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DEVELOPMENT AND EVALUATION OF A SUSTAINABLE HYBRID EPOXY COMPOSITE REINFORCED WITH TREATED NATURAL FABRICS AND AGRO-WASTE NANOPARTICLES FOR STRUCTURAL APPLICATIONS

RAZVOJ IN OVREDNOTENJE TRAJNOSTNIH HIBRIDNIH EPOKSIDNIH KOMPOZITOV OJAČANIH Z OBDELANIMI NARAVNIMI VLAKNI IN NANODELCI IZ KMETIJSKEGA ODPADA

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This study presents the fabrication and a preliminary evaluation of a hybrid epoxy composite reinforced with glass fibers, alkaline-treated natural fabrics – Gossypium herbaceum (cotton) and Corchorus olitorius (jute), and bio-derived particulate fillers from Cocos nucifera and eggshell waste. The composite was manufactured using a hand lay-up technique followed by compression molding, with a defined configuration of five layers: two outer layers of woven E-glass and three inner layers alternating between jute and cotton fabrics. All the reinforcements were treated with 5% NaOH to enhance the interfacial adhesion. A fixed filler loading of 5 w/% each of Cocos nucifera and eggshell powder was introduced into the epoxy matrix, with the nanoparticle size confirmed via direct characterization. Mechanical testing at room temperature yielded average tensile and flexural strengths of 90 MPa and 430 MPa, respectively, while the Charpy impact energy absorption averaged 24 J. The heat deflection temperature reached 145 °C under a 1.82 MPa load. SEM-EDS analysis revealed relatively uniform filler dispersion and adequate fiber-matrix bonding. The novelty of this work lies in integrating two natural fabrics with distinct structural characteristics and the dual incorporation of bio-based particulate fillers, offering a sustainable reinforcement approach utilizing agro-waste. These findings provide a foundation for future studies aimed at optimizing stacking sequence, filler concentration, and chemical treatments to tailor hybrid composites for advanced structural applications.

Keywords: Hybrid epoxy composite, Gossypium herbaceum, Corchorus olitorius, structural applications

V članku avtorji predstavljajo študijo izdelave in preliminarno ovrednotenje hibridnega epoksidnega kompozita ojačanega s steklenimi vlakni, alkalno obdelanim naravnim tekstilom iz zelnega bombaževca in jute, delcev biološko pridobljenega polnila iz kokosovih lupin ter prahu iz odpadkov jajčnih lupin. Avtorji so kompozit izdelali z ročno tehniko nalaganja plast na plas in oblikovanja pod tlakom. Pri tem so uporabili specifično konfiguracijo zlaganja petih plasti: dve zunanji plasti tkanine iz e-stekla in tri notranje plasti izmenično iz jute, delcev kokosovih lupin in bombažna. Vse ojačitvene faze so obdelali s 5% NaOH, da so izboljšali adhezijo med posameznimi plastmi. Konstantno vsebnost 5 mas. % delcev kokosovih lupin in prahu iz jajčnih lupin so vmešali v epoksidno matrico. Povprečno velikost nanodelcev (cca 100 nm) so potrdili z neposredno karakterizacijo. Sledila je določitev mehanskih lastnosti izdelanega kompozita. Izdelani kompozit je imel natezno trdnost 90 MPa, upogibno trdnost 430 MPa in povprečno Charpyjevo udarno energijo absorpcije 24 J. Ugotovljena mejna temperatura toplotne deformacije je bila 145 °C pri obremenitvi 1,82 MPa. SEM-EDS analize so pokazale relativno enakomerno porazdelitev polnila in ustrezno vezavo med vlakni in epoksidno matrico. Inovativnost te študije je v integraciji dveh naravnih tkanin z različnimi strukturnimi značilnostmi in dvojni vgraditvi bio delcev polnila (kokosa in jajčnih lupin), kar predstavlja trajnostni pristop uporabe ojačitvenih faz iz kmetijskih odpadkov. Avtorji v članku ugotavljajo, da ta študije predstavlja osnovo za nadaljnje raziskave in razvoj optimizacije dizajna novih hibridnih polimernih kompozitov za napredne strukturne aplikacije glede zaporedja zlaganja, koncentracije polnil in kemičnih obdelav.

Ključne besede: hibridni epoksidni kompozit, zelni bombaževec (Gossypium herbaceum), jutovec (Corchorus olitorius), strukturne aplikacije

1 INTRODUCTION

Hybrid polymer composites have garnered a lot of attention in recent years due to their potential to combine mechanical performance with reduced environmental impact. These composites typically incorporate synthetic fibers, such as glass or carbon, alongside natural fibers derived from agricultural resources, which balances strength, energy absorption, and sustainability.[1] Their relevance has grown in aerospace, automotive, and civil engineering applications, where the materials must be lightweight, strong, and environmentally aware.[2] Among

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the natural fibers, Gossypium herbaceum (cotton) and Corchorus olitorius (jute) have been widely investigated for their favorable specific strength, cost-effectiveness, renewability, and biodegradability.[3] However, these fibers often suffer from poor interfacial bonding with hydrophobic polymer matrices due to the presence of waxes and non-cellulosic components. Alkaline treatment using sodium hydroxide (NaOH) is a well-established method to improve the fiber-matrix adhesion by increasing the fiber surface roughness and removing hemicellulose and lignin.[4] Glass fibers, although non-biodegradable, are frequently used in hybrid systems to provide mechanical stiffness and load-bearing capacity.[5] Their incorporation enhances tensile properties, while the natural fibers contribute to energy absorption and weight reduction. In recent years, there has also been a shift toward incorporating bio-waste-derived fillers, such as Cocos nucifera (coconut sheath) and eggshell particles, as secondary reinforcements. Eggshells primarily consist of calcium carbonate, which can improve the thermal resistance and crack suppression, while coconut shells contain lignin and cellulose, enhancing the mechanical integrity.[6] Despite numerous studies on natural and synthetic fiber composites, there remains a lack of systematic investigation into the combined use of multiple natural fabrics and dual agro-waste fillers. Prior research often omits critical parameters such as fabric weave, tex value, layer stacking, and the orientation of the fibers, all of which significantly influence performance outcomes. Moreover, most studies do not provide control groups (e.g., untreated fibers, filler-free systems) or comparative data to validate the claims of enhanced properties.[7] The lack of standardized impact testing (Izod vs. Charpy) and discrepancies between the reported tensile and flexural properties further diminish the reproducibility and comparability of existing data.[8] To address these shortcomings, the present study focuses on developing and characterizing a five-layered hybrid epoxy composite consisting of two outer layers of woven E-glass and alternating layers of jute and cotton in the core. All the reinforcements were subjected to a NaOH treatment to improve the compatibility with the epoxy matrix. The matrix was further modified with 5 *w*/% of eggshell and Cocos nucifera powders, processed from local waste sources. The novelty of this study lies in integrating two structurally distinct natural fabrics with dual agro-waste-based fillers in a single composite system. The objective is to establish a baseline composite architecture for future optimization, while evaluating its mechanical and thermal properties under standardized testing conditions to assess its feasibility for structural applications.

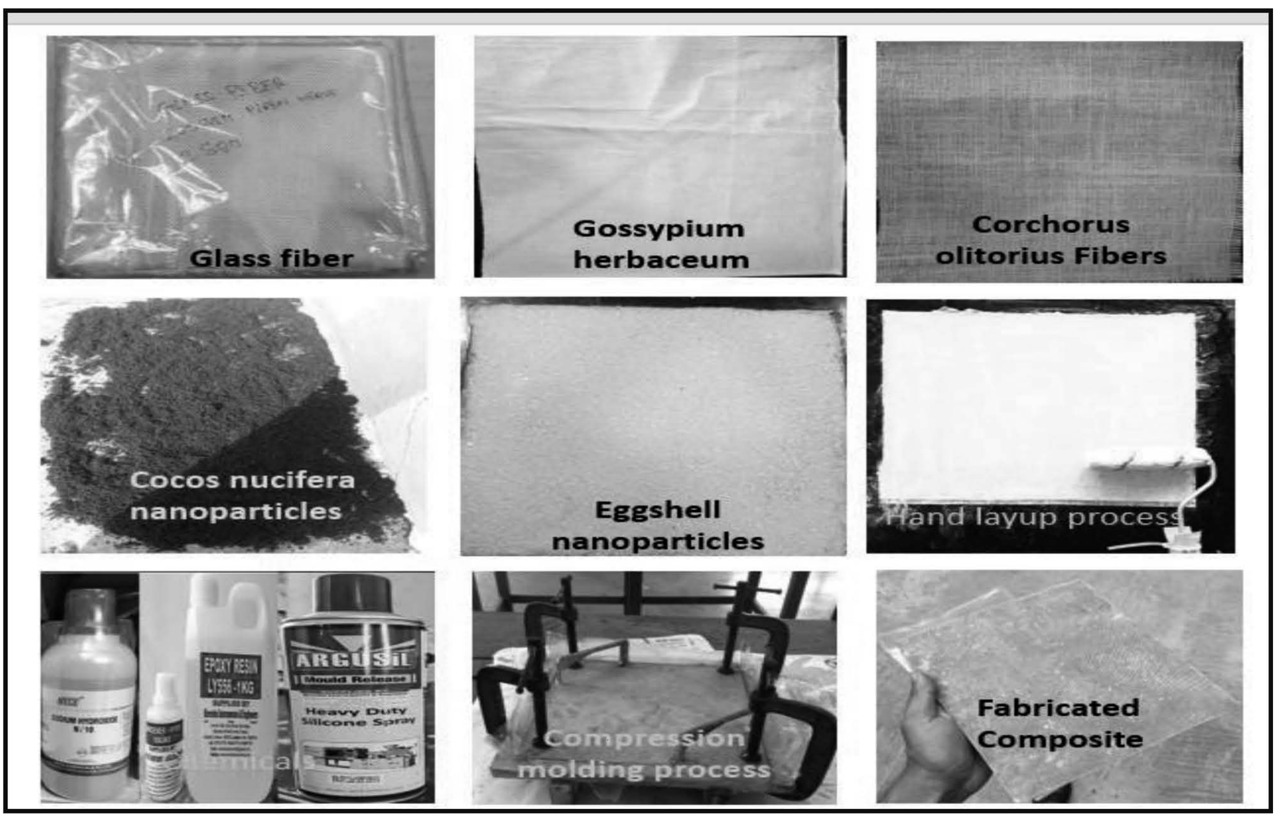

Figure 1: Materials selection

2 MATERIALS AND MANUFACTURING METHODS

2.1 Materials

The materials selected for this study were chosen for their complementary mechanical performance, natural origin, availability, and potential to enhance the interfacial bonding in epoxy-matrix systems. Bidirectionally woven E-glass fibers were used as the synthetic reinforcement due to their high tensile strength (3.5 GPa), stiffness, and durability. The glass fabric, with an areal density of 300 g/m^2, was procured from Herenba Private Limited, Chennai, Tamil Nadu, India. Two natural fabrics were incorporated as sustainable reinforcements: Gossypium herbaceum (cotton) and Corchorus olitorius (jute). The cotton fabrics had a plain weave with a thickness of 0.4 mm and a linear density of 250 tex, while the jute fabrics had a plain weave of 0.6 mm and a linear density of 300. Both natural fabrics were procured from Go Green Private Limited, Chennai, Tamil Nadu, India. These fibers were selected to investigate the effect of structural and textural differences on the composite's mechanical properties and to promote eco-friendly material utilization.[9]

Particulate bio-fillers were introduced into the epoxy matrix to improve the crack resistance and thermal behavior. Cocos nucifera (coconut sheath) powder and chicken eggshells were sourced from agricultural waste and hostel mess waste, respectively, collected from Namakkal District, Tamil Nadu. These fillers are rich in lignocellulosic material and calcium carbonate, offering potential toughness and thermal stability enhancements. Both fillers were cleaned, oven-dried at 60 °C for 24 h, and ball-milled to reduce the particle size (100 nm). The epoxy-matrix system consisted of bisphenol-A epoxy resin and a polyamine hardener in a 10:1 weight ratio. These were procured from a certified chemical distributor in Chennai, Tamil Nadu, India. This thermosetting matrix was chosen for its well-established mechanical performance, chemical resistance, and compatibility with synthetic and natural reinforcements. All the reinforcements were treated with an alkaline solution to improve their surface characteristics and promote better interfacial bonding. Cotton, jute, Cocos nucifera, and eggshells were immersed in a 5 *w*/% NaOH solution for 12 h at room temperature. This treatment removes surface waxes, hemicellulose, and lignin from natural fibers, increasing the surface roughness and wettability. The treated materials were rinsed with distilled water until they reached a neutral pH and air-dried for 24 h[10], see **Figure 1**. The figure shows the sequence of raw materials and manufacturing steps used in this study: (a) bidirectionally woven E-glass fiber, (b) Gossypium herbaceum (cotton) fabric, and (c) Corchorus olitorius (jute) fabric as reinforcements; (d) ball-milled Cocos nucifera (coconut sheath) nanoparticles and (e) eggshell nanoparticles as bio-fillers; (f) epoxy resin and hardener system used as matrix; (g) hand lay-up process for layer stacking and resin impregnation; (h) compression molding setup at 2.5 MPa and 70 °C for 2 hours to consolidate the laminate; and (i) final fabricated hybrid composite with approximately 5 mm thickness.

Figure 2: Alkaline treatment of nanoparticles (a. Cocos nucifera fibre & b. Eggshells)

Figure 2. Alkaline treatment process for agro-waste fillers. The figure shows the chemical treatment of (a) Cocos nucifera fiber and (b) eggshells using a 5 w/% NaOH solution. This alkaline treatment was performed to remove surface impurities, enhance surface roughness, and improve compatibility with the epoxy matrix.

2.2 Manufacturing Method

The hybrid composite was fabricated using a hand lay-up process followed by compression molding to ensure proper fiber alignment, resin infiltration, and a uniform consolidation. Five layers were utilized: the outer layers consisted of woven E-glass fibers for enhanced tensile and flexural performance, while the inner layers alternated between jute and cotton fabrics to improve the energy absorption and sustainability. All fabrics were oriented in a 0°/90° bidirectional configuration. The epoxy resin was combined with 5 *w*/% Cocos nucifera powder and five w/% eggshell powder using a mechanical stirrer at 50 min^{-1} for 15 min to achieve even dispersion. Each fabric layer was manually impregnated with the nanoparticle-modified epoxy mixture. The stacked lay-up was transferred into a steel mold and subjected to compression molding at 2.5 MPa and 70 °C for 2 h. This molding condition was chosen to ensure complete resin curing and minimize the void formation. The final laminate thickness was approximately 5 mm, measured with a digital micrometer. Specimens were cut from the cured laminate according to ASTM standard dimensions for mechanical and thermal testing. This method served as a baseline for integrating dual natural fabrics and bio-based fillers in hybrid epoxy composites, with future studies intended to investigate the layer sequencing, filler concentration, and alternative surface treatments.

3 EXPERIMENTAL TESTING

Mechanical and thermal testing was conducted on the fabricated hybrid epoxy composite to evaluate its structural performance. All the tests were performed at room temperature (23 ± 2 °C) under controlled laboratory conditions using standardized procedures. Five specimens were tested for each property to ensure statistical relevance. However, only average values are reported in this study, and standard deviations or statistical analyses were not included – an identified limitation for future work. Tensile properties were measured by ASTM D3039 using dog-bone-shaped specimens.[11] Tests were conducted using a Tinius Olsen H50KS Universal Testing Machine (UTM) equipped with a 100-kN load cell and an extensometer for strain measurement. The crosshead speed was set at 2 mm/min. Specimens were cut with a gauge length of 50 mm, a width of 15 mm, and a thickness of 5 mm. Each specimen was clamped securely between hydraulic grips, and the test was run until failure. While the tensile strength was recorded, this study did not calculate the tensile modulus and strain at break, and will be included in future analysis. Flexural behavior was assessed using a three-point bending test by ASTM D790.[12] Tests were performed on the same Tinius Olsen H50KS UTM, fitted with a flexural test jig. Each specimen was 100 mm long, with a cross-section of 15 mm and a thickness of 5 mm. The support span was 100 mm, maintaining a span-to-thickness ratio of 20:1. The crosshead speed was 1.3 mm/min. Load was applied at the midpoint until fracture or a significant deflection occurred. Only flexural strength was reported; modulus and strain data were not captured.

Figure 3. Mechanical testing equipment was used in the study. The figure displays (left) the Tinius Olsen H50KS Universal Testing Machine used for conducting tensile and flexural tests by ASTM D3039 and ASTM D790, and (right) the METTEST Charpy impact testing machine used for measuring absorbed energy following ASTM D6110.[13] Impact performance was evaluated using a Charpy impact test as per ASTM D6110. Testing was carried out on a METTEST digital Charpy impact tester, model MT-CIT25, equipped with a 25-J capacity pendulum. Notched specimens (80 mm × 10 mm × 5 mm) were prepared with a 2-mm deep V-notch at the midpoint. Each specimen was mounted horizontally, and the pendulum was released to strike the opposite face of the notch. Absorbed energy values were recorded in joules (J). Due to the absence of complete geometric data, the impact strength (J/m^2) could not be calculated. This will be corrected in future experiments. ASTM D648 measured Heat Deflection Temperature (HDT) using a CEAST HDT/Vicat tester. Each test was performed under a constant flexural load of 1.82 MPa, with the heating rate at 2 °C/min. Rectangular bar specimens of dimensions 120 mm × 10 mm × 5 mm were placed in the HDT apparatus.[14] The temperature at which a deflection of 0.25 mm was recorded was considered the HDT. Five specimens were tested, and mean values were reported.

4 RESULTS AND DISCUSSION

This section presents and interprets the mechanical and thermal testing results of the developed hybrid epoxy composites reinforced with E-glass, Gossypium herbaceum, Corchorus olitorius, and dual agro-waste-based fillers. The analysis includes tensile, flexural, impact, and heat deflection performance and microstructural evaluations using SEM-EDS techniques. Each result is discussed in the context of existing literature to identify the performance trends and potential mechanisms contributing to the observed behavior. While the composite exhibited generally favorable properties, the discussion also addresses the limitations of the current formulation and testing scope. These findings establish a foundational understanding of the hybrid material's perfor-

Figure 3: Experimental testing of hybrid composites

mance and highlight opportunities for further optimization in future studies.

4.1 Tensile Test

The developed hybrid composite exhibited an average tensile strength of 90 MPa, which is considered significant for systems incorporating synthetic and natural reinforcements. This mechanical performance is primarily attributed to the structural synergy between the outer layers of E-glass fibers and the inner layers of alkaline-treated Gossypium herbaceum (cotton) and Corchorus olitorius (jute). The high tensile strength of the E-glass layers provided stiffness and load-bearing support, while the natural fabrics contributed to enhanced strain distribution and toughness. Alkaline treatment of the natural fibers improved the fiber-matrix adhesion by increasing surface roughness and eliminating amorphous materials such as lignin and waxes.[15] This treatment enabled the epoxy resin to wet the fibers better, improving the load transfer across the composite interface. The observed strength aligns well with previously reported values for hybrid composites in the 70–95 MPa range.[16] However, the present study introduces novelty by integrating two structurally and chemically distinct natural fabrics–cotton and jute–within the same laminate and dual particulate fillers derived from waste Cocos nucifera sheath and eggshells. This dual-fiber, dual-filler approach has not been extensively explored in the literature and offers a unique route to balancing mechanical performance with sustainability. Though not directly responsible for tensile strength enhancement, the particulate fillers are believed to have supported microcrack resistance and stress distribution around the fiber-matrix interfaces.[17] Nevertheless, limitations in the current study include the absence of tensile modulus and strain-at-break data, which are critical for fully describing the tensile behavior. Moreover, no control specimens without chemical treatment or fillers were fabricated, which restricts the direct assessment of the isolated impact of each reinforcement strategy. Despite these limitations, the tensile results strongly indicate that when combined with optimally treated natural fibers and synthetic layers, agro-waste fillers can yield composites suitable for structural applications where moderate-to-high tensile performance is essential.

Figure 4. Tensile strength of five glass fiber-reinforced hybrid composite specimens with nanoparticles, showing consistent performance with values ranging from 88 MPa to 92 MPa.

4.2 Flexural test

The fabricated hybrid composite exhibited an average flexural strength of 430 MPa, which is high and exceeds its tensile strength. This performance can be primarily attributed to the structural design of the laminate, where the outer layers of woven E-glass fibers contributed to the bending stiffness and resistance under compressive and tensile stresses during flexural loading. Including natural fabrics–Gossypium herbaceum and Corchorus olitorius–in the core layers helped improve energy dissipation and delayed crack propagation through the laminate thickness.[18] The alkaline treatment of natural fibers enhanced the interfacial bonding with the epoxy matrix, reducing the likelihood of interfacial failure and delamination under bending loads.[19] Furthermore, the epoxy matrix was modified with 5 *w*/% each of Cocos nucifera and eggshell particles, which likely helped reduce the microvoids and acted as secondary reinforcements by filling interstitial spaces, thereby contributing to the improved load transfer and crack-bridging mechanisms. Compared with previous studies on similar hybrid composites, which reported flexural strengths typically ranging from 350 MPa to 420 MPa, the current result demonstrates a competitive performance.[19] The relatively high value may also be influenced by the optimized hand lay-up and compression molding process, which ensured good resin infiltration and reduced porosity. However, the span-to-thickness ratio (20:1) and the absence of flexural modulus and strain-at-break data make it difficult to validate this result fully. This work lies in the strategic hybridization of two natural fibers with different

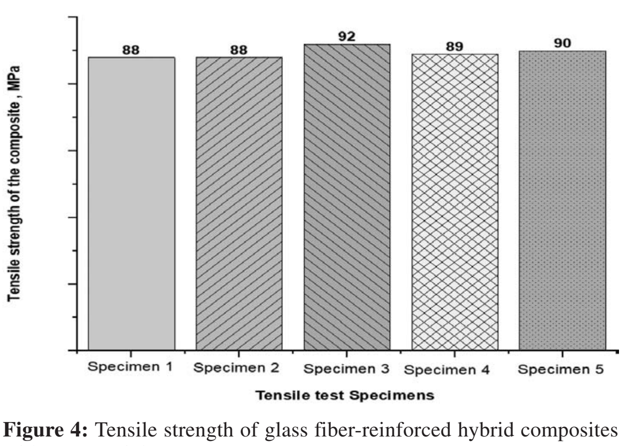

Figure 4: Tensile strength of glass fiber-reinforced hybrid composites with nanoparticles

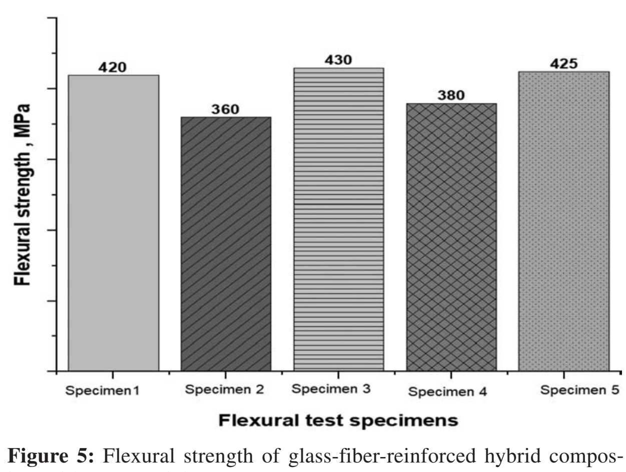

Figure 5: Flexural strength of glass-fiber-reinforced hybrid composites with nanoparticles

mechanical behaviors and the dual use of bio-based fillers, which together contribute to a more complex, synergistic reinforcement network. This combination enhances the load-bearing capability under flexural stress, making the composite particularly promising for applications such as automotive interior panels, structural insulation, and lightweight flooring requiring high flexural strength and stiffness.

Figure 5. The bar chart presents the flexural strengths of five glass-fiber-reinforced hybrid composite specimens with nanoparticles, showing values ranging from 360 MPa to 430 MPa. Specimen 3 exhibited the highest flexural strength (430 MPa), followed by Specimen 5 (425 MPa) and Specimen 1 (420 MPa). These results indicate good flexural performance of the nanoparticle-reinforced hybrid composite, attributed to effective fiber-matrix bonding, proper layer stacking, and filler dispersion. Slight variation among the specimens suggests uniform fabrication quality with minor deviations.

4.3 Impact Test

The developed hybrid composite's average Charpy impact energy absorption was recorded as 24 J. This value reflects the material's ability to dissipate impact energy effectively and resist sudden crack initiation. The relatively high impact energy absorption can be attributed to several synergistic factors in the laminate architecture.[20] The bidirectionally woven E-glass outer layers contributed to structural stiffness. They helped arrest the crack propagation, while the core layers of alkaline-treated cotton and jute fabrics enhanced the ductility and energy dissipation. Natural fibers are known for their capacity to deform plastically under impact, reducing the severity of catastrophic failure. Additionally, including Cocos nucifera and eggshell-based fillers in the epoxy matrix was critical to improving the impact resistance. These fillers, processed from agro-waste and treated to improve the matrix compatibility, are believed to act as micro-barriers within the matrix. They impede crack growth by promoting crack deflection and bridging mechanisms, thus delaying the propagation of impact-induced damage zones.[21] This behavior agrees with prior studies, where natural filler additions increased energy absorption in the range 18–25 J. Unlike most hybrid composites in the literature that focus on either fiber layering or filler inclusion individually, this study uniquely integrates both strategies by combining dual natural fabrics with dual bio-based fillers. This composite configuration offers a multifaceted toughening effect not commonly reported in similar systems, thereby reinforcing the novelty of the work.

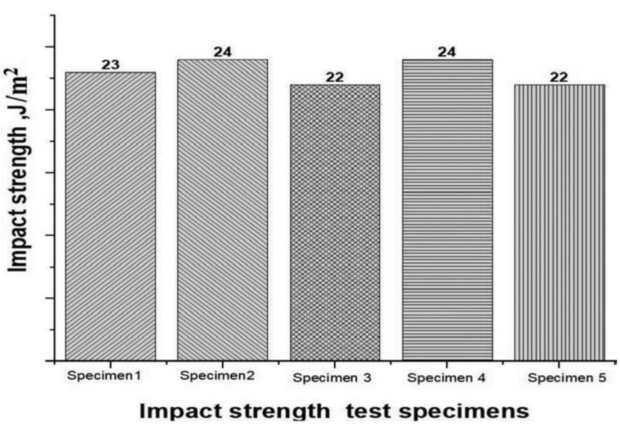

Figure 6: Impact strength of glass-fiber-reinforced hybrid composites with nanoparticles

The alternating jute-cotton core contributes layered compliance under sudden loading, while the nanoparticle-reinforced matrix absorbs and redistributes local stress concentrations. However, this result is limited by its reporting format. The impact test was conducted using ASTM D6110 (Charpy method). Still, the absorbed energy was reported in joules without normalizing for specimen cross-sectional area, preventing direct comparison to standardized impact strength (J/m^2). Furthermore, the absence of control specimens without fillers or untreated fibers restricts the attribution of toughness improvements to individual components. Despite these limitations, the findings demonstrate that hybrid composites with integrated bio-fillers and chemically treated dual-natural-fiber systems can significantly enhance impact energy absorption. This makes them suitable for applications requiring improved crashworthiness and energy dissipation, such as vehicle-door panels, protective casings, and structural packaging components. **Figure 7**. Impact strength of hybrid composite with nanoparticles. The chart displays the impact strength (in joules) of five test specimens, with values ranging from 22 J to 24 J. Specimens 2 and 4 showed the highest impact strength of 24 J, while specimens 3 and 5 recorded the lowest at 22 J. These results indicate good energy-absorption capability, with minimal variation across all specimens. The consistent performance can be attributed to effective fiber-matrix bonding, enhanced toughness due to alkaline-treated natural fibers, and crack-arresting behavior introduced by well-dispersed Cocos nucifera and eggshell nanoparticles.

4.4 Head Deflection Test

The hybrid epoxy composite demonstrated an average Heat Deflection Temperature (HDT) of 145 °C under a load of 1.82 MPa, which is notably higher than typical HDT values reported for unmodified epoxy composites reinforced solely with untreated natural fibers, which usually range between 120 °C and 135 °C. This enhancement directly results from the synergistic effects of fiber treatment, filler incorporation, and a hybrid fiber architecture.[22] The improved thermal stability is partly attributed to the inclusion of calcium-carbonate-rich eggshell powder, which acts as a heat-resistant filler. Its presence within the polymer matrix reduces molecular mobility

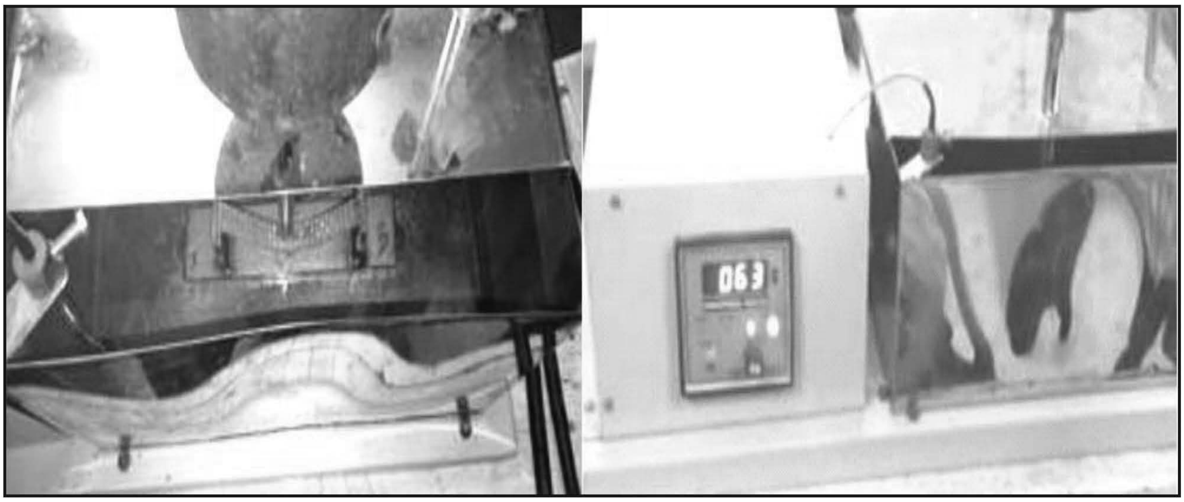

Figure 7: Heat deflection temperature test of a glass-fiber-reinforced hybrid composite specimen

and serves as a thermal barrier, delaying the onset of softening under load. Likewise, Cocos nucifera particles, containing lignin and other thermally stable constituents, reinforce the matrix and resist thermal deformation. The alkaline treatment of natural fibers also plays a crucial role, as it reduces the content of thermally sensitive non-cellulosic compounds, thus improving the thermal tolerance of the fiber-matrix interface. Furthermore, the composite's layered configuration, with alternating jute and cotton fabrics flanked by outer E-glass layers, promotes uniform heat distribution and slows the build-up of internal thermal stress. The E-glass fibers, known for their thermal resistance, act as a reinforcement that maintains the structural integrity under elevated temperatures. Compared to prior work on hybrid composites with single natural fiber types and untreated fillers, this study achieves superior HDT performance without compromising sustainability.

The integration of dual natural fabrics with dual agro-waste-based fillers, processed via NaOH treatment, and uniformly distributed in the matrix. This combination has not been widely explored, but it offers a cost-effective and environmentally responsible approach to improving the thermal resistance of structural composites.

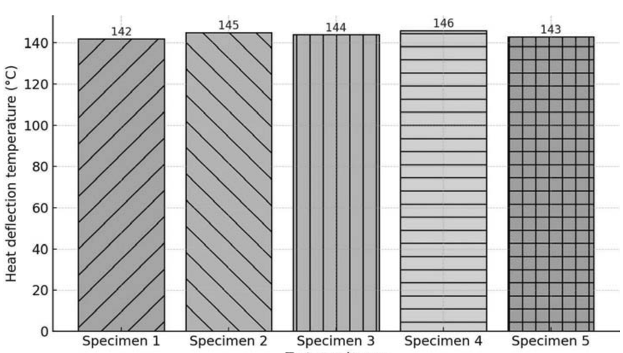

Figure 8: Heat deflection temperature of glass-fiber-reinforced hybrid composites with nanoparticles

The result supports the viability of this hybrid composite system for applications involving moderate-to-high thermal loads, such as automotive under-hood components, thermal insulation panels, and housing enclosures for electronic devices. **Figure 7**. Heat deflection temperature (HDT) testing of the hybrid composite. The figure shows the HDT testing setup used to evaluate thermal performance. The left image captures the specimen under flexural loading in a heated medium, while the right image shows the temperature-monitoring unit displaying the real-time temperature during testing. The test was conducted according to ASTM D648 with a constant load of 1.82 MPa and a heating rate of 2 °C/min. The setup was used to determine the temperature at which the composite specimen deforms under thermal stress, reflecting its suitability for structural applications exposed to moderate thermal environments.

Figure 8. Heat Deflection Temperature (HDT) of hybrid composite specimens. The bar chart illustrates the HDT values of five specimens tested under a constant load of 1.82 MPa, showing results ranging from 142 °C to 146 °C. Specimen 4 recorded the highest HDT at 146 °C, while Specimen 1 exhibited the lowest at 142 °C. The narrow range of variation (±2 °C) indicates consistent thermal performance across the composite samples. The enhanced HDT is attributed to thermally stable fillers – eggshells (rich in calcium carbonate) and Cocos nucifera – and improved fiber-matrix bonding from alkaline treatment. These results confirm the suitability of the hybrid composite for structural applications exposed to moderate thermal environments.[23]

4.7 Microstructural Analysis

Scanning Electron Microscopy (SEM) was conducted on the fractured surfaces of the tensile and impact test specimens to investigate the interfacial characteristics, filler dispersion, and failure modes. The micrographs revealed relatively uniform dispersion of the Cocos

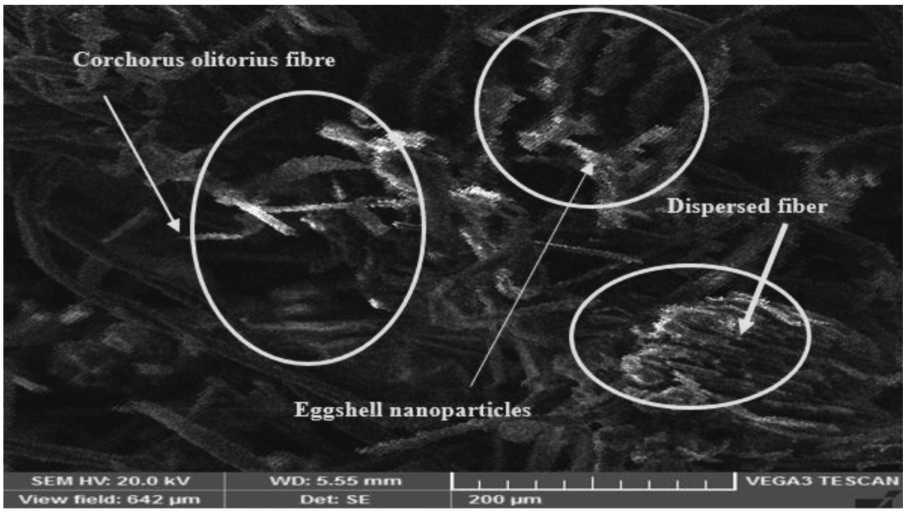

Figure 9: Tensile fracture of nanoparticle-reinforced hybrid composite

nucifera and eggshell powders throughout the epoxy matrix, with minimal agglomeration or clustering. This homogeneity indicates the effective mixing and compatibility of the bio-fillers with the matrix, likely enhanced by prior NaOH treatment and mechanical stirring during fabrication. The SEM images also showed strong fiber-matrix interlocking, particularly along the surfaces of the jute and cotton fabrics. The alkaline-treated fibers displayed roughened textures and clean interfaces, confirming improved wettability and adhesion to the matrix. Minimal fiber pull-out and matrix residues on fiber surfaces suggest efficient load transfer during the mechanical testing. These characteristics contribute positively to both the tensile and flexural strength performance. Additionally, microcracks were observed propagating around filler particles and terminating at the fiber interfaces, indicating that the fillers acted as stress distributors and crack-arresters. This phenomenon supports the enhanced impact-energy absorption observed in the mechanical tests. The ductile fracture zones with embedded particles demonstrate a composite failure mode governed by energy dissipation rather than brittle separation[23].

Figure 9. SEM image of the tensile fracture surface of the nanoparticle-reinforced hybrid composite. The image illustrates the microstructural characteristics of the fractured region, highlighting the presence of Corchorus olitorius (jute) fibers, dispersed natural fibers, and embedded eggshell nanoparticles. The rough fracture surface and well-anchored fibers indicate good fiber-matrix adhesion, enhanced by alkaline treatment. The visible dispersion of eggshell nanoparticles within the matrix suggests effective filler integration, contributing to crack

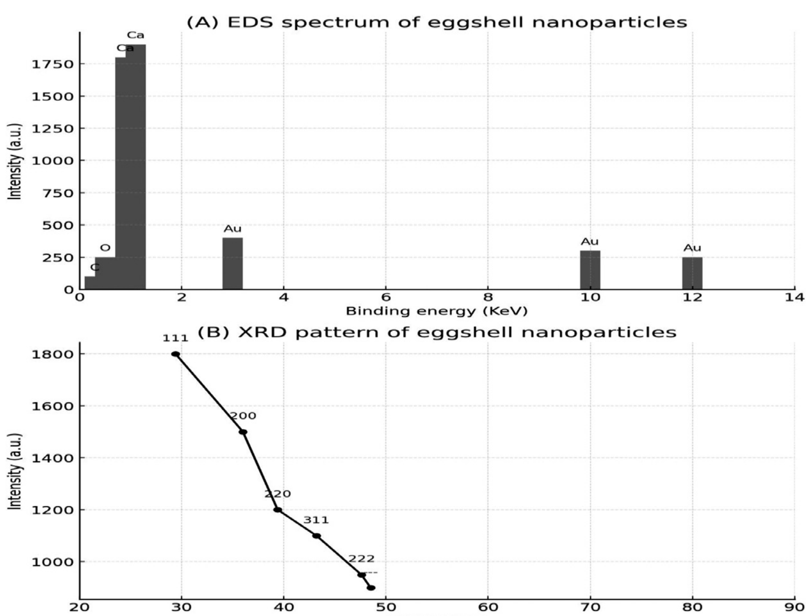

Figure 10: EDS and XRD characterization of eggshell nanoparticles used in the hybrid composite

deflection and energy absorption. These features collectively support the observed mechanical performance, particularly tensile strength and fracture toughness.[24] Energy-Dispersive X-ray Spectroscopy (EDS) confirmed the elemental presence of calcium (from eggshell), and carbon and oxygen (from both fillers), validating the successful incorporation of agro-waste-based reinforcements. These bio-fillers contributed to improved thermal and mechanical performance and enhanced the composite's environmental value by utilizing readily available, biodegradable waste materials. The novelty of this study's microstructural aspect lies in using dual alkaline-treated natural fabrics combined with dual agro-waste fillers, creating a complex yet efficient reinforcement network. Most existing studies focus either on single-fiber hybridization or conventional filler use; very few have attempted such multi-component sustainable hybridization at the macro- and micro-scales.

Figure 10a. The Energy-Dispersive X-ray Spectroscopy (EDS) spectrum displays prominent peaks corresponding to calcium (Ca), oxygen (O), and carbon (C), confirming the presence of calcium carbonate ($CaCO_3$) as the principal component of the eggshell powder. Additional minor peaks for gold (Au) result from the sputter-coating process used during SEM sample preparation. The elemental profile supports the role of eggshell powder as a thermally stable and chemically compatible filler in the composite matrix. **Figure 10b** shows the X-ray diffraction (XRD) pattern reveals sharp and intense peaks at 2θ values of 29.4°, 36.0°, 39.4°, 43.2°, 47.6°, and 48.5°, corresponding to the (111), (200), (220), (311), and (222) planes of crystalline calcite, confirming the high crystallinity of the eggshell filler. The presence of well-defined peaks suggests the structural stability and reinforcing capability of the nanoparticles when embedded in the epoxy matrix.

5 CONCLUSION

This study presents the fabrication and preliminary evaluation of a sustainable hybrid epoxy composite reinforced with E-glass, Gossypium herbaceum (cotton), Corchorus olitorius (jute), and agro-waste-derived fillers from Cocos nucifera and eggshells. All reinforcements underwent a 5 *w*/% NaOH treatment to enhance the fiber-matrix interaction, and the composite was fabricated using a hand lay-up followed by compression molding. The composite demonstrated a tensile strength of 90 MPa, flexural strength of 430 MPa, impact energy absorption of 24 J (Charpy), and a heat deflection temperature (HDT) of 145 °C. These results reflect significant improvements over untreated natural fiber composites due to the synergistic effects of treated dual natural fabrics and the dual bio-filler system. SEM-EDS analysis confirmed the good dispersion of fillers, improved interfacial bonding, and minimal fiber pull-out, reinforcing the mechanical findings. The novelty of this study lies in its combined use of two structurally distinct, chemically treated natural fabrics and two different bio-fillers in a single hybrid composite –an approach not extensively reported in prior literature. While promising, this work is preliminary and limited by the absence of tensile/flexural modulus, strain-at-break data, statistical analysis, and control specimens. Future research should focus on expanding the experimental design to include untreated and filler-free composites, varying filler concentrations, exploring alternative surface treatments, and applying statistical tools to validate the performance trends. These efforts will help establish a more comprehensive understanding of how each constituent influences the composite's behavior and support the optimization of green hybrid composites for structural and semi-structural applications in automotive, construction, and thermal insulation domains.

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