

Effect of Hybrid Graphene and Silicon Dioxide Nano-Fillers on the Mechanical and Morphological Properties of Aloe Vera Fibre Reinforced Epoxy Composites

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ABSTRACT

Effective solutions to improve fibre–matrix adhesion, mechanical performance and structural durability are necessary to build sustainable fibre-reinforced polymer composites. This work explores the synergistic effect of graphene nanoplatelets and silicon dioxide (SiO₂) nanoparticles on alkali- and silane-treated Aloe vera fibre-reinforced epoxy composites. The fibres of Aloe vera were treated with an alkaline treatment with 5 wt.% sodium hydroxide solution and then washed to neutral pH and dried at 60°C for 24 h. A 2 wt.% 3-aminopropyl triethoxysilane solution in a 60:40 ethanol–water medium was used for surface modification. A sequential alkaline–silane treatment was adopted to further enhance fibre surface reactivity. Graphene nanoplatelets and SiO₂ nanoparticles were disseminated independently by mechanical stirring and ultrasonication prior to inclusion in the epoxy matrix. The laminates were produced by hand lay-up, compression moulding and post-curing. Tensile, flexural, impact, hardness and scanning electron microscopy (SEM) examinations were taken into consideration to evaluate the influence of nano-reinforcement and surface treatment on composite performance. The experimental tensile results showed that the tensile strength of the hybrid AV-GS2 02 formulation was the greatest at 63.79 N/mm² and was a significant improvement over the control specimen AV-0 01 at 36.64 N/mm². The improved performance is ascribed to better stress transmission, matrix densification, fracture deflection, decreased interfacial flaws and stronger fibre–matrix contact. The SiO₂-containing formulations showed positive tensile behaviour, whereas the graphene-only formulations showed decreased tensile strength compared to the other formulations, which emphasises the necessity of nanoparticle dispersion and agglomeration management. SEM investigations also revealed less void formation and enhanced interfacial bonding in the hybrid nano-reinforced composites. Overall, the findings show that graphene–SiO₂ hybrid nano-reinforcement coupled with suitable fibre surface treatment is an efficient way to improve the structural performance of Aloe vera fibre/epoxy composites for lightweight and sustainable engineering applications.

Keywords: Aloe vera fibre; graphene nanoplatelets; silicon dioxide; epoxy composite; hybrid nanofiller; natural fibre composite; interfacial adhesion; SEM

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1. Introduction

The transition toward low-carbon and resource-efficient engineering materials has intensified research on natural fibre-reinforced polymer composites. Renewable fibres can reduce material density and dependence on mineral or petroleum-derived reinforcements, while offering potential advantages in cost, biodegradability, and resource availability. Recent work on aloe vera-based composites confirms that the fibre can function as a viable reinforcement in polymer matrices, although moisture sensitivity and fibre–matrix compatibility remains important limitations [1–3]. The study on aloe vera/epoxy composites highlighted the significance of these materials for sustainable tribological applications. Recent comparative studies

on aloe vera, corn, eucalyptus and soybean fibers showed that aloe vera/epoxy systems may have relatively high water uptake but can offer competitive mechanical performance [1, 2]. Aloe vera fibre is a lignocellulosic reinforcement containing cellulose together with hemicellulose, lignin, pectin, and surface impurities. The hydrophilic character of the fibre can produce poor compatibility with hydrophobic polymer matrices, causing interfacial debonding, fibre pull-out, moisture uptake, and reduced stress-transfer efficiency. Alkali treatment is therefore commonly adopted to remove non-cellulosic constituents and increase surface roughness. Recent investigations of aloe vera/ramie epoxy hybrids have shown that fibre length and fibre content strongly affect mechanical, wear, and

absorption behaviour, reinforcing the importance of controlling the fibre–matrix interface during composite design [3]. Nanofillers provide a second route for improving the performance of natural fibre composites. Graphene and graphene derivatives possess a high specific surface area and exceptional stiffness, and recent reviews identify their ability to modify fibre surfaces, improve interfacial interactions, restrict crack growth, and introduce multifunctional properties into natural-fibre composites [4]. Recent study on graphene nanoplatelets in hemp/epoxy composites likewise reports that controlled low-level graphene addition can improve tensile and flexural performance through improved stress transfer and crack-arrest mechanisms [5]. Silicon dioxide nanoparticles are complementary reinforcement. High hardness, thermal stability and fine particle size can promote the densification of the matrix and decrease the microvoids, which will improve the resistance of local deformation. Recent research on natural-fibre/nano-SiO₂ epoxy systems has demonstrated that nano-silica can enhance mechanical and physical performance [6]. More broadly, nano-silica is increasingly investigated as a barrier and reinforcement phase in polymer composites because of its ability to modify diffusion pathways and interfacial structure. The combination of graphene and nano-silica is particularly attractive because the two fillers can provide complementary functions. Graphene can contribute stiffness, crack bridging and load transfer, whereas silica can improve matrix rigidity, surface hardness, barrier behaviour and interfacial packing. A recent study on jute/epoxy composites showed a significant improvement in tensile, flexural, impact, hardness, wear, thermal stability and water resistance by hybridization of nano-silica and graphene [7]. Another study on epoxy [8] also showed the synergistic mechanical and barrier effects of silica/graphene nanoparticle architectures. These results indicate that hybrid nanofillers can be better than single-filler approaches if dispersion and filler concentration are well controlled. Research work on aloe vera fiber/epoxy composites with graphene and SiO₂ is very less. Exploring aloe vera fiber reinforced epoxy composites with graphene, SiO₂, and their hybrid combinations fills this experimental gap. The research objective is to identify the effect of nano-filler type and hybridisation on tensile, flexural, impact, hardness, and fracture morphology, with particular attention to the GS-series hybrid composites. The working hypothesis is that controlled hybridisation can improve interfacial stress transfer and reduce microstructural defects through a synergistic combination of graphene and silica. The novelty of the present work is therefore the

integration of an underutilised natural fibre, aloe vera, with a dual nano-reinforcement strategy based on graphene and SiO₂. The study also compares single-filler and hybrid formulations using the same epoxy matrix and fabrication route. The results are interpreted in the context of recent developments in sustainable natural-fibre nanocomposites [1–8].

2. Materials and Methods

2.1 Materials

Aloe vera fibres extracted from mature leaves were used as the primary reinforcement. Epoxy resin LY556 was selected as the matrix, and HY951 was used as the curing agent. As nanoscale fillers graphene nanoplatelets and SiO₂ nanoparticles were introduced. The fibers were treated with alkaline sodium hydroxide. The manuscript describes the fiber as a lignocellulosic reinforcement and the epoxy system as having good adhesion, low shrinkage, mechanical strength and chemical resistance.

2.2 Fiber Treatment Process

2.2.1 Alkaline Treatment

To improve the interfacial bonding and removal of hemicellulose, waxes and lignin, Aloe vera fibers were soaked in 5 wt% NaOH aqueous solution at room temperature (27±2°C) for 4h. The alkaline treated fibers were then washed several times with distilled water until the pH of the rinse water was neutral (≈7). The cleaned fibres were oven-dried at 60°C for 24 hours and stored in a desiccator prior to composite fabrication. This treatment increased fibre surface roughness and promoted better resin adhesion.

2.2.2 Silane (Saline) Treatment

Silane treatment was carried out using a 2 wt% solution of 3-Aminopropyl triethoxysilane prepared in a 60:40 (v/v) ethanol–water mixture. The pH of the solution was adjusted to 4.5 using acetic acid to facilitate hydrolysis of the silane. The fibers were dipped in this solution for 2h at room temperature, and then rinsed with distilled water and dried at 60 °C for 24h. Silane coupling agents form covalent bonds with both the hydroxyl groups on the fibre surface and the epoxy resin, thereby enhancing fibre–matrix compatibility.

2.2.3 Combined Alkaline + Silane Treatment

Graphene nanoplatelets were dispersed in acetone using an ultrasonic bath for 30 min and then gradually introduced into epoxy resin under mechanical stirring at 500 rpm for 1h. SiO₂ nanoparticles were dispersed in ethanol and ultrasonicated for 30 min before mixing with the epoxy. For the hybrid formulations, graphene and SiO₂ were mixed in predetermined proportions and subjected to simultaneous ultrasonication and mechanical stirring. The dispersion procedure was

designed to reduce nanoparticle clustering and promote homogeneous filler distribution.

2.3 Nano-filler dispersion

Graphene nanoplatelets were dispersed in acetone using an ultrasonic bath for 30 min and then gradually introduced into epoxy resin under mechanical stirring at 500 rpm for 1h. SiO₂ nanoparticles were dispersed in ethanol and ultrasonicated for 30 min before mixing with the epoxy. For the hybrid formulations, graphene and SiO₂ were mixed in predetermined proportions and subjected to simultaneous ultrasonication and mechanical stirring. The dispersion procedure was designed to reduce nanoparticle clustering and promote homogeneous filler distribution.

2.4 Composite fabrication

The composites were fabricated using hand lay-up followed by compression moulding. The mould surface was cleaned and coated with a release agent. The nano-filled epoxy mixture was prepared and applied to the treated aloe vera fibres layer by layer, with entrapped air removed during impregnation. Compression moulding was subsequently used to reduce voids and improve fibre wetting and dimensional accuracy. The laminate was cured for 24 h at room temperature and post-cured at 60°C for 2h.

2.5 Mechanical and morphological characterization

Tensile test was performed according to ASTM D3039 using a universal testing machine. Flexural testing followed ASTM D790 using a three-point bending configuration. Impact resistance was evaluated according to ASTM D256, and surface hardness was measured using a Shore-D hardness tester. SEM analysis was used to examine fracture morphology, including fibre pull-out, matrix cracking, void distribution, nano-filler dispersion, fibre-matrix adhesion, and crack propagation.

Table. 1: Various Composite Formulations and Plate Percentages

Sample Code	Nano-Filler Type	Nano-Filler Content (wt%)	Aloe Vera Fibre (wt%)	Resin (wt%)
AV-0	None	0	30	70
AV-G1	Graphene	1	30	69
AV-S1	SiO ₂	1	30	69
AV-GS1	Graphene + SiO ₂	0.5 + 0.5	30	69
AV-GS2	Graphene + SiO ₂	1 + 1	30	68

3. Results and Discussion

3.1 Tensile Properties

The tensile dataset supplied with the manuscript is summarised in Table 1. The control AV-0 01 specimen recorded a break-load value of 36.64

N/mm², while the AV-GS2 02 hybrid formulation reached 63.79 N/mm². Thus, AV-GS2 02 provided approximately 74.1% higher tensile strength than AV-0 01. The graphene only formulations AV-G1 01 and AV-G1 02 showed lower tensile values than the control, which is consistent with the potential for incomplete dispersion or local agglomeration. Conversely, the SiO₂ containing samples AV-S1 01 and AV-S1 02 showed higher values of 51.41 N/mm² and 53.47 N/mm² respectively. The hybrid AV-GS2 01 and AV-GS2 02 formulations reached 53.03 N/mm² and 63.79 N/mm² respectively, proving that the combined filler system could lead to a stronger reinforcement effect than graphene only.



Figure. 1: Tensile Testing Machine with samples

The enhanced tensile performance of AV-GS2 02 can be explained by a multiscale stress-transfer mechanism. Graphene nanoplatelets can bridge nanoscale defects and limit crack propagation, while SiO₂ particles can enhance matrix rigidity and fill microvoids. When adequately dispersed, these mechanisms can increase the efficiency of load transfer from the epoxy matrix to the treated aloe vera fibres. This interpretation is consistent with recent hybrid nano-silica/graphene research in natural-fibre epoxy systems [7] and with recent work on graphene-modified natural-fibre composites [4, 5].

Table. 2: Tensile Test Result

Sample	Ultimate load (kN)	Break load / tensile strength (N/mm ²)
AV-0 01	4.2	36.64
AV-0 02	3.9	42.03
AV-G1 01	2.6	24.35
AV-G1 02	2.8	27.45
AV-S1 01	5.2	51.41
AV-S1 02	5.1	53.47
AV-GS1 01	2.3	25.48
AV-GS1 02	2.5	22.59
AV-GS2 01	5.3	53.03
AV-GS2 02	5.8	63.79

The lower performance of some graphene-containing samples also emphasises that graphene concentration alone does not guarantee improvement. Strong van der Waals interactions between graphene sheets can

cause stacking and agglomeration, generating stress-concentration sites. Therefore, the dispersion route used in this study is an important processing variable. Similar concerns are highlighted in recent graphene/natural-fibre literature [4].

3.2 Flexural Behaviour



Figure. 2: Flexural testing machine with samples

The flexural performance of the Aloe Vera (AV)-based composite specimens was evaluated using the reported flexural ultimate values. The unmodified reference specimen AV-0 exhibited the highest flexural ultimate value, with individual values of 130.92 N/mm² and 136.99 N/mm², corresponding to an average of 133.96 N/mm². The AV-G1 samples showed 106.40 N/mm² and 103.54 N/mm² with an average of 104.97 N/mm², which corresponds to a reduction of approximately 21.63% relative to the AV-0 reference. The flexural ultimate value of the AV-S1 specimens was the lowest, with measured values of 64.81 N/mm² and 66.35 N/mm² and an average of 65.58 N/mm², corresponding to a reduction of about 51.04% relative to AV-0. The average value for the AV-GS1 specimens was 94.27 N/mm², with individual values of 88.61 N/mm² and 99.93 N/mm², which is a reduction of approximately 29.62% compared to the reference specimen. The specimens of AV-GS2 however achieved 98.56 N/mm² and 103.09 N/mm² with the average value of 100.83 N/mm². Although this value was still approximately 24.73% lower than AV-0, AV-GS2 showed better flexural performance than AV-G1, AV-S1, and AV-GS1. Overall, the results showed that AV-0 had the highest flexural ultimate value while AV-S1 had the lowest value. Among the modified formulations, AV-GS2 provided the best flexural performance, suggesting that the combined reinforcement associated with the GS2 formulation contributed to better resistance to bending-induced deformation and failure.

Table. 3: Flexural Test Result

Sample	Flexural ultimate load (N/mm ²)
AV-0 01	130.92
AV-0 02	136.99

AV-G1 01	106.40
AV-G1 02	103.54
AV-S1 01	64.81
AV-S1 02	66.35
AV-GS1 01	88.61
AV-GS1 02	99.93
AV-GS2 01	98.56
AV-GS2 02	103.09

The interpretation attributes the relatively stable hybrid response to improved stress distribution and crack resistance. However, because the available table contains load rather than calculated flexural strength, conclusions regarding percentage improvement in flexural strength should be made only after the specimen dimensions and complete load-displacement data are verified.

3.3 Impact and Hardness



Figure. 3: Impact testing machine with samples

The impact performance of the Aloe Vera (AV)-based composite specimens was evaluated to assess their ability to absorb and dissipate energy under sudden loading. The reference AV-0 composite exhibited impact values of 3.1 J and 3.3 J, with an average value of 3.20 J. The impact resistance was improved by the incorporation of the individual and hybrid reinforcements. The AV-G1 formulation showed 3.8 J and 4.0 J which means an average of 3.90 J and about 21.88% improvement over AV-0. The average impact value of the AV-S1 formulation was found to be 3.45 J (3.5 J, 3.4 J) which was 7.81% superior over the reference composite.

Table. 4: Impact Test Result

Sample	Impact Energy (J)
AV-0 01	3.1
AV-0 02	3.3
AV-G1 01	3.8
AV-G1 02	4.0

AV-S1 01	3.5
AV-S1 02	3.4
AV-GS1 01	3.6
AV-GS1 02	3.7
AV-GS2 01	4.3
AV-GS2 02	4.1

In a similar fashion, AV-GS1 reported 3.6 J and 3.7 J with an average of 3.65 J, which corresponds to 14.06% improvement over AV-0. The highest impact resistance was obtained for AV-GS2, with individual values of 4.3 J and 4.1 J and an average of 4.20 J, representing a 31.25% improvement over the unmodified AV-0 composite. Thus, the impact performance followed the order AV-GS2 > AV-G1 > AV-GS1 > AV-S1 > AV-0, demonstrating the beneficial effect of hybrid reinforcement on the energy-absorption capability of the composite.

The observed improvement in impact resistance can be associated with the combined chemical and physical interactions developed at the fibre–matrix and fibre–nanofiller interfaces. Aloe vera fibre contains cellulose as the major structural component, along with hemicellulose and lignin, and consequently possesses abundant hydroxyl (–OH) groups. Alkaline treatment can remove a portion of the surface impurities, hemicellulose, lignin and waxy constituents, thereby exposing cellulose-rich surfaces and increasing fibre roughness and surface activity. The resulting surface modification promotes improved mechanical interlocking and interfacial adhesion with the polymer matrix. In the presence of silica, the surface silanol (Si–OH) groups can interact with the hydroxyl groups of the treated Aloe Vera fibre through hydrogen bonding and other interfacial interactions, while appropriate processing conditions may further promote interfacial condensation. When graphene or graphene oxide is incorporated, its surface functional groups, particularly oxygen-containing groups in the case of graphene oxide, can interact with the hydroxyl groups of cellulose, contributing to improved interfacial compatibility and stress transfer.

These interfacial interactions are particularly important under impact loading because they reduce premature fibre–matrix debonding and facilitate the transfer of the applied impact energy from the polymer matrix to the reinforcing phases. During fracture, the presence of well-bonded fibres and nanofillers can promote crack deflection, crack bridging, crack branching and increased crack-path tortuosity, thereby requiring greater energy for crack propagation. The hybrid reinforcement can also act as additional energy-dissipation sites, resulting in improved resistance to sudden fracture. The superior impact value of AV-GS2 (4.20 J) therefore indicates

a more effective combination of reinforcement and interfacial interaction than the other investigated formulations. Overall, the results indicate that the addition of suitable hybrid reinforcement into Aloe Vera fiber composites can significantly improve the impact resistance via enhanced interfacial adhesion, effective stress transfer and multiple energy-dissipation mechanisms. The 31.25% improvement in AV-GS2 over AV-0 confirms its better ability to resist impact damage among the formulations studied.

Table. 5: Hardness Test Result

Sample	Hardness Mean Values (N/mm ²)
AV-0	70.4
AV-G1	75.6
AV-S1	73.2
AV-GS1	71.8
AV-GS2	76.6

The hardness properties of the AV based composite specimens were tested to evaluate the resistance of the composites to localized indentation and surface deformation. The reference composite AV-0 exhibited a mean hardness value of 70.4 N/mm². The variation in hardness was noticed with the addition of reinforcement depending on the formulation. The composite AV-G1 showed a hardness value of 75.6 N/mm², which is about 7.39% higher than that of AV-0. The average hardness obtained for the formulation AV-S1 was 73.2 N/mm² which was an increase of about 3.98%. The hardness value of the composite AV-GS1 was 71.8 N/mm² which was 1.99% higher than the reference composite. The AV-GS2 presented the highest hardness value, with a mean of 76.6 N/mm², which is an increase of about 8.81% compared to the AV-0. The hardness performance therefore followed the order AV-GS2 > AV-G1 > AV-S1 > AV-GS1 > AV-0.

The higher hardness may be related to the increased stiffness and surface resistance by the addition of the reinforcing phases. The presence of graphene and/or silica can restrict the localised movement of polymer chains and improve the resistance of the composite surface to indentation. In addition, improved fibre–matrix adhesion facilitates effective load transfer from the polymer matrix to the Aloe Vera fibres and dispersed reinforcing particles. The relatively higher hardness of AV-GS2 (76.6 N/mm²) suggests that its hybrid reinforcement system provided a more effective combination of stiffness, interfacial bonding and resistance to localised deformation. In contrast, the comparatively lower value obtained for

AV-GS1 (71.8 N/mm²) indicates that the reinforcement effect depends not only on the presence of the fillers but also on their concentration, dispersion and interaction with the polymer matrix. Overall, the results indicate that the incorporation of suitable hybrid reinforcement can improve the surface hardness of Aloe Vera fiber composites with AV-GS2 exhibiting the maximum improvement in hardness of about 8.81% in comparison to the unreinforced AV-0 formulation.

3.4 SEM morphology

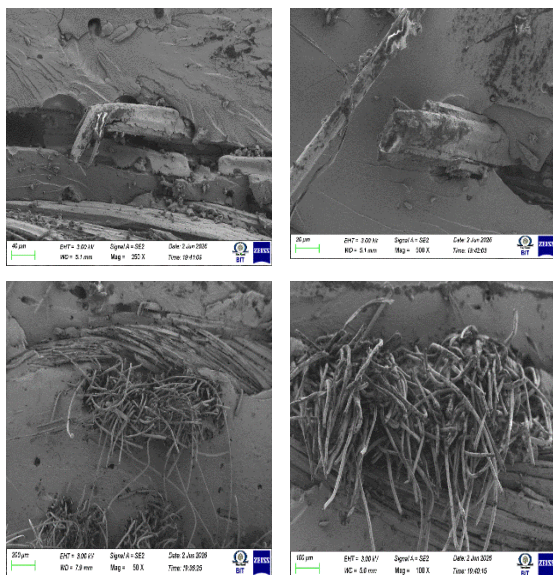


Figure. 4: SEM Analysis Images for Aloe Vera Fiber Composites

The SEM images of the Aloe Vera fibre composites were examined to understand the fibre–matrix interaction and fracture behaviour of the different formulations. The AV-0 sample, used as the reference composite, showed visible fibre–matrix gaps, microvoids and fibre debonding. These defects indicate relatively weak interfacial bonding and provide easy paths for crack initiation and propagation. The graphene reinforcement in the AV-G1 composite produced a denser surface with better coverage of matrix around the Aloe Vera fibers. Graphene particles effectively inhibited the crack propagation and improved the stress transfer between the fiber and polymer matrix. The silica nanoparticles produced lesser voids in the case of AV-S1 composite, although some localized particle clustering could have acted as regions of stress concentration. The fracture surface of the AV-GS1 hybrid composite was more heterogeneous and rougher, indicating crack deflection and fiber bridging, with the combined action of graphene and

silica. Of all the formulations, AV-GS2 exhibited the most compact and uniform morphology with better matrix wetting, less visible voids and less fiber pull out. The cracks path was more tortuous and it required more energy to crack the cracks due to better interfacial bonding in AV-GS2. These microstructural features are consistent with its superior mechanical performance, including the highest hardness of 76.6 N/mm² and impact value of 4.20 J. Major elements and presence of reinforcing phases in the composite specimens were characterized by SEM-EDS. The AV-0 specimen was predominantly composed of carbon (C) and oxygen (O), which are attributed to the Aloe Vera fiber and polymer matrix. The composite AV-G1 showed a composition as expected rich of carbon associated to the graphene reinforcement. The presence of silicon (Si) and oxygen (O) in the AV-S1 sample indicated the incorporation of silica. Fig. 4. Elemental composition of the organic matrix and silica reinforcement of the hybrid AV-GS1 and AV-GS2 samples. C, O and Si were observed in the analyzed areas. In particular, a more uniform distribution of the reinforcing elements in AV-GS2 indicates better filler dispersion and reduced localised agglomeration compared with AV-S1. This improved elemental distribution supports better fibre–matrix interaction and stress transfer, which contributes to the enhanced hardness and impact resistance observed for AV-GS2. Overall, the SEM and EDS results demonstrate that improved filler dispersion, reduced void formation and stronger interfacial bonding play important roles in enhancing the mechanical performance of the hybrid Aloe Vera composites.

4. Mechanism of Reinforcement

The performance of the hybrid aloe vera fibre composite can be explained by a hierarchical reinforcement mechanism operating at the fibre, micro and nano scales. At the fibre scale, alkali treatment improves the fibre surface characteristics by removing surface impurities and portions of non-cellulosic constituents, thereby increasing surface roughness and improving fibre–matrix adhesion and mechanical interlocking [1–3, 9]. This enhanced interfacial interaction facilitates more efficient stress transfer from the epoxy matrix to the Aloe Vera fibres.

At the micro-scale, the incorporation of SiO₂ nanoparticles can reduce microvoids and restrict localised deformation of the epoxy matrix. The uniform distribution of rigid silica particles in the composite can also improve the matrix stiffness and the interfacial load transfer [6, 11]. Graphene nanoplatelets at the nanoscale provide a high aspect ratio

reinforcing phase to encourage stress transfer and restrict the movement of the polymer chains. Graphene can also act as a barrier to crack propagation, making the cracks deviate from their original path and increasing the energy required for fracture [4, 5, 10, 12].

The two nanofillers in the hybrid graphene-SiO₂ system can offer complementary reinforcement mechanisms. Graphene is mainly responsible for stress transfer and crack deflection, while SiO₂ is mainly responsible for matrix stiffening, reduction of local defects and resistance to localized deformation. Their combined action can promote crack deflection, crack branching, crack pinning and a more tortuous fracture path, thereby reducing premature fibre pull-out and increasing energy dissipation during fracture [7, 8, 10–12]. The synergistic effect of graphene and silica has also been reported to improve the mechanical and multifunctional behaviour of epoxy-based composites when suitable filler dispersion and interfacial interactions are achieved [7, 8].

The superior mechanical response observed for the optimised AV-GS2 composite can therefore be attributed to the combined effects of improved fibre-matrix adhesion, efficient stress transfer, filler-induced matrix stiffening and crack-restriction mechanisms. However, the reinforcement efficiency depends strongly on filler concentration and dispersion. Excessive graphene or SiO₂ loading can cause agglomeration, which may generate stress-concentration regions and reduce the effectiveness of the reinforcing phase [4, 7, 8]. Optimum graphene/SiO₂ ratio and homogeneous dispersion of the nanoparticles are essential to achieve enhanced mechanical performance in aloe vera fiber reinforced epoxy composites.

5. Conclusions

- Aloe vera fibre-reinforced epoxy composites containing graphene and SiO₂ nanoparticles were successfully investigated using alkali- & silane-treated fibres and a hand lay-up/compression-moulding route.
- The tensile dataset identified AV-GS2 02 as the best-performing formulation, reaching 63.79 N/mm² compared with 36.64 N/mm² for AV-0 01, corresponding to an approximately 74.1% increase.
- SiO₂ containing formulations generally produced stronger tensile behaviour than graphene-only formulations, while the hybrid system provided the most favourable tensile response.
- SEM observations indicated improved fibre-matrix adhesion, reduced voids and improved matrix

continuity in hybrid nano-filled specimens.

- The combined graphene-SiO₂ system provides a plausible synergistic reinforcement mechanism involving stress transfer, crack deflection, matrix densification and reduced interfacial defects.
- The work supports the potential of aloe vera/epoxy hybrid nanocomposites for lightweight automotive, structural, packaging and consumer-product applications.

6. References

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