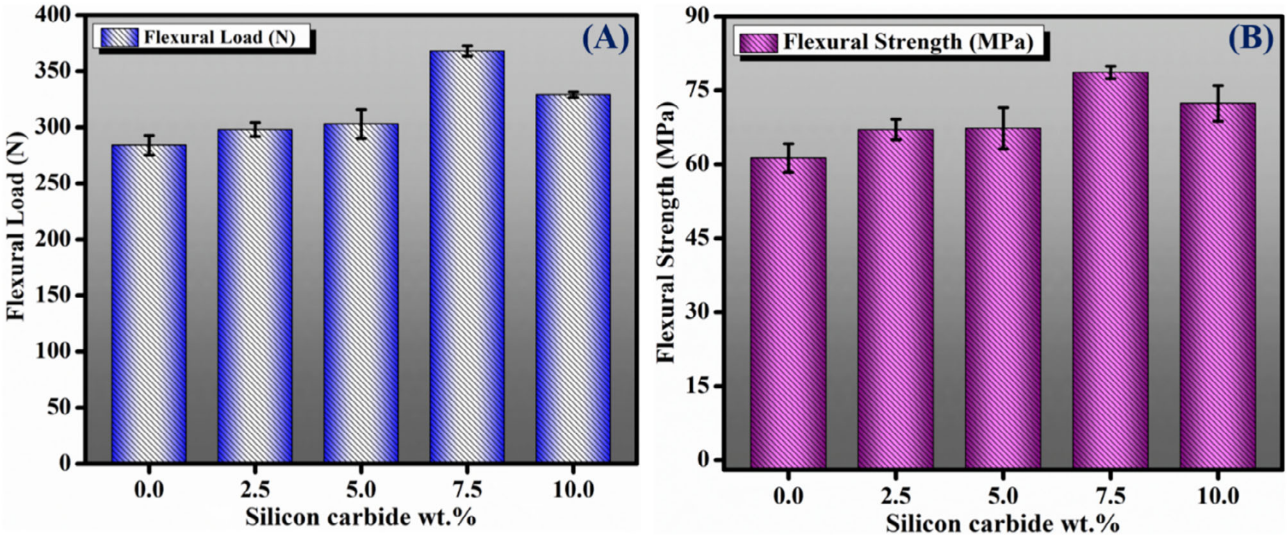

FIGURE 5 Flexural properties of snake grass/luffa cylindrica fiber-based hybrid composites (A) Flexural load vs. silicon carbide wt% (B) Flexural strength vs. silicon carbide wt%.

TABLE 4 Flexural behavior of snake grass/luffa cylindrica samples.

S. No	Specimen code	Silicon carbide wt%	Flexural strength (MPa)	Flexural load (N)	% Increment
1	SG/LC	0.0	61.27 ± 2.53	284 ± 8.8	–
2	SG/LC-2.5	2.5	67.05 ± 1.33	298 ± 6.2	9.43
3	SG/LC-5.0	5.0	67.32 ± 4.61	303 ± 12.9	9.87
4	SG/LC-7.5	7.5	78.63 ± 0.7	368 ± 4.6	28.33
5	SG/LC-10	10.0	72.36 ± 3.78	329 ± 2.5	18.10

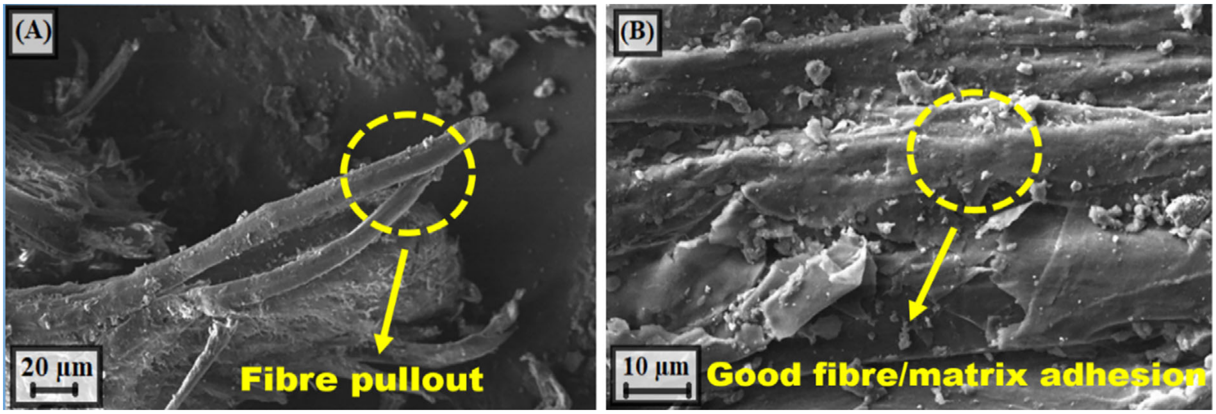

FIGURE 6 SEM images of flexural tested snake grass/luffa cylindrica fiber-based hybrid composites, (A) Neat composite, (B) SG/LC 7.5.

and mechanical performance. These findings highlight that optimizing SiC content is crucial to enhancing the flexural properties of SG/LC fiber-based composites.

Figure 6 presents SEM images of fractured composite samples. It shows that neat snake grass and luffa cylindrica-based composites suffer from damage to fiber bundles, fiber pull-out, and matrix cracking (Figure 6A), which leads to early failure under flexural loading. In contrast, the composites reinforced with 7.5 wt% SiC exhibit improved interfacial adhesion between the fibers and the matrix (Figure 6B). This enhanced bonding facilitates better load transfer and increases resistance to failure, resulting in greater FS compared to other composite configurations.

3.3 | Impact behavior of snake grass/luffa cylindrica hybrid composites

Figure 7 shows the impact strength of HC made from snake grass and luffa cylindrica fibers with varying amounts of SiC. The addition of SiC significantly increases the impact resistance of these composites by improving their toughness and energy absorption capacity. Table 5 shows that SiC-reinforced composites display superior impact strength compared to neat (unreinforced) composites.

Incorporating SiC into the epoxy matrix strengthens the fiber-matrix interface, enabling better load distribution and improving the HC ability to absorb and dissipate impact energy. The HC with 7.5 wt% SiC demonstrates the maximum impact strength of 2.3 J, representing a 53.33% enhancement over the neat composite, which has an impact strength of 1.5 J. This enhancement can be attributed to SiC particles increasing stiffness, reinforcing the composite structure, and promoting uniform stress distribution under impact forces.

However, at 10.0 wt% SiC, the impact strength decreases to 1.9 J, which is still a 26.66% improvement but less than that achieved with 7.5 wt%. This reduction is likely due to particle aggregation, which can act as stress concentrators. These agglomerates reduce the efficacy of load transfer and weaken the bonding between the fibers and the matrix.

Overall, the HC impact resistance is optimized at 7.5 wt% SiC. This composition provides the best balance of strength, stiffness, and energy absorption, making the material more resistant to impact forces while avoiding the negative effects of particle agglomeration observed at higher concentrations of SiC.

3.4 | Water absorption behavior of snake grass/luffa cylindrica hybrid composites

Figure 8 shows the variation in WA for SG/LC-SiC composites. The addition of SiC significantly alters the composite's WA behavior. As the SiC content increases, WA initially decreases due to improved interfacial bonding and reduced void content, reaching a minimum of 7.5 wt% SiC with a WA rate of 14.89%. This reduction is attributed to SiC's ability to enhance the matrix's

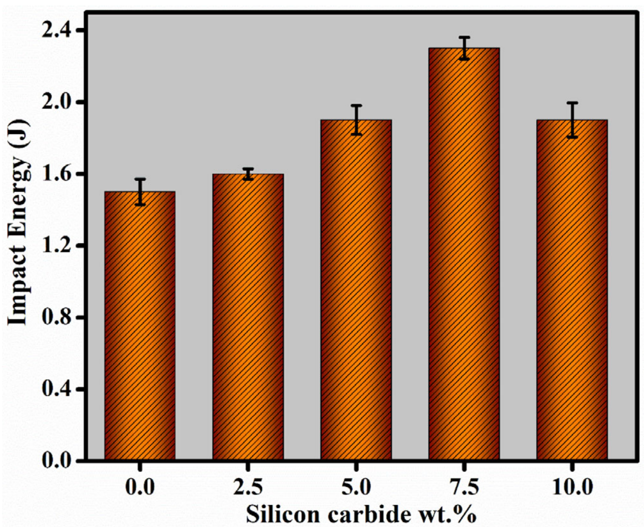

FIGURE 7 Impact strength of snake grass/luffa cylindrica fiber-based hybrid composites.

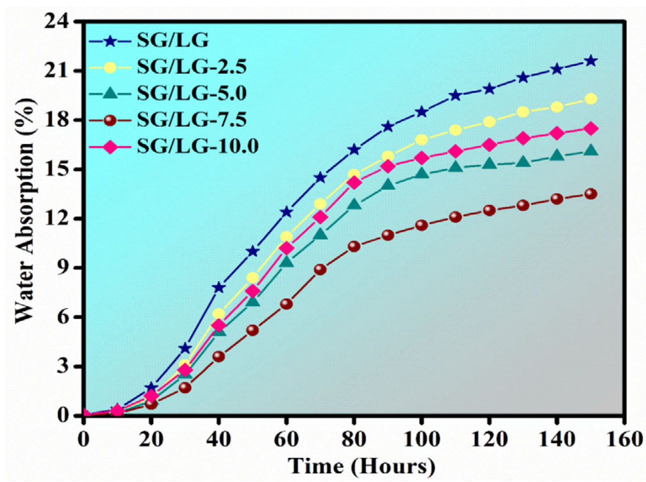

FIGURE 8 Water absorption behavior of snake grass/luffa cylindrica fiber-based hybrid composites.

TABLE 5 Impact behavior of snake grass/luffa cylindrica samples.

S. No	Specimen code	Silicon carbide wt%	Impact strength (J)	% Increment
1	SG/LC	0.0	1.5 ± 0.071	–
2	SG/LC-2.5	2.5	1.6 ± 0.028	6.6
3	SG/LC-5.0	5.0	1.9 ± 0.080	26.66
4	SG/LC-7.5	7.5	2.3 ± 0.060	53.33
5	SG/LC-10	10.0	1.9 ± 0.095	26.66

resistance to water infiltration and physically obstruct water molecule movement by minimizing voids and defects.

However, beyond 7.5 wt%, the WA rate increases slightly, reaching 18.43% at 10.0 wt% SiC. This increase may be due to SiC particle aggregation, which creates microvoids and imperfections in the matrix, allowing water molecules to penetrate more easily. The neat composite (SG/LC) shows the highest WA at 22.52%, indicating a weaker fiber-matrix interface and higher void content.

Overall, the adding of SiC improves the composite's resistance to WA, with optimal performance observed at 7.5 wt% SiC. This highlights the importance of achieving a balanced dispersion of SiC to minimize water uptake while maintaining mechanical integrity.

4 | CONCLUSIONS

The present examination has assessed the influence of SiC inclusion on the mechanical and WA behavior of the LC/SG fiber-based HC. The mechanical testing of samples revealed that the addition of SiC up to 7.5 wt% has improved the strength of the luffa cylindrical/ snake grass fiber-based composite. The adding of 7.5 wt% SiC to epoxy matrix has enhanced the tensile, flexural, and impact strength by 38.91%, 28.33%, and 53.33%, respectively. Further addition of SiC lowered the strength of the luffa cylindrica/ snake grass fiber-based composite due to poor adhesion between fibers and the matrix. The fractured analysis using SEM has revealed that incorporating 7.5 wt% SiC into the composite results in significant improvements in the bonding between the fibers and the matrix. Meanwhile, neat snake grass and luffa cylindrica-based composites had damage in fiber bundles, fiber pull-out, and matrix cracking, which led to early premature failure. Overall, adding SiC enhances the composite's resistance to WA, with the best performance seen at 7.5 wt% SiC. This emphasizes the need for a well-balanced dispersion of SiC to reduce water uptake while preserving mechanical integrity.

ACKNOWLEDGMENTS

The authors would like to thank Qatar National Library for providing open access funding. The authors extend their appreciation to the Researchers Supporting Project number (RSPD2025R956), King Saud University, Riyadh, Saudi Arabia.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

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How to cite this article: Suriya Prakash M, Dhilipkumar T, Sadeq AM, et al. Synergistic enhancement of mechanical and water resistance properties in snake grass/luffa cylindrica fiber composites integrated with silicon carbide additive. *Polym Compos*. 2025;46(15):13881-13892. doi:10.1002/pc.30030