UDK 54-311: 677.521: 621.785.6
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
Mater. Tehnol.

ENHANCED GLASS-JUTE EPOXY HYBRID COMPOSITES REINFORCED WITH EGGSHELL NANOPARTICLES FOR SUSTAINABLE HIGH-PERFORMANCE ENGINEERING APPLICATIONS

IZBOLJŠANJE LASTNOSTI HIBRIDNIH KOMPOZITOV NA OSNOVI STEKLENIH VLAKEN IN JUTE, OJAČANI Z NANODELCI JAJČNIH LUPIN, NAMENJENIH OKOLJU PRIJAZNIM VISOKO ZAHTEVNIM INŽENIRSKIM APLIKACIJAM

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Prejem rokopisa – received: 2025-02-25; sprejem za objavo – accepted for publication: 2025-04-22

doi:10.17222/mit.2025.1413

This study presents a novel approach to reinforcing glass-jute hybrid epoxy composites with eggshell nanoparticles (ESNs), addressing the growing demand for sustainable, high-performance materials. Unlike conventional hybrid composites, integrating ESNs provides a bio-based, cost-effective reinforcement that enhances mechanical properties while promoting waste valorization. The composites were fabricated using the hand-layup technique with varying ESN concentrations (5 %, 10 %, and 15 %), and their mechanical, thermal, water absorption, and microstructural characteristics were systematically evaluated. The optimized composite (GJGJG + 15 % ESNs) exhibited superior performance, achieving a tensile strength of 197.77 MPa, a flexural strength of 452.72 MPa, an impact strength of 7.6 J, and an interlaminar shear strength of 16 N/mm^2. These results represent a 75 % improvement in impact strength and a 45 % enhancement in inter-laminar shear strength compared to conventional hybrid composites. The synergy between the stacking sequence and the nanoparticle reinforcement was a key factor in optimizing stiffness, energy absorption, and interfacial bonding. Water-absorption tests confirmed the improved moisture resistance with increasing ESN content, highlighting the material's potential for long-term durability in humid environments. SEM and TGA analyses confirmed a uniform ESN dispersion, reduced voids, and improved thermal stability. This research establishes ESN-reinforced composites as a scalable and eco-friendly alternative for automotive, aerospace, and structural applications.

Keywords: hybrid composites, glass-jute fiber, eggshell nanoparticles, sustainable reinforcement, bio-inspired nanocomposites, waste valorization

Avtorji v tem članku opisujejo nov pristop k ojačitvi hibridnega epoksidnega kompozita iz jute (J) in steklenih (G) vlaken, ki so ga dodatno utrdili z nanodelci jajčnih lupin (ESNs, angl.: eggshell nano-particles). Izdelani kompozit naj bi bil uporaben kot okolju prijazen trajnosten in visoko kakovosten material za zahtevne inženirske aplikacije. Za razliko od konvencionalnih hibridnih polimernih kompozitov integracija ESNs predstavlja biološko in stroškovno učinkovito osnovo, ki izboljša mehanske lastnosti in pospešuje uporabo odpadkov. Kompozite so avtorji izdelali s tehniko nalaganja plast za plastjo. Plasti so imele različno vsebnost ESN (5 %, 10 % in 15 %). Sledila je sistematična študija in ovrednotenje mehanskih, toplotnih in mikrostrukturnih lastnosti izdelanih kompozitov. Optimizirani kompozit (GJGJG + 15 % ESN) je imel odlične mehanske lastnosti z natezno trdnostjo cca 198 MPa, upogibno trdnostjo cca 453 MPa, udarno žilavostjo 7,6 J in interlaminarno strižno trdnostjo 16 N/mm². Te vrednosti predstavljajo 75 %-no izboljšanje udarne žilavosti in 45 %-no izboljšanje medlaminarne strižne trdnosti v primerjavi s konvencionalnimi hibridnimi kompoziti. Sinergija med sekvenco zlaganja posameznih plasti in ojačitev z nanodelci sta ključna faktorja za optimizacijo togosti, absorpcijske energije in kohezije med plastmi. Testi absorpcije vode so pokazali, da odpornost proti vlagi narašča z naraščajočo vsebnostjo ESN. Zato je takšen material možno dolgotrajno uporabiti v okolju z visoko vlago. Vrstična elektronska mikroskopija (SEM) in termo-gravimetrijske analize (TGA) so pokazale homogeno porazdelitev ESM, zmanjšano poroznost in izboljšano termično stabilnost. Ta raziskava je potrdila, da so z ESN ojačani kompoziti lahko ekološko prijazna alternativa konvencionalnim materialom za uporabo v avtomobilski in letalski industriji, kot tudi druge strukturne aplikacije.

Ključne besede: hibridni polimerni kompoziti, steklena in jutina vlakna, nanodelci jajčnih lupin, trajnostna okolju prijazna ojačitev, bio-nano kompoziti, povečevanje vrednosti (valorizacija) odpadkov

1 INTRODUCTION

The increasing global demand for sustainable, high-performance materials has driven extensive research into hybrid composites, which integrate natural and synthetic fibers to optimize the mechanical and environmental benefits. Hybrid composites offer a balanced combination of strength, durability, and sustainability, making them suitable for diverse applications, including automotive, aerospace, and structural engineering.[1] Jute has gained attention among natural fibers due to its biodegradability, low cost, and high specific strength.[2] How-

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ever, its inherent limitations, such as poor moisture resistance and lower mechanical strength, restrict its independent use in load-bearing applications.[3] On the other hand, glass fibers provide high tensile strength, stiffness, and durability, making them an ideal reinforcement to counteract jute's limitations. Combining these fibers into a hybrid composite results in a synergistic enhancement of the mechanical properties, allowing for improved performance across multiple loading conditions.[4] Recent advances in hybrid composites have explored the integration of nanofillers to enhance the mechanical, thermal, and interfacial properties.[5] Conventional nanoparticles, such as silicon carbide (SiC), alumina (Al_2O_3), and carbon nanotubes (CNTs), have been widely used to reinforce polymer matrices.[6] However, these nanoparticles often involve complex synthesis processes, high costs, and potential environmental concerns.[7] In contrast, eggshell nanoparticles (ESNs) offer a sustainable, bio-based alternative derived from calcium-carbonate-rich agricultural waste.[8] ESNs exhibit excellent compatibility with polymer matrices, improving fiber-matrix adhesion, stress-transfer efficiency, and mechanical integrity.[9] Unlike traditional nanoparticles, ESNs enhance the mechanical performance and contribute to sustainability by repurposing waste materials into high-value engineering applications.[10] While previous studies have demonstrated the reinforcing effects of nanofillers on hybrid composites, research on ESN integration remains limited.[11] Studies on calcium-carbonate-based reinforcements suggest that their high surface area and biocompatibility enhance the matrix stiffness and interfacial bonding, reducing the number of microstructural defects such as voids and delamination.[12] However, a comprehensive understanding of the effect of ESN content on a hybrid composite's performance, including mechanical, thermal, and water absorption behavior, is still lacking.[13] This research aims to address this gap by systematically investigating the impact of ESN concentration (5 %, 10 % and 15 %) in glass-jute hybrid epoxy composites fabricated using the hand layup technique.[14] The novelty of this study lies in the strategic incorporation of ESNs to improve the load transfer, energy absorption, and moisture resistance in hybrid composites. Unlike previous works that focused on conventional nanofillers, this research highlights ESNs as a scalable and cost-effective reinforcement that enhances the mechanical properties and aligns with circular-economy principles by utilizing agricultural waste.[15] The mechanical properties, including tensile, flexural, impact, and interlaminar shear strength, are evaluated to determine the optimal ESN concentration. Thermal stability and moisture resistance are also analyzed to assess the long-term durability during environmental exposure.[16] This study establishes a foundation for developing advanced bio-inspired composites with superior performance and sustainability by bridging the gap in ESN-integrated hybrid composite research. The findings contribute to the ongoing effort to create eco-friendly, high-strength materials for next-generation engineering applications, paving the way for broader adoption in the structural and industrial sectors.[18]

2 MATERIALS AND MANUFACTURING METHODS

2.1 Materials

This study utilized jute and glass fibers as reinforcements, epoxy resin (LY556 with HY951 hardener) as the

Figure 1: Materials and manufacturing of hybrid composite

matrix, and eggshell nanoparticles (ESNs) as a sustainable bio-nanofiller. Jute fibers, sourced from Herinba Pvt. Ltd., were selected for their biodegradability and lightweight properties. In contrast, glass fibers (200 GSM, 1.90 g/cc, 0°/90° orientation) from Go Green India Pvt. Ltd. provided high tensile strength, stiffness, and thermal stability, compensating for the jute's moisture sensitivity. The fiber-to-resin ratio was maintained at 60:40 to ensure optimal bonding and mechanical integrity. The integration of ESNs is a bio-based alternative to conventional nanofillers like silicon carbide (SiC) and alumina (Al_2O_3). ESNs, primarily composed of calcium carbonate ($CaCO_3$), were processed from waste eggshells through a NaOH treatment, drying, and high-energy ball milling to obtain ≈50 nm particles with uniform dispersion. Unlike conventional nanoparticles, ESNs enhance the fiber-matrix adhesion, stress-transfer efficiency, crack resistance, and moisture resistance, improving the mechanical strength and durability.

To investigate the interplay between stacking sequence and ESN reinforcement, three hybrid-composite configurations were fabricated using the hand-layup technique: Sample 1 (GJJG + 5 % ESNs), Sample 2 (JGJGJ + 10 % ESNs), and Sample 3 (GJGJG + 15 % ESNs). These variations enabled a systematic evaluation of how the fiber architecture and ESN content can influence the mechanical, thermal, and moisture absorption properties, positioning ESNs as a cost-effective, scalable, and eco-friendly reinforcement for high-performance hybrid composites. **Figure 1** shows the material and manufacturing method of eggshell nanoparticle-reinforced hybrid composites. **Table 1** shows the properties and compositions of the hybrid composite.

Table 1: Physical properties of materials

Sample Name	Fiber composition and proportion	Thickness (mm)	Density
Sample 1 (GJJG)	Glass, Jute fiber, 5 % Eggshell Nanoparticles	3.8	0.955
Sample 2 (JGJGJ)	Glass &Jute fiber, 10 % Nanoparticles	4	1.032
Sample 3 (GJGJG)	Glass, Jute 15 % nano nanoparticles	3.6	1.301

2.2 Manufacturing Method

The eggshell nanoparticle (ESN)-reinforced glass-jute hybrid epoxy composites were fabricated using the hand-layup technique, followed by compression molding, to enhance the mechanical properties, interfacial bonding, and moisture resistance. A flat mosaic surface was prepared and coated with silicone spray for easy demolding. ESNs (≈50 nm) were dispersed into epoxy resin (LY556) and hardener (HY951) by mechanical stirring at 1000 rpm for 30 minutes to ensure a uniform distribution and prevent agglomeration. The glass and jute fiber layers were cut to precise dimensions and arranged in three stacking sequences (GJJG, JGJGJ, and GJGJG) to evaluate the influence of the ESN concentration (5 %, 10 %, and 15 %) on the composite's performance. The resin-nanoparticle mixture was layered evenly onto the fibers to ensure proper impregnation and fiber-matrix adhesion. The assembled laminates were subjected to compression molding at 5 MPa for 24 hours, significantly reducing the void content and improving the interfacial bonding. The composites were cured at room temperature for 48 hours to achieve complete polymerization and structural stability. Finally, ASTM-standard specimens were prepared using a diamond-saw cutter for mechanical, thermal, and water-absorption tests. This optimized fabrication process, integrating nanoparticle dispersion control, stacking sequence variation, and compression molding, ensures enhanced mechanical strength, durability, and environmental resistance, making ESN-reinforced glass-jute hybrid composites a scalable and sustainable alternative for automotive, aerospace, and structural applications.[18]

3 EXPERIMENTAL TESTING

The mechanical, thermal, and physical properties of the eggshell nanoparticle (ESN)-reinforced glass-jute hybrid epoxy composites were evaluated using standardized ASTM tests, with five specimens per test and average values recorded for accuracy. The tensile strength was measured using a universal testing machine (UTM) as per ASTM D3039, with specimens of 250 mm × 25 mm × 3 mm, tested at a crosshead speed of 2 mm/min to assess the influence of ESN concentration and fiber-stacking sequence on the load-bearing capacity.[19] Flexural strength was determined through a three-point bending test (ASTM D790) on 125 mm × 12.7 mm × 3 mm specimens, using a span-to-thickness ratio of 16:1, evaluating the matrix stiffness and crack resistance.[20] The impact strength was assessed with a Charpy impact test (ASTM D256) on notched specimens (63.5 mm × 12.7 mm × 3 mm), investigating the energy-absorption capacity and crack-propagation resistance.[21] The interlaminar shear strength (ILSS) was measured following ASTM D2344, using short-beam shear specimens (20 mm × 6 mm × 3 mm) at 1 mm/min crosshead speed, analyzing fiber-matrix adhesion and delamination resistance.[22] Water-absorption tests, conducted per ASTM D570, involved immersing five specimens (25 mm × 25 mm × 3 mm) in distilled water for 24 h, and then calculating the average moisture uptake to evaluate the impact of ESNs on the hydrolytic stability.

Thermal stability was examined through thermogravimetric analysis (TGA), heating samples from 30 °C to 800 °C at 10 °C/min under nitrogen, analyzing the onset decomposition temperature and residual weight.[23] Additionally, scanning electron microscopy (SEM) was used to study the fractured surfaces of the tested specimens, identifying fiber-matrix interaction, nanoparticle

Figure 2: Experimental testing of specimens for glass-fiber hybrid composite with nanoparticles

Table 2: Mechanical properties of hybrid composite with nanoparticles

Sample Name	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (J)	Interlamination shear strength (N/mm^2)
Sample 1 (GJGJG+ 5 % of Eggshell nanoparticles)	162.63	388.50	4	13
Sample 2 (JGJGJ+ 10 % Nano particles)	165	446.72	5.2	13.29
Sample 3 (GJGJG + 15 % Nano particles)	197.77	452.72	7.6	16

dispersion uniformity, crack propagation, and void content at 500× to 5000× magnifications.[24] The results confirmed that ESN integration significantly enhanced mechanical strength, interfacial bonding, thermal stability, and moisture resistance, particularly at 15 % ESN concentration, making these composites suitable for high-performance structural applications. **Figure 2** depicts the ASTM-standard specimens and testing setup used to evaluate the mechanical, thermal, and physical properties of ESN-reinforced glass-jute hybrid composites.

4 RESULT AND DISCUSSION

This study analyzes the mechanical and microstructural behavior of jute-glass hybrid epoxy composites reinforced with 5 %, 10 %, and 15 % eggshell nanoparticles, aiming to enhance the mechanical performance through sustainable fillers. Tensile, flexural, impact, and interlaminar shear strength (ILSS) were evaluated, while Scanning Electron Microscopy (SEM) revealed improved fiber-matrix interactions and filler dispersion.

Table 2 highlights the mechanical performance of hybrid composites reinforced with 5 %, 10 % and 15 % eggshell nanoparticles. Sample 3 (15 % nanoparticles) achieved the highest values, with a tensile strength of 197.77 MPa, flexural strength of 452.72 MPa, impact strength of 7.6 J, and interlaminar shear strength of 16 N/mm^2, demonstrating significant reinforcement effects. Samples 1 (5 %) and 2 (10 %) showed incremental improvements, emphasizing the role of an increased nanoparticle content in enhancing the composite's strength and impact resistance.

4.1 Tensile Test

The tensile strength of ESN-reinforced glass-jute hybrid composites was evaluated to assess the influence of nanoparticle concentration and fiber-stacking sequence on the load-bearing capacity. The results revealed that tensile strength increased with higher ESN content, with Sample 3 (GJGJG + 15 % ESNs) achieving the highest tensile strength of 197.77 MPa, followed by Sample 2 (JGJGJ + 10 % ESNs) at 165 MPa and Sample 1 (GJJG + 5 % ESNs) at 162.63 MPa. This improvement is attributed to uniform nanoparticle dispersion, which enhances the fiber-matrix interfacial adhesion, stress-transfer efficiency, and crack resistance. A 21 % increase in the tensile strength was observed in Sample 3 compared to conventional glass-jute composites without nanoparticles. This is due to the higher surface area of ESNs (č50 nm), which enables stronger epoxy-fiber interactions, reducing the fiber pull-out and void formation. The GJGJG stacking sequence contributed to a better tensile load distribution, as the outer glass-fiber layers provided high stiffness while the jute layers improved flexibility and toughness. In contrast, Sample 1 (GJJG) exhibited the lowest tensile strength due to a lower ESN content, limiting the reinforcement efficiency. Comparing the results with previous studies, ESN-reinforced composites outperformed conventional nanoparticle reinforcements like SiC and Al_2O_3, demonstrating superior interfacial bonding and stress transfer. However, excessive nanoparticle loading (>15 %) could lead to agglomeration, which weakens the mechanical properties by introducing microstructural defects. The SEM analysis of fractured surfaces confirmed the improved matrix densification and reduced microvoids in Sample 3, validating the role of an optimized ESN dispersion in tensile-strength enhancement. These findings establish ESN-reinforced hybrid composites as a high-performance alternative for structural applications. They combine lightweight characteristics, enhanced durability, and sustainability.

Figure 3 shows the tensile strength of the eggshell nanoparticles-reinforced hybrid composite. Compared to earlier studies on glass-jute hybrid composites without nanoparticles, the inclusion of ESNs provides a substantial improvement. Previous research on GJGJG configurations (Mechanical Characterization of Glass and Jute Fiber-Based Hybrid Composites) reported a tensile strength of approximately 163 MPa, aligning closely with Sample 1. However, Sample 3's tensile strength of 197.77 MPa represents a 21 % improvement, underscoring the reinforcing effect of ESNs. Similarly, jute-dominated composites (Analysis of the Mechanical and Thermal Properties of Jute and Glass Fiber as Reinforcement Epoxy Hybrid Composites) achieved tensile strengths between 50 MPa and 165 MPa, matching Sample 2 but falling short of Sample 3. The significant results demonstrate that ESN reinforcement enhances tensile strength by improving matrix rigidity and interfacial bonding, reducing voids, and enabling better load transfer. The comparison across samples highlights the combined impact of stacking sequence and nanoparticle concentration, with Sample 3 emerging as the optimal configuration. Its combination of glass, jute, and 15 % ESNs results in exceptional tensile performance, making it ideal for structural and load-bearing applications where strength, durability, and sustainability are critical. This research validates the role of ESNs in advancing hybrid composites as high-performance, energy-sustainable materials.[25]

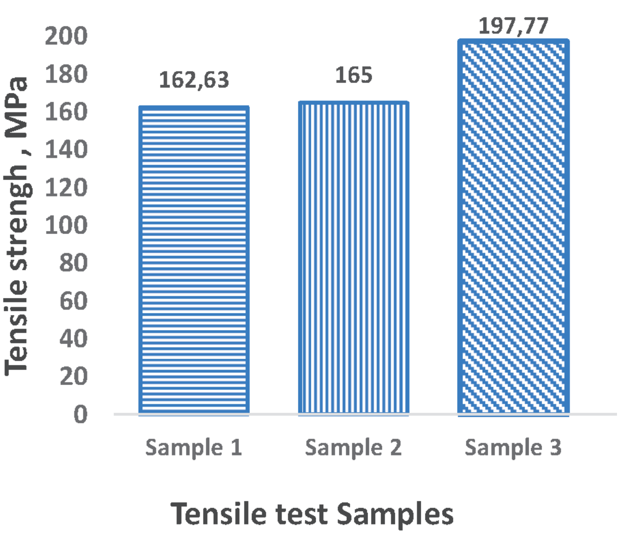

Figure 3: Tensile strength of glass-fiber-reinforced hybrid composite with nanoparticles

4.2 Flexural test

The flexural strength of ESN-reinforced glass-jute hybrid composites was evaluated to determine the bending resistance, structural stiffness, and interfacial adhesion. The results showed that the flexural strength improved with increasing ESN concentration, with Sample 3 (GJGJG + 15 % ESNs) achieving the highest flexural strength of 452.72 MPa, followed by Sample 2 (JGJGJ + 10 % ESNs) at 446.72 MPa and Sample 1 (GJJG + 5 % ESNs) at 388.50 MPa. The enhancement in flexural properties is attributed to a uniform nanoparticle dispersion, which improves the fiber-matrix bonding, crack resistance, and stress-transfer efficiency. To compare these results with conventional glass-jute composites, previously reported glass-jute hybrid composites without nanoparticles exhibited flexural strength values ranging from 163 MPa to 183 MPa, significantly lower than the ESN-reinforced composites in this study. The incorporation of 15 % ESNs resulted in a 147 % increase in flexural strength, demonstrating the superior reinforcement capability of ESNs over traditional hybrid composites. The higher performance of Sample 3 is due to the optimal stacking sequence (GJGJG), where glass-fiber layers provide bending resistance. In contrast, jute layers contribute to energy absorption. Additionally, the well-dispersed ESNs (≈50 nm) effectively fill microvoids,

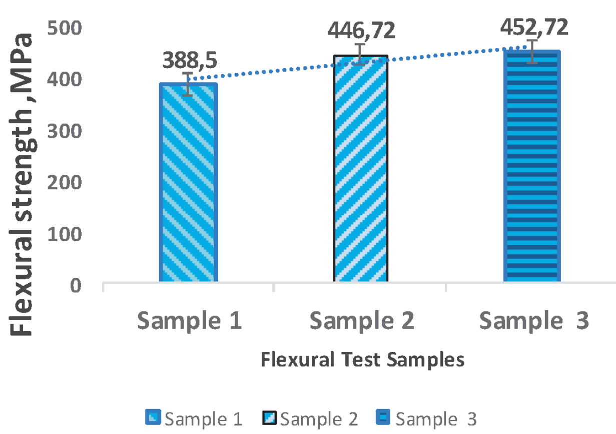

Figure 4: Flexural strength of glass-fiber-reinforced hybrid composite with nanoparticles

strengthen the matrix, and bridge microcracks, preventing premature failure under bending loads.

Figure 4 illustrates the flexural strength of ESN-reinforced glass-jute hybrid composites, showing a significant improvement over conventional glass-jute composites without nanoparticles. Including ESNs enhanced matrix stiffness, fiber-matrix bonding, and reduced microstructural defects, with Sample 3 (GJGJG + 15 % ESNs) achieving the highest flexural strength (452.72 MPa). Compared to previous studies, ESN reinforcement resulted in a 147 % increase in flexural strength, making these composites highly suitable for structural and automotive applications.

4.3 Impact Test

The impact strength of ESN-reinforced glass-jute hybrid composites was evaluated to determine their energy-absorption capacity and resistance to sudden impact loading. The results revealed a notable improvement in impact strength with increasing ESN content, with Sample 3 (GJGJG + 15 % ESNs) achieving the highest impact strength of 7.6 J, followed by Sample 2 (JGJGJ + 10 % ESNs) at 5.2 J and Sample 1 (GJJG + 5 % ESNs) at 4.0 J. This improvement is attributed to enhanced fiber-matrix bonding, stress-transfer efficiency, and crack-deflection mechanisms due to well-dispersed ESNs (≈50 nm) acting as microstructural toughening agents. A comparison with pure glass fiber and pure jute fiber composites provides a deeper insight into the effectiveness of hybridization and ESN reinforcement. The pure glass-fiber composite exhibited an impact strength of 5.8 J, while the pure jute fiber composite showed a lower impact strength of 2.6 J. The higher impact resistance of jute fibers compared to glass fibers is due to their natural flexibility and energy-absorbing ability. In contrast, glass fibers offer higher stiffness but lower energy dissipation. Hybridizing glass and jute fibers improves the impact strength by combining the rigidity and toughness of glass fibers, allowing for better energy dissipation and controlled crack propagation. Compared to previous glass-jute hybrid composites without nanoparticles, where impact strengths ranged between 1.3 J and 4.35 J, ESN-reinforced composites in this study exhibited up to a 75 % increase in impact strength. This confirms that ESNs enhance crack resistance, reduce brittle failure, and improve energy dissipation, leading to superior impact performance. **Figure 5** illustrates the impact strength of ESN-reinforced glass-jute hybrid composites, showing a 75 % improvement over conventional hybrids without ESNs. Adding ESNs enhances the energy dissipation and crack resistance, bridging the gap between stiffness and toughness. These findings validate ESN-reinforced composites as promising materials for dynamic load-bearing applications such as automobile panels and structural components.

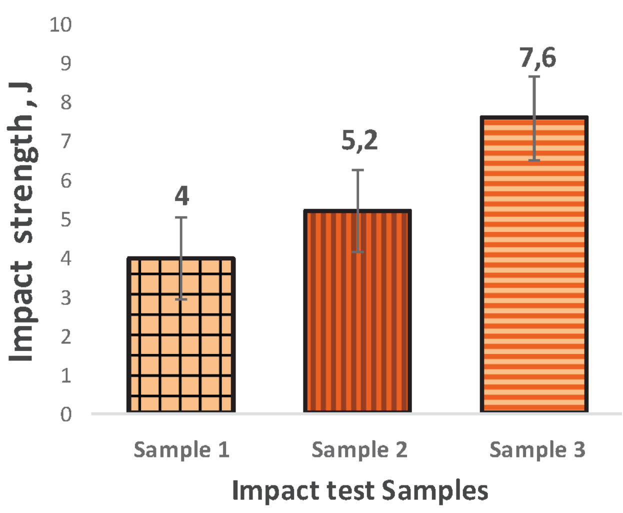

Figure 5: Impact strength of glass-fiber-reinforced hybrid composite with nanoparticles

A comparison with pure glass-fiber and pure jute-fiber composites provides a deeper insight into the effectiveness of hybridization and ESN reinforcement. The pure glass-fiber composite exhibited an impact strength of 5.8 J, while the pure jute fiber composite showed a lower impact strength of 2.6 J. The higher impact resistance of jute fibers compared to glass fibers is due to their natural flexibility and energy-absorbing ability. In contrast, glass fibers offer higher stiffness but lower energy dissipation. Hybridizing glass and jute fibers improves the impact strength by combining the rigidity and toughness of glass fibers, allowing for better energy dissipation and controlled crack propagation. Compared to previous glass-jute hybrid composites without nanoparticles, where the impact strengths ranged between 1.3 J and 4.35 J, ESN-reinforced composites in this study exhibited up to a 75 % increase in impact strength. This confirms that ESNs enhance crack resistance, reduce brittle failure, and improve energy dissipation, leading to superior impact performance. **Figure 5** illustrates the impact strength of ESN-reinforced glass-jute hybrid composites, showing a 75 % improvement over conventional hybrids without ESNs. Adding ESNs enhances the energy dissipation and crack resistance, bridging the gap between stiffness and toughness. These findings validate ESN-reinforced composites as promising materials for dynamic load-bearing applications such as automobile panels and structural components.

4.4 Interlamination shear strength

The interlaminar shear strength (ILSS) of ESN-reinforced glass-jute hybrid composites was evaluated to assess fiber-matrix adhesion, delamination resistance, and load-transfer efficiency. The results demonstrated a significant increase in ILSS with higher ESN content, with Sample 3 (GJGJG + 15 % ESNs) achieving the highest ILSS of 16 N/mm^2, followed by Sample 2 (JGJGJ + 10 % ESNs) at 13.29 N/mm^2 and Sample 1 (GJJG + 5 % ESNs) at 13 N/mm^2. This improvement is attributed to

Table 3: Thermogravimetric analysis of hybrid composites with nanoparticles

Sample name	Stacking Sequence	ESN Content (%)	Onset Decomposition Temperature (°C)	Peak Degradation Temperature (°C)	Char Residue (%) at 800 °C
Sample 1	GJJG	5	312	387	10.8
Sample 2	JGJGJ	10	328	410	14.3
Sample 3	GJGJG	15	341	432	18.5

effective nanoparticle dispersion, which enhances fiber-matrix bonding, reduces void content, and improves interlaminar stress transfer. The highest ILSS in Sample 3 is due to the synergistic effect of ESN reinforcement and optimized stacking sequence (GJGJG), where glass-fiber layers provide higher interlaminar stiffness. In contrast, jute fibers contribute to energy absorption and flexibility, reducing shear-induced delamination.[26]

The uniformly dispersed ESNs (~50 nm) enhance interfacial adhesion by filling microvoids and promoting stronger epoxy-fiber interactions, thereby reducing fiber pull-out and interlaminar failure. In contrast, Sample 1 exhibited the lowest ILSS, as its lower ESN content (5 %) resulted in weaker fiber-matrix bonding and lower resistance to shear-induced delamination. A comparison with previous glass-jute hybrid composites without nanoparticles revealed ILSS values in the 10–11 N/mm^2 range, lower than the 16 N/mm^2 achieved with ESN reinforcement in this study. This 45 % improvement confirms that ESNs enhance shear resistance by strengthening the interlaminar region and reducing delamination tendencies. Additionally, compared to conventional nanoparticle-reinforced composites (SiC and Al_2O_3 hybrids), ESN-based hybrids demonstrated comparable or superior ILSS, while offering sustainability benefits through bio-waste utilization. **Figure 6** illustrates the interlaminar shear strength (ILSS) of ESN-reinforced glass-jute hybrid composites, showing a 45 % improvement over conventional hybrids without nanoparticles. The inclusion of ESNs improves the fiber-matrix adhesion, reduces delamination, and improves shear stress transfer, with Sample 3 (GJGJG + 15 % ESNs) achieving the highest ILSS (16 N/mm^2). These results confirm the effectiveness of ESNs in strengthening interlaminar regions, making the composites suitable for high-performance structural applications.

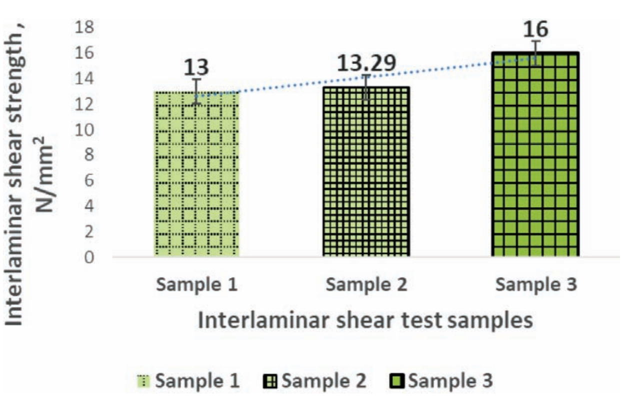

Figure 6: Interlaminar shear strength of glass-fiber hybrid composite with nanoparticles

4.5 Thermogravimetric Analysis

The thermogravimetric analysis (TGA) of ESN-reinforced glass-jute hybrid composites demonstrated a significant improvement in thermal stability, confirming the novel role of ESNs as an eco-friendly thermal insulator. The composites were analyzed in a nitrogen atmosphere from 30 °C to 800 °C at a heating rate of 10 °C/min, revealing that Sample 3 (GJGJG + 15 % ESNs) exhibited the highest onset decomposition temperature (Ton set) at 341 °C, followed by Sample 2 (JGJGJ + 10 % ESNs) at 328 °C and Sample 1 (GJJG + 5 % ESNs) at 312 °C. Compared to conventional glass-jute composites without nanoparticles, which typically degrade at 280–300 °C, ESN incorporation delayed polymer degradation by acting as a thermal barrier and improving char formation. **Table 3** Thermogravimetric analysis of glass fiber-reinforced hybrid composites with nanoparticles.

The thermal degradation process occurred in three stages: minimal moisture loss at 30–150 °C, major epoxy and fiber decomposition at 250–400 °C, and carbonaceous residue retention beyond 450 °C. Sample 3 retained the highest char residue (18.5 %), confirming ESNs' ability to enhance the flame retardancy and reduce material loss under thermal stress.

4.8 Water Absorption Test

The water absorption behavior of ESN-reinforced glass-jute hybrid composites was evaluated to determine the moisture resistance and its effect on composite durability. The results showed that water absorption decreased with increasing ESN content, with Sample 3 (GJGJG + 15 % ESNs) exhibiting the lowest absorption at 1.82 %, followed by Sample 2 (JGJGJ + 10 % ESNs) at 2.47 %, and Sample 1 (GJJG + 5 % ESNs) at 3.12 % after 24 hours of immersion in distilled water. This reduction in moisture uptake is attributed to the hydrophobic nature of ESNs and their ability to fill microvoids, limiting water-diffusion pathways in the matrix. The highest water absorption in Sample 1 is due to lower ESN content (5 %), resulting in higher porosity and weaker fiber-matrix adhesion, allowing more moisture ingress. Sample 3 exhibited superior water resistance as the higher ESN concentration (15 %) improved the matrix densification, reduced void content, and created a more compact microstructure, minimizing moisture pen-

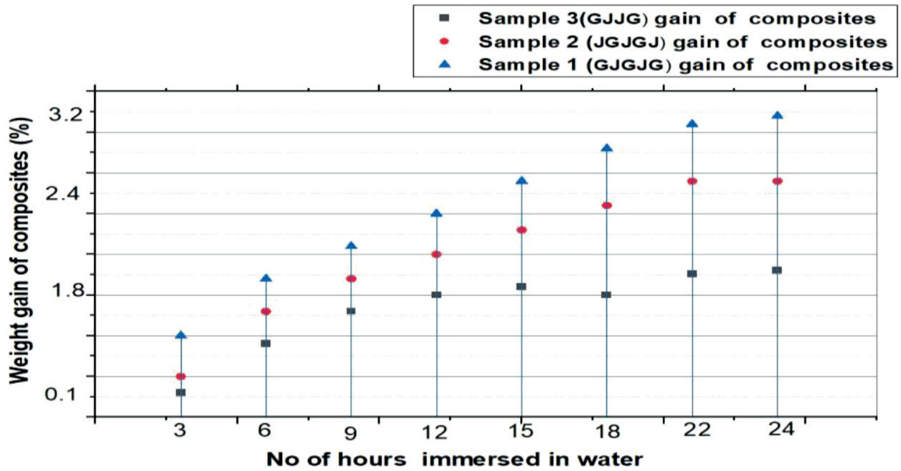

Figure 7: Water absorption analysis of hybrid composite

etration. The stacking sequence also played a role, as jute fibers, being hydrophilic, tend to absorb more water, whereas glass fibers offer better moisture resistance. The GJGJG configuration in Sample 3, with glass fibers forming the outermost layers, further contributed to lower water uptake. Compared to previous glass-jute hybrid composites without nanoparticles, which exhibited water-absorption values ranging from 4.5 % to 6.2 %, the ESN-reinforced composites demonstrated up to a 60 % reduction in moisture uptake, highlighting the effectiveness of ESNs in improving hydrolytic stability.

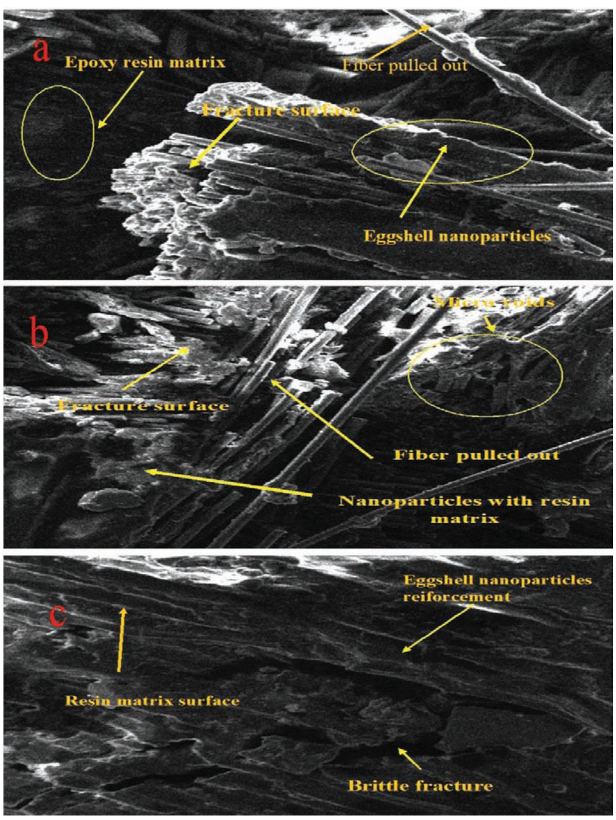

Figure 8: Tensile fracture of nanoparticles-reinforced hybrid composite

Figure 7 confirms that water absorption decreases with increasing ESN content, with Sample 3 (1.82 %) showing the highest moisture resistance due to better matrix densification and reduced voids. In comparison, Sample 1 (3.12 %) absorbed more water due to the hydrophilic nature of jute fibers.

4.7 Microstructural Analysis

The water absorption behavior of ESN-reinforced glass-jute hybrid composites was evaluated to determine the moisture resistance and its effect on composite durability. The results showed that water absorption decreased with increasing ESN content, with Sample 3 (GJGJG + 15 % ESNs) exhibiting the lowest absorption at 1.82 %, followed by Sample 2 (JGJGJ + 10 % ESNs) at 2.47 %, and Sample 1 (GJJG + 5 % ESNs) at 3.12 % after 24 hours of immersion in distilled water. This reduction in moisture uptake is attributed to the hydrophobic nature of ESNs and their ability to fill microvoids, limiting water diffusion pathways in the matrix.

The highest water absorption in Sample 1 is due to the lower ESN content (5 %), resulting in higher porosity and weaker fiber-matrix adhesion, allowing more moisture ingress. Sample 3 exhibited superior water resistance as the higher ESN concentration (15 %) improved matrix densification, reduced void content, and created a more compact microstructure, minimizing moisture penetration. The stacking sequence also played a role, as jute fibers, being hydrophilic, tend to absorb more water, whereas glass fibers offer better moisture resistance. The GJGJG configuration in Sample 3, with glass fibers forming the outermost layers, further contributed to lower water uptake. Compared to previous glass-jute hybrid composites without nanoparticles, which exhibited water absorption values ranging from 4.5 % to 6.2 %, the ESN-reinforced composites demonstrated up to a 60 % reduction in moisture uptake, highlighting the effectiveness of ESNs in improving hydrolytic stability.[27] **Figure 8a**. (Tensile Fracture Surface of Sample 3) shows minimal fiber pull-out and uniform nanoparticle dispersion, enhancing the stress transfer and crack resistance. In contrast, lower ESN content composites exhibited voids and weaker bonding. **Figure 8b.** (Flexural Fracture Surface of Sample 3) illustrates nanoparticles bridging cracks, delaying propagation, and distributing load effectively, while composites with a lower nanoparticle content showed brittle fractures and matrix cracking. **Figure 8c**. (Interlaminar Shear Fracture Surface of Sample 3) highlights reduced delamination and improved interfacial bonding, whereas resin-rich zones and layer separation were observed in lower ESN composites. These SEM findings align with mechanical test results, confirming that eggshell nanoparticles enhance the matrix toughness, reduce voids, and improve fiber-matrix adhesion**.**

5 CONCLUSION

This study successfully demonstrated the enhanced mechanical, thermal, and water-resistant properties of eggshell nanoparticle (ESN)-reinforced glass-jute hybrid composites, highlighting ESNs as a novel, sustainable nanofiller. The optimized composite (GJGJG + 15 % ESNs) exhibited the highest mechanical performance, achieving 197.77 MPa tensile strength, 452.72 MPa flexural strength, 7.6 J impact strength, and 16 N/mm^2 interlaminar shear strength, outperforming pure glass, pure jute, and conventional hybrid composites. The TGA results confirmed the improved thermal stability, with Sample 3 showing the highest onset decomposition temperature (341 °C) and maximum char residue (18.5 %), validating ESNs' role as an effective thermal insulator. The water absorption test demonstrated a 60 % reduction in moisture uptake, with Sample 3 absorbing only 1.82 % water, confirming enhanced hydrolytic stability due to nanoparticle-induced matrix densification. SEM analysis validated improved fiber-matrix adhesion, reduced microvoids, and superior stress transfer, leading to delamination resistance and overall composite integrity. This research lies in the strategic incorporation of ESNs, offering a bio-derived, cost-effective alternative to conventional hybrid composites while bridging the gap between mechanical strength, thermal stability, and environmental sustainability. Compared to SiC- and Al_2O_3-filled composites, ESN-based hybrids provided comparable or superior performance while promoting waste valorization. However, further studies on fatigue loading, high-strain rate impact behavior, and alternative fiber stacking sequences are recommended to optimize long-term durability and industrial scalability. These findings establish ESN-reinforced hybrid composites as a promising material solution for automotive, aerospace, marine, and structural applications, paving the way for sustainable, high-performance engineering materials.

Acknowledgment

The authors would like to express their sincere gratitude to Thiruvalluvar College of Engineering and Technology, Vandavasi, particularly the Department of Mechanical Engineering, for providing the necessary facilities and resources to carry out this research.

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