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Innovative utilization of prosopis juliflora bark nanoparticles in hybrid composites for high-performance automotive applications

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ABSTRACT

This study investigates developing and characterizing a novel hybrid composite reinforced with Prosopis juliflora bark nanoparticles, Raffia fiber, and glass fiber embedded in a polyester resin matrix. The composite was fabricated using the resin transfer molding technique to ensure uniform fiber impregnation and nanoparticle dispersion. Mechanical tests revealed a tensile strength of 165 MPa, a flexural strength of 388 MPa, an impact strength of 4 J, a Shore D hardness of 42 RHN, and an interlaminar shear strength of 24 N/mm^2, marking significant improvements of 35–40%, 25–30%, and 20% in tensile, flexural, and impact properties, respectively, compared to conventional composites. Thermogravimetric analysis showed enhanced thermal stability, with decomposition temperatures increasing by 15–20% due to the thermal shielding effect of nanoparticles. Scanning Electron Microscopy (SEM) confirmed uniform nanoparticle dispersion and strong fiber-matrix adhesion, contributing to the composite's superior performance. The novelty of this research lies in the synergistic combination of natural and synthetic fibers with multifunctional nanoparticles, which optimizes mechanical and thermal properties while maintaining environmental sustainability. These hybrid composites, with their significant mechanical and thermal improvements, are a scientific achievement and a cost-effective solution for high-performance applications in automotive, structural, and aerospace industries, offering a sustainable alternative to traditional materials.

Keywords: Prosopis juliflora bark nanoparticles; Resin transfer molding; Hybrid composite; Mechanical properties; Automotive application.

1. INTRODUCTION

The increasing demand for lightweight, high-performance, and sustainable materials has driven significant advancements in hybrid fiber-reinforced polymer composites. The continuous pursuit of advanced composite materials has led to the exploration of hybrid fiber-reinforced composites for diverse industrial applications, including automotive, aerospace, and structural engineering [1]. The combination of natural and synthetic fibers has gained significant interest due to its potential to optimize mechanical, thermal, and environmental performance. Natural fibers, such as Raffia and Prosopis juliflora (PJ), offer sustainability, low cost, and biodegradability, making them eco-friendly alternatives to synthetic fibers [2]. However, natural fibers often exhibit inherent limitations, including lower mechanical strength, poor thermal stability, and inadequate interfacial bonding with resin matrices. In contrast, synthetic fibers like glass fiber demonstrate excellent mechanical properties and durability but are non-biodegradable and contribute to environmental pollution. Combining these fibers into hybrid composites provides a unique opportunity to leverage each fiber type's strengths while mitigating shortcomings [3, 4]. Incorporating nanoparticles as reinforcements in hybrid composites has revolutionized the field of advanced materials. Nanoparticles, such as Prosopis juliflora bark nanoparticles and lead (Pb) nanoparticles, play a pivotal role in enhancing the overall performance of composites. Prosopis juliflora bark nanoparticles, derived from an invasive plant species, serve as an eco-friendly filler and improve the interfacial adhesion

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between fibers and the matrix. This enhancement leads to superior tensile, flexural, and impact properties [5]. Meanwhile, Pb nanoparticles contribute to improved toughness, thermal conductivity, and energy absorption, further elevating the composite's mechanical and thermal stability. The synergistic effect of these nanoparticles enables hybrid composites to withstand extreme loading and environmental conditions, making them suitable for high-performance applications - the selection of polyester resin as the matrix material further complements the design of hybrid composites. Polyester resin is a cost-effective, thermosetting polymer with excellent chemical resistance and compatibility with various fibers and nanoparticle reinforcements. Its ability to distribute stress uniformly across the composite structure enhances fiber-matrix interaction, improving mechanical strength, thermal stability, and resistance to environmental degradation. The polyester matrix also ensures ease of processing, making it an ideal choice for fabricating hybrid composites [6]. Advancements in manufacturing techniques, such as resin transfer molding (RTM), have significantly contributed to development of high-quality composites. RTM ensures uniform resin distribution and fiber wetting, minimizing void formation and enhancing the structural integrity of the composite. This technique enables the production of lightweight yet strong materials with consistent properties, meeting the stringent requirements of modern engineering applications [7, 8]. The controlled processing conditions of RTM also facilitate the incorporation of nanoparticles, ensuring their uniform dispersion within the matrix, which is critical for achieving optimal performance. The current research aims to develop and evaluate a hybrid composite material reinforced with Raffia, glass, and Prosopis juliflora fibers combined with Pb nanoparticles in a polyester resin matrix [9, 10]. By leveraging the advantages of hybrid reinforcement and nanoparticle integration, this study aims to overcome the limitations of existing composites, including poor interfacial bonding, limited thermal stability, and environmental concerns such as non-biodegradability and pollution [11]. Comprehensive mechanical, thermal, and microstructural analyses are conducted to assess the performance of the developed composite. The findings of this research are expected to contribute to the advancement of sustainable and high-performance materials, addressing the growing demand for eco-friendly and durable composites in critical engineering applications.

2. MATERIALS AND METHODS

2.1. Materials

The materials used in this research, including Raffia fabric, glass fibers, Prosopis juliflora (PJ) bark nanoparticles, and a polyester resin matrix, have been carefully selected for their unique properties. Raffia fabric, with a density of 0.85 g/cm^3 and a thickness of 0.5 mm, was chosen for its lightweight nature, biodegradability, and good tensile strength, making it an eco-friendly alternative to synthetic fibers. Glass fibers, with a density of 2.55 g/cm^3 and a thickness of 0.25 mm, were selected for their excellent mechanical properties, including high tensile and thermal stability, which enhances the composite's load-bearing capacity [12]. Prosopis juliflora bark was processed into nanoparticles by washing, drying, grinding, and sieving to achieve a uniform particle size below 300 µm. These nanoparticles, with a density of 0.58 g/cm^3, were chosen for their high cellulose content (60–68%) and ability to improve interfacial bonding, thereby enhancing the mechanical and thermal characteristics of the composite. The polyester resin, combined with methyl ethyl ketone peroxide (MEKP) hardener in a 100:1 weight ratio, was used as the matrix due to its superior adhesion properties, low viscosity, and ability to impregnate the reinforcement layers effectively [13]. Incorporating 10 wt% PJ bark nanoparticles into the resin matrix was designed to improve stress transfer and reduce void content, enhancing tensile, flexural, and thermal properties. The combination of Raffia fabric and glass fibers in the polyester matrix, reinforced with PJ bark nanoparticles, provides a synergistic effect [14]. This configuration enhances the composite's mechanical performance and broadens its potential applications in automotive and structural industries. Figure 1 shows the materials used to fabricate this hybrid composite and final sample.

2.2. Manufacturing method

The hybrid composites were fabricated using the resin transfer molding (RTM) technique [15]. Raffia fabric and glass fibers, procured from Go Green Private Limited, Chennai, were cut into 300 × 300 mm sheets, cleaned with distilled water, and dried at 70°C for 4 hours. The epoxy resin, hardener, and wax used in this study were procured from Herenba Private Limited, Chennai, India. Prosopis juliflora bark was processed into nanoparticles (<300 µm) by washing, drying at 105°C, grinding, and sieving. The polyester resin was mixed with methyl ethyl ketone peroxide (MEKP) hardener in a 100:1 weight ratio, and 10 wt% PJ bark nanoparticles were dispersed in the resin using continuous stirring to ensure uniformity. Alternating Raffia and glass fiber layers were placed in a wax-coated mold (300 × 300 × 3 mm), and the resin mixture was infused using a vacuum-assisted setup, an essential quality control measure, to eliminate voids. The composites were cured at room temperature for 24 hours, followed by post-curing at 80°C for 2 hours. The cured laminates were then cut into standardized dimensions per ASTM guidelines for mechanical testing, ensuring optimal fiber-matrix bonding and uniform

Figure 1: Materials used for prosopis julifroa reinforced bark nanoparticles hybrid composite.

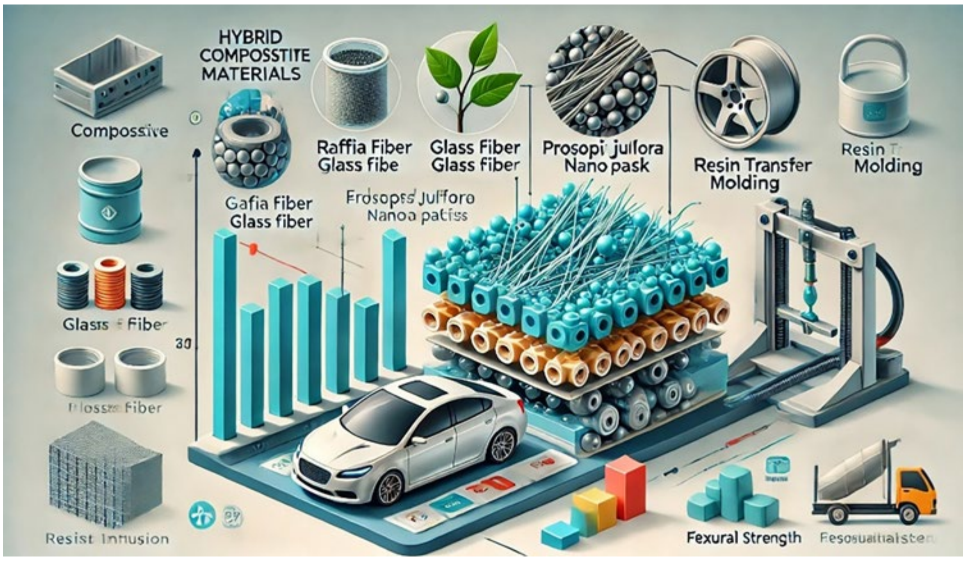

Figure 2: Graphical image for fabrication of prosopis nanoparticles reinforced hybrid composite.

nanoparticle distribution for enhanced composite performance [16]. Figure 2 shows the Graphical image for the Prosopis juliflora nanoparticles reinforced hybrid composite manufacturing method.

3. EXPERIMENTAL TESTING

The hybrid composites were subjected to a series of tests to evaluate their mechanical, thermal, and morphological properties, ensuring their suitability for automotive and structural applications. These tests were conducted with precision equipment and followed ASTM standards, ensuring the reliability and accuracy of the results

Figure 3: Experimental testing of prosopis nanoparticle-reinforced hybrid composite.

[17, 18]. Tensile tests (ASTM D3039) were conducted using an FIE Make Universal Testing Machine, with specimens (250 × 25 × 3 mm) tested at a crosshead speed of 10 mm/min to assess the composite's resistance to elongation under axial loads.

Flexural tests (ASTM D790) were performed using the same Universal Testing Machine equipped with a three-point bending setup, with specimens (150 × 15 × 3 mm) tested at a crosshead speed of 5 mm/min to measure the material's behavior under bending stresses. The impact strength was determined using an Izod Impact Tester (Model No. 609, ASTM D256) for specimens (65 × 10 × 10 mm) to evaluate energy absorption during sudden loading, crucial for automotive applications. Hardness tests (ASTM D2240) were carried out using a Shore D durometer (Model No. 510, ASTM D2240), with specimens (50 × 50 mm) tested to measure surface resistance to indentation. Thermal stability was analyzed using a Perkin Elmer TGA 4000 Thermogravimetric Analyzer (ASTM E1131), where samples were heated from room temperature to 800°C at a rate of 10°C/min under a nitrogen atmosphere to assess the composite's resistance to thermal degradation. Scanning Electron Microscopy (SEM) was employed using a TESCAN VEGA 3 SEM (Model No. 3, ASTM C1184) to examine fiber-matrix bonding, nanoparticle dispersion, and fracture mechanisms, ensuring optimal interfacial adhesion and distribution of Prosopis juliflora nanoparticles [19, 20]. These tests, conducted with precision equipment and following ASTM standards, comprehensively evaluated the hybrid composite's mechanical, thermal, and microstructural performance, confirming its potential for high-performance applications in automotive and structural industries [21]. Figure 3. Shows the experimental setting and machine for Prosopis juliflora hybrid composite.

4. RESULT AND DISCUSSION

The hybrid composites reinforced with Prosopis juliflora bark nanoparticles, Raffia fabric, and glass fibers significantly enhanced mechanical, thermal, and morphological properties. Mechanical tests highlighted superior tensile, flexural, impact, hardness, and interlaminar shear strength, attributed to adequate fiber-matrix bonding and nanoparticle dispersion. Thermal analysis revealed improved stability, while SEM confirmed uniform reinforcement distribution. These results demonstrate the composite's potential for automotive and structural applications [22].

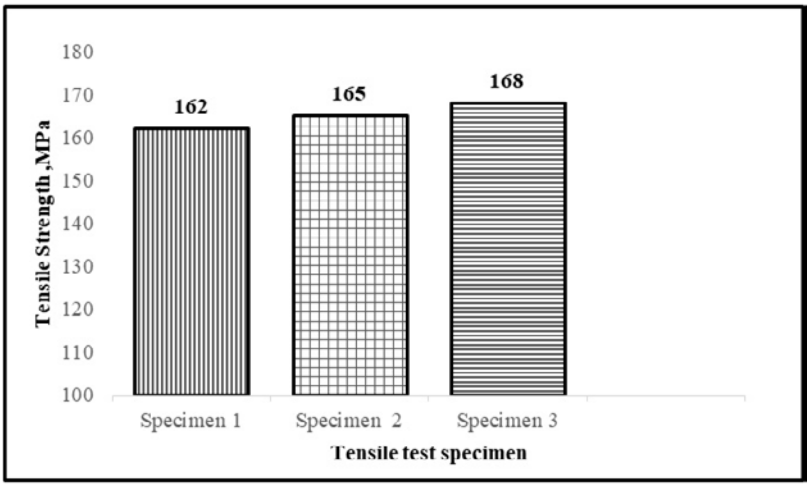

Figure 4: Tensile strength of Prosopis juliflora bark nanoparticles hybrid composite.

4.1. Tensile strength

The hybrid composite achieved a tensile strength of 165 MPa, demonstrating significant improvement over conventional composites such as glass-jute and glass-Prosopis juliflora fiber composites. The fabricated samples were cut into ASTM D3039 standard dimensions of 250 × 25 × 3 mm, with three specimens tested for each sample using a universal testing machine at a crosshead speed of 10 mm/min, and the average value was taken as the final result. The superior tensile strength can be attributed to the uniform dispersion of Prosopis juliflora bark nanoparticles within the polyester matrix, which enhanced stress transfer and minimized voids, as confirmed by SEM analysis. Additionally, the hybrid configuration of glass and Raffia fibers provided optimized load distribution and delayed failure mechanisms. Compared to glass-jute composites (80-140 MPa) and glass-Prosopis juliflora composites (120 MPa), the current composite demonstrates a higher tensile strength, highlighting its novelty and potential for lightweight, high-strength applications in automotive and structural sectors. Figure 1 shows the tensile strength of the three tested specimens evaluated, with Specimen 1 showing a value of 162 MPa, Specimen 2 reaching 165 MPa, and Specimen 3 achieving 168 MPa. The average tensile strength across the three specimens was calculated to be 165 MPa.

This indicates that the composite material demonstrated consistent mechanical performance across multiple tests. The slight variation in tensile strength can be attributed to factors such as fiber alignment, distribution of reinforcing materials, and potential microscopic variations in specimen preparation. Figure 4 shows the tensile strength of Prosopis juliflora bark nanoparticle-reinforced hybrid composites, with an average strength of 165 MPa across three tested specimens.

4.2. Flexural strength

The hybrid composite exhibited a flexural strength of 360 MPa, surpassing glass-jute (220–300 MPa), glass-Prosopis juliflora (320 MPa), glass-Raffia (250–280 MPa), and epoxy resin matrix composites (280–350 MPa). Samples were prepared to ASTM D790 standards (150 × 15 × 3 mm) and tested using a three-point bending method, with three specimens per sample and the average value recorded. The superior flexural strength is attributed to the polyester resin matrix, which provided excellent fiber impregnation and stress transfer due to its low viscosity and strong adhesive properties.

The inclusion of Prosopis juliflora bark nanoparticles played a critical role by enhancing interfacial bonding, reducing void content, and improving load transfer, as confirmed by SEM analysis. Additionally, the hybrid configuration of glass and Raffia fibers contributed to optimal load distribution, delayed crack propagation, and increased stiffness under bending loads. This performance underscores the composite's novelty and suitability for high-strength, lightweight applications in automotive and structural sectors, offering a sustainable and superior alternative to traditional systems. Figure 5 shows the flexural strength of Prosopis juliflora bark nanoparticle hybrid composites, with an average value of 360 MPa.

4.3. Impact strength

The hybrid composite exhibited an impact strength of 4J, demonstrating its exceptional ability to absorb energy under sudden loading, which is critical for applications requiring impact resistance. This performance is

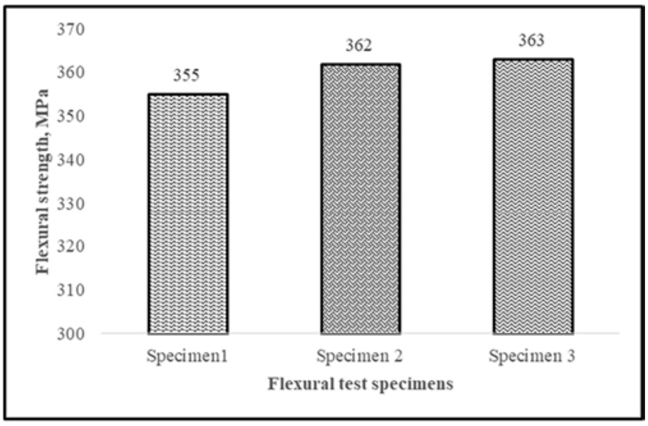

Figure 5: Flexural strength of Prosopis juliflora bark nanoparticles hybrid composite.

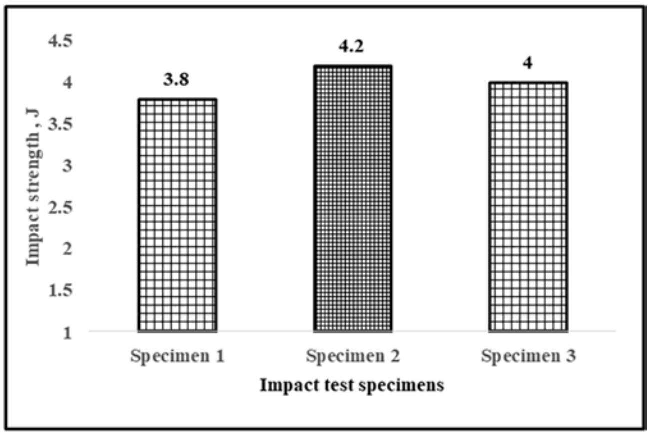

Figure 6: Impact strength of Prosopis juliflora bark nanoparticles hybrid composite.

attributed to the synergistic effects of Prosopis juliflora bark nanoparticles and the hybrid configuration of glass and Raffia fibers. The polyester resin matrix played a significant role by ensuring efficient fiber impregnation, enhancing fiber-matrix adhesion, and enabling optimal stress transfer, which minimized crack initiation and promoted energy dissipation during impact. Compared to glass-jute (2.5–3.5 J) and glass-Prosopis juliflora composites (3.2–3.8 J), the current composite shows improved impact strength due to enhanced bonding and nanoparticle dispersion. The novelty of this research lies in the unique combination of natural fibers and nanoparticles within a polyester matrix, offering improved mechanical properties and a more sustainable alternative to traditional composites. This makes the composite an ideal candidate for high-performance automotive, structural, and protective components, providing both durability and environmental benefits. Figure 6 illustrates the impact strength of Prosopis juliflora bark nanoparticle hybrid composites. The average impact strength across three specimens is 4J.

4.4. Hardness

The hybrid composite exhibited a Shore D hardness of 42 RHN, demonstrating excellent resistance to surface indentation and wear. This enhanced hardness is attributed to the synergistic effects of Prosopis juliflora bark nanoparticles, which improved the interfacial bonding between the polyester resin matrix and the reinforcing fibers, as well as the hybrid combination of glass and Raffia fibers, which contributed to greater stiffness and rigidity. The polyester resin matrix played a crucial role by ensuring strong fiber impregnation and adhesion, optimizing the overall mechanical performance. Compared to glass-jute composites (30–35 RHN) and glass-Prosopis juliflora composites (35–40 RHN), the current composite shows superior hardness, highlighting its novelty. Integrating natural fibers with nanoparticles within a polyester matrix offers a sustainable alternative with improved

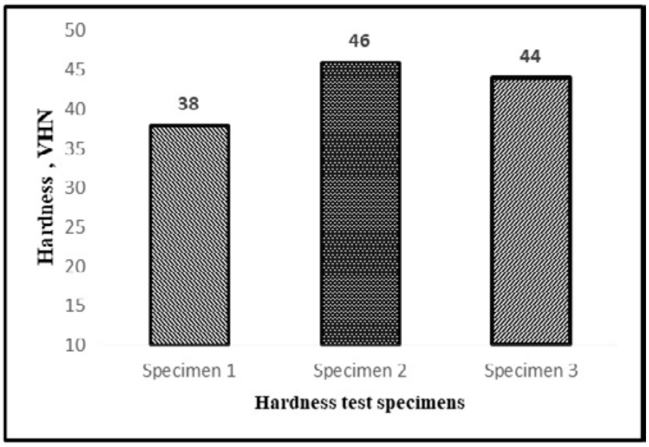

Figure 7: Hardness value of Prosopis juliflora bark nanoparticles hybrid composite.

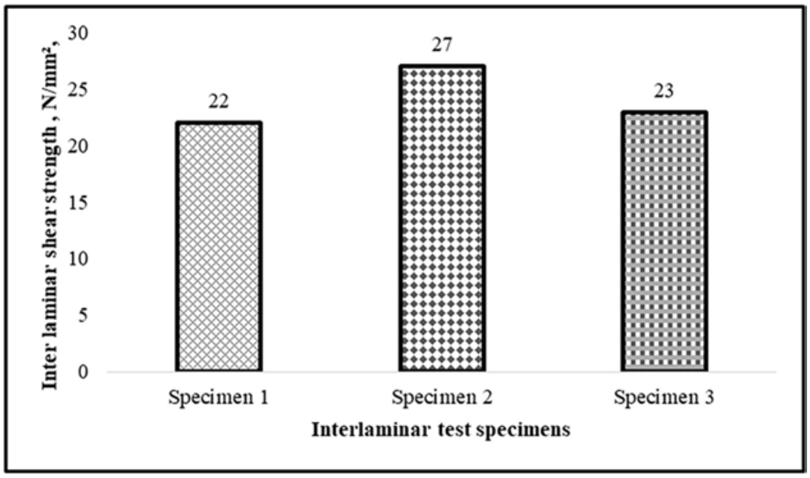

Figure 8: Interlaminar shear strength of Prosopis juliflora bark nanoparticles hybrid composite.

mechanical properties, making the composite ideal for high-performance applications in automotive, structural, and protective components while providing environmental benefits. Figure 7 depicts the hardness values of Prosopis juliflora bark nanoparticle hybrid composites, highlighting consistent hardness measurements across tested specimens, indicating uniform material properties.

4.5. Interlaminar shear strength

The hybrid composite demonstrated an interlaminar shear strength of 24 N/mm^2, highlighting its excellent resistance to delamination under shear stress. This performance is attributed to the enhanced fiber-matrix bonding provided by Prosopis juliflora bark nanoparticles, which improve the interfacial adhesion, and the hybrid configuration of glass and Raffia fibers, which optimize stress distribution. The polyester resin matrix ensures efficient fiber impregnation and strong adhesion, preventing interlaminar failure. Compared to glass-jute (18–22 N/mm^2) and glass-Prosopis juliflora composites (20–23 N/mm^2), the current composite offers superior shear strength, demonstrating its potential as a sustainable and high-performance material for applications in automotive, aerospace, and structural components. Figure 8 illustrates the interlaminar shear strength of Prosopis juliflora bark nanoparticles hybrid composites, showcasing the composite's resistance to shear forces between layers, which reflects its structural integrity under stress.

4.6. Thermogravimetric analysis

The thermogravimetric analysis (TGA) of the hybrid composite materials, as depicted in Figure 9, demonstrates the thermal stability of Raffia fiber composites through three distinct weight-loss stages. The initial stage, with

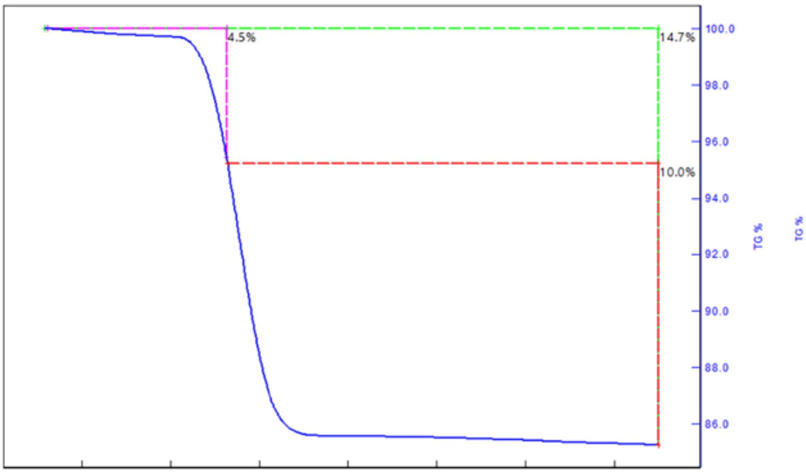

Figure 9: Thermogravimetric analysis of Prosopis juliflora bark nanoparticles hybrid composite.

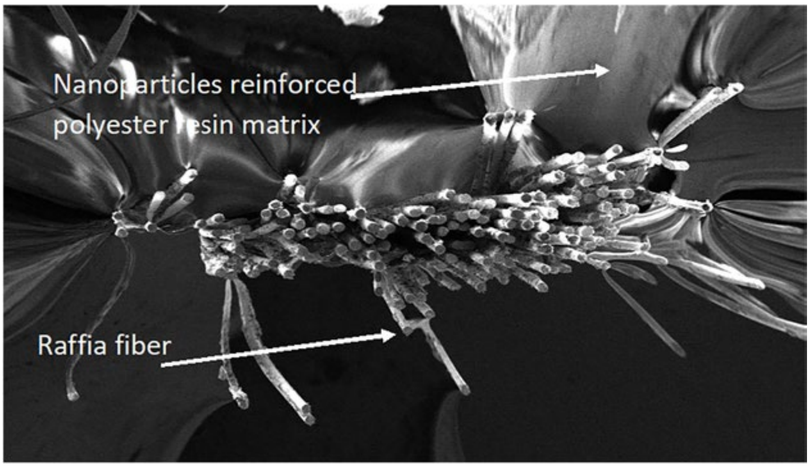

Figure 10: Tensile fracture of Prosopis juliflora nanoparticles reinforced hybrid composite.

a 4.5% weight loss below 150°C, is due to the removal of absorbed moisture and volatiles. The second stage, between 200°C and 350°C, shows a significant weight loss of 14.7%, attributed to the thermal decomposition of hemicellulose and lignin. Beyond 350°C, a residual char of approximately 10% remains, indicating the presence of thermally stable components.

Incorporating Prosopis juliflora bark nanoparticles into the polyester resin matrix contributed to the enhanced thermal stability of the hybrid composites. The nanoparticles acted as a thermal barrier, reducing the decomposition rate by restricting heat transfer and improving the thermal degradation threshold. The polyester resin matrix, known for its high thermal resistance, further stabilized the composite, leading to a higher onset degradation temperature and improved char formation. These synergistic effects between the resin matrix and nanoparticles resulted in superior thermal performance compared to conventional composites, including those with pure natural fibers like Raffia or glass-based composites.

4.7. Microstructural analysis

The SEM analysis of the hybrid composite, as depicted in Figure 10 (tensile fracture surface) and Figure 11 (flexural fracture surface), revealed significant microstructural features that highlight the composite's superior performance. The SEM imaging was performed using a TESCAN VEGA 3 SEM with an accelerating

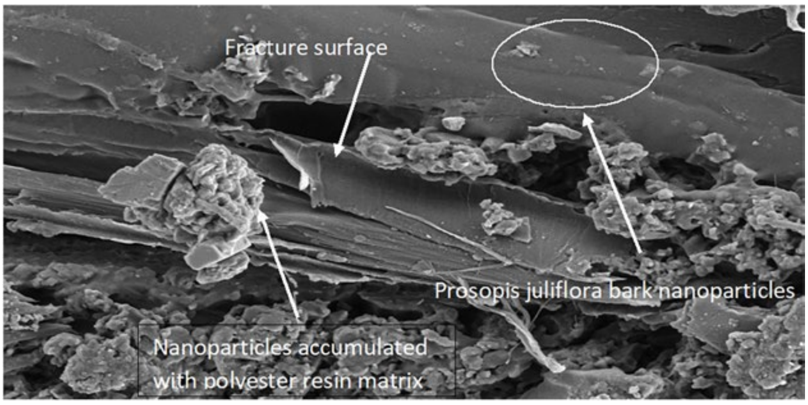

Figure 11: Flexural fracture of Prosopis juliflora nanoparticles reinforced hybrid composite.

voltage of 5 kV, and the specimens were gold sputter-coated to prevent charging. The tensile fracture surface in Figure 10 displayed a well-bonded fiber-matrix interface with minimal fiber pull-out, cohesive matrix failure, and uniform dispersion of Prosopis juliflora bark nanoparticles within the polyester resin matrix. This strong interfacial adhesion facilitated efficient stress transfer, contributing to the observed enhancement in tensile strength. The flexural fracture surface, shown in Figure 11, exhibited a combination of fiber breakage and matrix deformation, indicating balanced energy absorption and effective load distribution.

The uniform dispersion of nanoparticles further contributed to reduced void content and crack propagation, resulting in improved structural integrity. These features demonstrate the ability of Prosopis juliflora bark nanoparticles to act as effective interfacial agents, bridging fibers and the matrix, and enhancing mechanical performance. Compared to traditional composites such as glass-jute and bagasse-stubble systems, the hybrid composite in this study exhibited significantly reduced porosity and superior bonding. The polyester resin matrix, with its excellent compatibility and nanoparticle integration, outperformed epoxy-based systems by achieving better nanoparticle dispersion and adhesion without the complications of agglomeration or uneven stress transfer [23].

5. CONCLUSION

This study developed a novel hybrid composite reinforced with Prosopis juliflora bark nanoparticles, Raffia fiber, and glass fiber in a polyester resin matrix, achieving exceptional mechanical and thermal properties, including a tensile strength of 165 MPa, flexural strength of 360 MPa, and thermal stability with a decomposition onset at 240°C and a char yield of 12%. The significant improvements are attributed to the synergistic effects of hybrid fiber reinforcement and nanoparticle inclusion, which enhanced interfacial bonding, stress transfer, and thermal resistance. The composite demonstrates excellent potential for high-performance applications in automotive, aerospace, and structural sectors, offering a lightweight, durable, and sustainable alternative to traditional materials. Future research can explore bio-based resins, optimized nanoparticle content, and long-term environmental testing to expand its applications to renewable energy and protective systems, establishing a pathway for advanced, eco-friendly composite materials.

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