

Enhancing Polyester Composites with Nano *Aristida hystrix* Fibers: Mechanical and Microstructural Insights

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The utilization of natural fibers in polymer composites is increasingly popular due to their sustainability, cost-effectiveness, and favorable mechanical properties. This study introduces the novel use of *Aristida hystrix* fibers, processed for the first time into nano-sized particles *via* ball milling, to enhance dispersion and bonding within a polyester matrix. These nanoparticles were incorporated into polyester resin at various weight percentages (0 wt%, 1 wt%, 3 wt%, 5 wt%, 7 wt%, and 9 wt%), and composite laminates were fabricated using solvent casting and compression molding techniques. Mechanical properties were evaluated through tensile, flexural, and impact strength tests following ASTM standards. The composite containing 5 wt% nano fiber exhibited the optimum mechanical performance, with tensile strength of 30.13 MPa, flexural strength of 43.685 MPa, and impact strength of 1.87 kJ/m². At higher fiber loadings, particle agglomeration led to performance reduction. Water absorption studies indicated that increased nano fiber content resulted in higher moisture uptake, influencing long-term durability. Scanning Electron Microscopy (SEM) provided insights into fiber–matrix interfacial behavior, dispersion quality, and fracture mechanisms. Overall, this work establishes the first-time development of polyester composites reinforced with nano *Aristida hystrix* fibers, demonstrating their potential as a sustainable and high-performance material for lightweight structural applications in automotive, aerospace, and marine sectors.

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INTRODUCTION

Natural fibers have garnered significant interest as reinforcing materials in polymer composites, outpacing synthetic fibers due to their environmental sustainability, economic

efficiency, widespread availability, recyclability, low density, and high specific strength and stiffness. Moreover, natural fibers do not inflict considerable wear on processing machinery, rendering them a compelling option for composite material applications (Thakur *et al.* 2010, 2014; Marichelvam *et al.* 2023). The application of natural fiber-reinforced composite laminates has proliferated in many sectors, such as construction, aerospace, automotive, and packaging, because of its lightweight characteristics, renewability, and biodegradability (Satyanarayana *et al.* 2007; Malkapuram *et al.* 2009; Binoj *et al.* 2016). Nonetheless, despite their myriad advantages, natural fibers exhibit specific limitations, including moisture absorption, low thermal stability, incompatibility with polymer matrices, poor dimensional stability, and variability in mechanical properties, which can affect the overall performance of the composites (Rowell *et al.* 1997; Athijayamani *et al.* 2009; de Oliveira Braga *et al.* 2017; Junio *et al.* 2022).

In response to these constraints, many chemical and physical treatment procedures have been devised. These treatments are essential for altering the fiber surface to diminish moisture absorption and enhance interfacial adhesion with the polymer matrix. Common chemical treatments encompass alkali treatment, silane treatment, acetylation, and benzylation, which augment fiber-matrix adhesion, hence improving the mechanical performance of the composite (Bozaci *et al.* 2013; Sarikanat *et al.* 2016; Aruchamy *et al.* 2025). Physical treatments, including plasma treatment, thermal treatment, and stretching, can enhance fiber surface roughness, hence augmenting mechanical interlocking between the fiber and the matrix. Nonetheless, although these treatments are efficacious, the discovery of novel procedures is essential to further improve the mechanical characteristics and durability of natural fiber composites.

Recently, the utilization of nano-sized fiber particles as reinforcing agents has surfaced as a viable approach to address the intrinsic limitations of natural fibers. Material scientists and engineers have recognized nano fiber particles as promising reinforcements because of their distinctive properties, which encompass a high surface area-to-volume ratio, elevated aspect ratio, exceptional strength, high modulus of elasticity, diminished moisture absorption, and a low coefficient of thermal expansion (Naganuma and Kagawa 2002; John and Anandjiwala 2008; Prasad *et al.* 2015; Thangavel *et al.* 2024; Manickaraj *et al.* 2025). The remarkable attributes of nano fiber-reinforced composites render them widely sought after for sophisticated applications in aerospace, automotive, construction, electrical, and electronic sectors, where superior performance and durability are imperative (Zhi Rong *et al.* 2001; Ramesh *et al.* 2020; Manickaraj *et al.* 2024b; Mylsamy *et al.* 2025).

The extraction of nano fiber particles from raw fibers may be accomplished using several methods, including chemical vapor deposition, electrodeposition, plasma arcing, sol-gel synthesis, and high-energy ball milling (Chirayil *et al.* 2014; Palanisamy *et al.* 2024). High-energy ball milling has been prominent among these technologies because of its simplicity, cost-effectiveness, scalability, and capacity to manufacture new materials with improved mechanical and physical qualities (Wypych and Satyanarayana 2005; Gokul *et al.* 2024; Aruchamy *et al.* 2025). This approach entails the mechanical reduction of raw fiber particles into nanoscale structures *via* repetitive impact and attrition pressures, assuring homogeneous particle size distribution and enhanced dispersion within the polymer matrix.

This work involves the processing of *Aristida hystrix* raw fiber into nanofiber particles *via* the high-energy ball milling technology. *Aristida hystrix*, a naturally occurring fiber, was chosen for its advantageous mechanical qualities, accessibility, and sustainability.

Extensive testing was performed in accordance with ASTM standards to assess the mechanical properties of these composites. Tensile strength, flexural strength, and impact resistance were evaluated to ascertain the load-bearing capacity and durability of the composite laminates. Water absorption tests were conducted to evaluate the moisture uptake characteristics of the composites, a crucial aspect in determining their long-term durability and environmental resilience. Additionally, scanning electron microscopy (SEM) was utilized to analyze the distribution of nano fiber particles inside the matrix, offering insights into fiber-matrix interactions, particle distribution, and possible failure processes.

The novelty of this research lies in the first-time development and investigation of polyester composites reinforced with nano *Aristida hystrix* fiber particles. Composites were fabricated with 0 to 9 wt% filler loading and evaluated for tensile, flexural, and impact strength, water absorption, and microstructural behavior (Kalimuthu *et al.* 2019). Particular emphasis was placed on identifying the optimum filler concentration that maximizes mechanical performance without compromising durability (Saba *et al.* 2014).

By integrating a novel fiber source (*Aristida hystrix*) with a nanoscale processing route, this research contributes to advancing the field of natural fiber composites, offering a sustainable, lightweight, and high-performance alternative for structural and engineering applications (Pandiarajan *et al.*, 2019).

The major aim of this research is to investigate the efficacy of nano *Aristida hystrix* fiber particles as a reinforcing agent in polyester composites and to identify the best fiber loading that enhances mechanical performance while ensuring durability. The research is to enhance the existing knowledge on nano fiber-reinforced polymer composites, providing significant insights into the creation of high-performance and sustainable materials for structural uses (Syduzzaman *et al.* 2023).

Industries are increasingly pursuing lightweight and eco-friendly substitutes for traditional materials, making the incorporation of nano-sized natural fiber reinforcements into polymer matrices a feasible approach to improving mechanical qualities and overall performance. This research highlights the significance of unique material processing methods and sophisticated reinforcing strategies in producing better composite materials applicable to many engineering fields (Arasu and Manickaraj 2025; Somasundaram *et al.*, 2025). This inquiry aims to position *Aristida hystrix* nano fiber-reinforced polyester composites as a viable option for next-generation composite materials, integrating sustainability with high-performance engineering solutions.

EXPERIMENTAL

Fiber Materials

The fiber used in this study was derived from the leaf of the *Aristida hystrix* plant, as shown in Fig. 1A. The raw fiber was sourced from Vellakulam village, located in the Virudhunagar district of Tamil Nadu, India. The selection of this fiber was based on its availability, sustainability, and potential reinforcement properties (Ravichandran *et al.*, 2025).



Fig. 1. A. *Aristida hystris* plant fiber; B. Extracted and dried macro fiber

Matrix Material

This research employed unsaturated polyester resin as the matrix material. The resin, procured from GVR Traders in Madurai, exhibited a density of 1258 kg/m³ and a viscosity of 500 cps at 25 °C. The curing process was facilitated with Methyl Ethyl Ketone Peroxide (MEKP) as the catalyst and acetone as the accelerator. Unsaturated polyester was selected due to its superior mechanical performance, ease of processing, and compatibility with natural fiber reinforcements (Karuppusamy *et al.* 2025).

Methods

The methodology of this study consists of three key steps: extraction of macro fiber from *Aristida hystris* plant leaves, synthesis of nano fiber particles from macro fiber, and preparation of nano fiber-reinforced polyester composite laminates. These processes are detailed below (Manickaraj *et al.* 2025a).

Extraction of Macro Fiber

Macro fibers were manually harvested from the leaves of the *Aristida hystris* plant (Fig. 1B). The fibers were carefully isolated to maintain strand integrity and then naturally dried at ambient temperature for four days to minimize moisture content. Proper drying was crucial for improving fiber–matrix adhesion during composite fabrication. The dried fibers were subsequently stored under controlled conditions to prevent reabsorption of moisture (Gurusamy *et al.* 2025).

Preparation of Nano Fiber Particles

The dried macro fibers were processed into nano-sized particles using a high-energy ball milling technique (Model: PM 100, Retsch, Germany). Ball milling was selected for its efficiency in reducing fiber size, achieving uniform distribution, and enhancing fiber–matrix interfacial bonding (Karuppusamy *et al.* 2025a). The process operated through the combined effects of impact and friction generated by tungsten carbide balls colliding with the chamber walls, as shown in Fig. 2A. The reverse rotation of the supporting disc further intensified the crushing effect, reducing the fibers to nanoscale particles. Milling parameters such as speed, time (10 h), and ball-to-fiber ratio were optimized to obtain nano-sized particles without compromising the intrinsic mechanical properties of the fiber. The resultant nano *Aristida hystris* fiber (AHF) particles are shown in Fig. 2B.

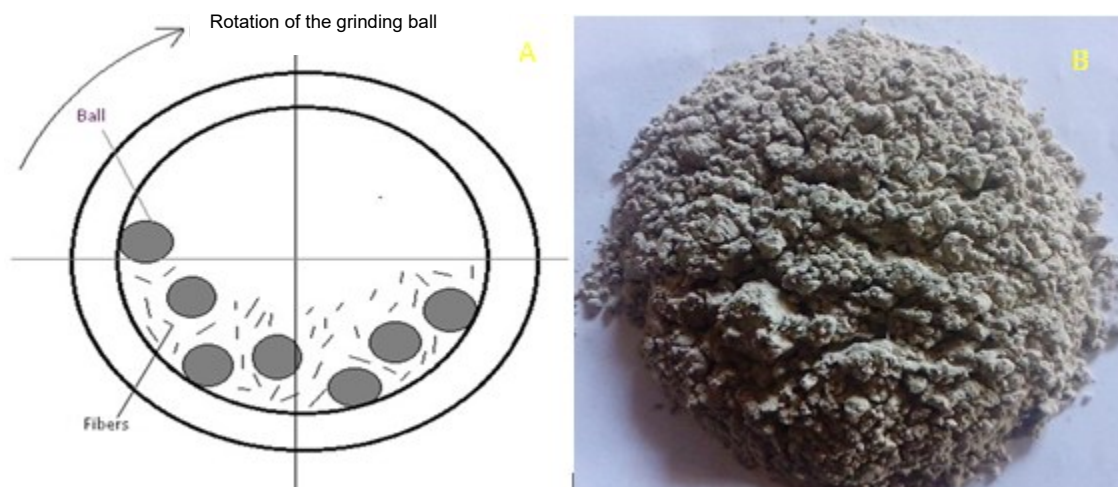


Fig. 2. A. Working principle of ball; B. Nano fiber particles after 10 h of milling process

Fabrication of Nano AHF/Polyester Composites

Nano fiber particles were integrated into polyester resin at different weight percentages (0%, 1%, 3%, 5%, 7%, and 9%) to produce composite laminates using solvent casting and compression molding. These approaches guarantee consistent fiber distribution and flawless laminates. The nano *Aristida hystrix* fiber (AHF) particles were initially combined with acetone, serving as an accelerator, and subsequently incorporated into the polyester matrix. The mixture was sustained at 65 to 75 °C and agitated constantly with a mechanical stirrer for uniform dispersion. The mixture was thereafter put into a steel mold measuring $260 \times 220 \times 3 \text{ mm}^3$ and distributed uniformly. The mold underwent compression at 12 MPa, and the resin was let to cure for 30 h at ambient temperature. The fabricated composite plates are seen in Fig. 3 (A through F). The composites were subjected to mechanical testing, including evaluations of tensile, flexural, and impact strength, in accordance with ASTM standards. Water absorption experiments were performed to evaluate moisture resistance, while SEM analysis investigated fiber dispersion and interfacial adhesion (Manickaraj *et al.* 2025b). The prepared composites are shown in Fig. 3.

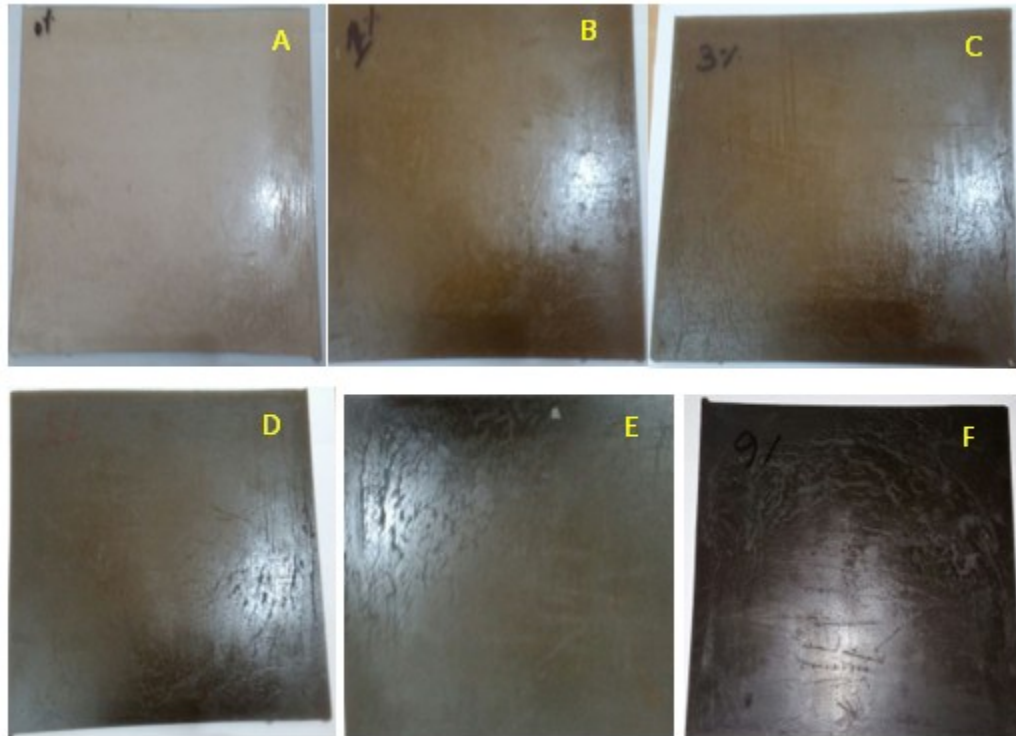


Fig. 3. Composite plates: **A.** 0%; **B.** 1%; **C.** 3%; **D.** 5%; **E.** 7%; **F.** 9%

Mechanical Testing of Composite Laminates

The prepared composite laminates underwent various mechanical testing to investigate their mechanical properties as per ASTM standards. The testing methods were explained below.

Tensile Test (ASTM D638-14 2022)

The tensile properties, including tensile strength, tensile modulus, and elongation at break, for the different weight percentages of composite plates were assessed using the KALPAK, KIC-2, 100 C universal testing machine. The ASTM D638-14 (2022) type-I method is employed for conducting tensile testing (Farah *et al.* 2016; Gurusamy *et al.* 2024; Manickaraj *et al.* 2024a). The measurements of the specimens are 165 x 13 x 3 mm³. Fig 4A illustrates the testing specimens. The specimen was secured within the tensile testing machine, featuring a gauge length of 50 mm, as illustrated in Fig. 4B. The test involves applying a tensile load to the specimen until fracture occurs, conducted at a cross-head speed of 2mm/min. Three samples were analyzed to ensure precise outcomes.

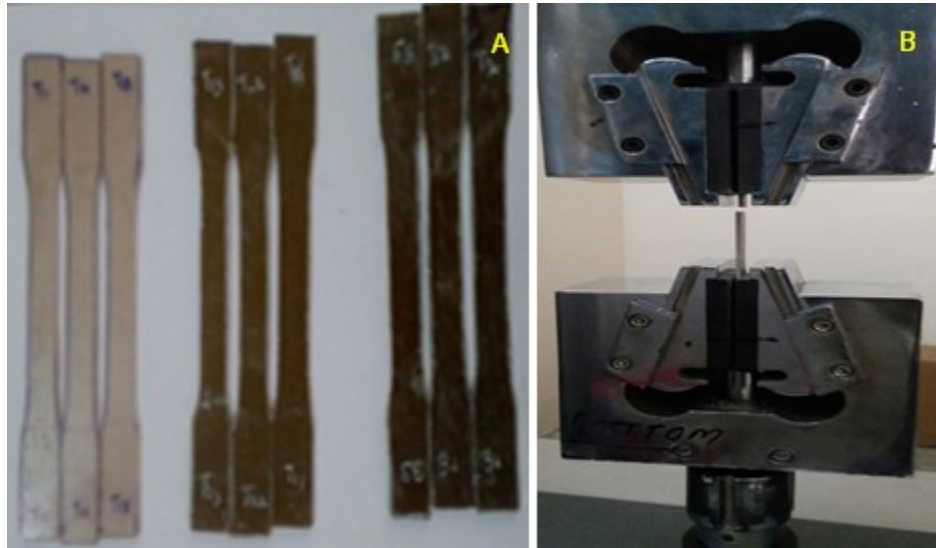


Fig. 4. A. Tensile testing samples; **B.** Tensile testing machine

Flexural Test (ASTM D790 2017)

The flexural characteristics of nano-reinforced *Aristida hystrix* were evaluated by the three-point bending test technique, adhering to ASTM D790-17 (2017), with the use of a universal testing machine (Dasari *et al.* 2009; Kapil Dev *et al.* 2022). The specimen measurements for this test are 127 x 12.7 x 3.2 mm³. The specimen is positioned horizontally on two supports of the testing apparatus, with a gauge length of 63 mm, as seen in Fig. 5A. The crosshead speed is uniformly established at 2 mm/min.



Fig. 5. A. Flexural testing samples; **B.** Impact testing machine

Impact Test (ASTM D256 2023)

The impact test was conducted using the Izod impact setup within the impact testing apparatus, as illustrated in Fig. 5B. The ASTM D256-23 (2023) standard is utilized for conducting impact testing (Zhang *et al.* 2015; Melkamu *et al.* 2019). The dimensions of the testing specimen were 65 x 13 x 3 mm³, and featured a notch cut at a 45° angle to a depth of 2.6 mm. The impact pendulum struck the notched specimen until it fractured, allowing for the measurement of the energy absorbed by the material.

Morphological Study

The fracture surfaces of Nano AHF composites were analyzed using a scanning electron microscope (VEGA TESCAN, Brno, Czech Republic). To improve imaging quality, the samples were sputter-coated with gold, allowing clear visualization of fiber dispersion and matrix bonding at various loadings.

Water Absorption Test (ASTM D570 2022)

The research examined the water absorption properties of Nano AH fiber reinforced composite laminates, performed in compliance with ASTM Standard D570-22. The dimensions of the sample size are 20 x 20 x 2mm³, as seen in Fig. 6. The samples were subjected to an oven at 50 °C for 1 h to remove moisture content. The specimens were immersed in distilled water at room temperature for 24 h. After immersion in water, the specimens were promptly removed and weighed at regular intervals of every 2 h. To ascertain the volume of water absorbed by the specimens, they were dried using absorbent paper and then reweighed using an accurate four-digit scale. The percentage of water absorption is calculated using the following formulae,

$$\text{Moisture absorption (\%)} = \frac{Ws2 - Ws1}{Ws1} \times 100$$

where $Ws1$ is the weight (g) of the samples before immersion in water and $Ws2$ is the weight (g) of the samples after immersion in water.



Fig. 6. Water absorption test samples

RESULTS AND DISCUSSION

Mechanical Properties

The mechanical properties, including tensile strength, tensile modulus, percentage of elongation, flexural strength and modulus, impact strength, and water absorption test, of AH nano fiber reinforced composite laminates were evaluated according to ASTM standards. The morphological investigation was conducted to examine the fiber matrix interaction of the fractured composite samples during the tensile test. The fractured specimens are shown in Fig. 7 (A through C) and findings and discussions are presented below.



Fig. 7. Fractured Specimens: **A**-Tensile; **B**- Flexural; **C**- Impact

Tensile Properties

The tensile behavior of polyester composites reinforced with different weight percentages of *Aristida hystrix* (AH) nano fiber particles (0, 1, 3, 5, 7, and 9 wt%) was investigated to determine tensile strength, tensile modulus, and elongation. All specimens fractured within the gauge length during testing (Fig. 7A). The interfacial adhesion between nano fiber particles and the polyester matrix plays a decisive role in governing tensile performance (Raja *et al.* 2021; Palanisamy *et al.* 2023).

Influence on Tensile Strength

The pure polyester laminate exhibited a tensile strength of 13.01 MPa. With incremental nano fiber loading, tensile strength steadily increased, reaching a maximum of 30.13 MPa at 5 wt% (Fig. 8A), corresponding to a 2.315-fold improvement over the neat matrix (Kathirselvam *et al.* 2019; Raju *et al.* 2021). This enhancement can be attributed to the uniform dispersion of nanoparticles at moderate loading, which facilitated effective stress transfer and reduced matrix-dominated failures (Cai *et al.* 2021). SEM analysis of the fractured surfaces revealed well-dispersed nano fibers embedded within the resin at 5 wt%, supporting the presence of strong interfacial adhesion and crack-bridging phenomena.

Beyond this threshold, the tensile strength declined to 29.28 MPa and 13.25 MPa at 7 wt% and 9 wt%, respectively. The reduction correlates with SEM observations of nanoparticle clustering and void formation, which created localized stress concentrations that acted as crack initiation sites. Thus, the results demonstrate that the optimum tensile strength arises from a balance between uniform dispersion and interfacial adhesion, which is disrupted at higher loadings due to agglomeration.

Influence on Tensile Modulus and Elongation

The tensile modulus exhibited a similar increasing trend up to 5 wt% fiber content before declining with higher loadings (Fig. 8B). The improved stiffness at 5 wt% is consistent with uniform nanoparticle reinforcement within the polyester matrix, which effectively restricted polymer chain mobility (Nayak *et al.* 2016; Jenish *et al.* 2022). However, excessive fiber loading led to particle agglomeration and poor stress distribution, lowering modulus values. Elongation decreased progressively with increasing fiber loading, indicating that nano fiber reinforcement reduced ductility by restricting polymer chain deformation. At 5 wt%, the matrix retained a favorable balance of stiffness and limited strain capacity, consistent with SEM observations of crack resistance without excessive brittleness (Athith *et al.* 2018; Karuppiah *et al.* 2020, 2022).

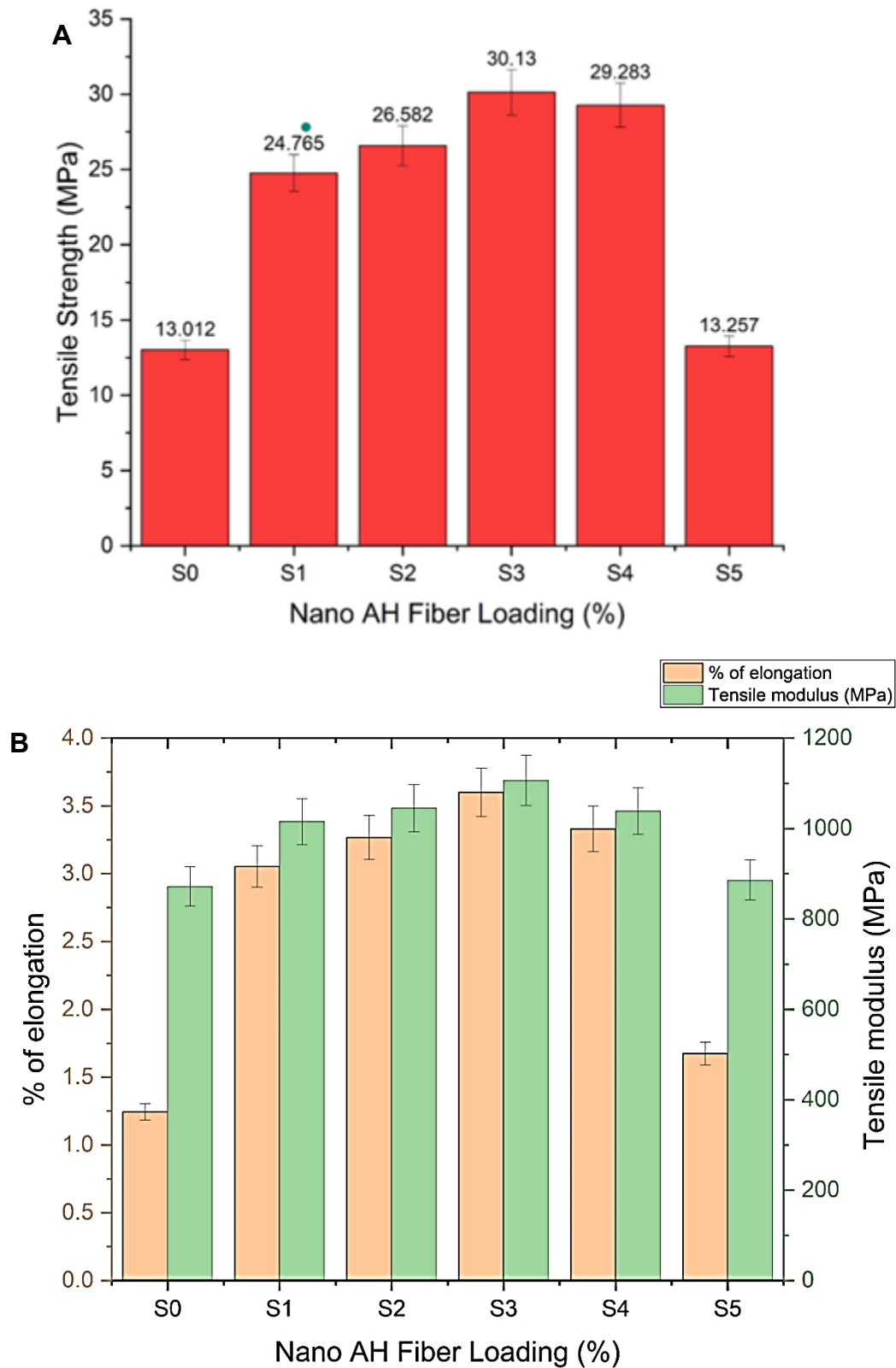


Fig. 8. Effect of fiber loading with respect to: **A.** Tensile Strength; **B.** Tensile modulus and % of elongation

Flexural Properties

Flexural strength and modulus were determined using a three-point bending test, where all specimens fractured within the span length, confirming the test reliability (Fig. 7B). The neat polyester composite exhibited a flexural strength of 28.025 MPa, highlighting the inherent brittleness and limited load-bearing ability of the unreinforced resin. Upon addition of *Aristida hystrix* nano fibers, a clear improvement in flexural behavior was observed up to an optimum loading. At 1 wt% and 3 wt% reinforcement, flexural strength increased steadily, reflecting the positive contribution of fibers to crack resistance and bending load distribution (Joseph *et al.* 2002; Ramesh *et al.* 2020; Sethuraman *et al.* 2020). The highest flexural strength of 43.685 MPa was achieved at 5 wt%, corresponding to a ~56% enhancement compared with the neat polyester resin (Fig. 9A). This significant improvement is attributed to the establishment of a strong interfacial bond between the fibers and matrix, which promoted effective stress transfer, reduced localized strain accumulation, and enhanced the composite's overall bending resistance. SEM micrographs supported this interpretation by revealing a well-bonded interface at 5 wt%, with fewer interfacial gaps and reduced microvoids. Evidence of fiber pull-out, crack pinning, and crack deflection was noted, all of which contributed to energy dissipation and delayed catastrophic failure during bending. These mechanisms indicate that, at optimum fiber dispersion, the reinforcement not only strengthens but also toughens the matrix. However, with further increases in loading to 7 wt% and 9 wt%, flexural strength dropped to 42.884 MPa and 38.344 MPa, respectively. The decline is mainly attributed to nanoparticle agglomeration and inadequate resin wetting, which created weak points within the microstructure. Such agglomerates acted as stress raisers under bending loads, leading to localized stress concentration, premature crack initiation, and compromised load-bearing efficiency.

The flexural modulus (Fig. 9B). results exhibited a similar trend, reflecting the balance between stiffness and dispersion quality. The neat resin recorded a modulus of 1284.311 MPa, which improved consistently with fiber addition, reaching 1798.715 MPa at 5 wt%. This increase in stiffness confirms that the presence of well-dispersed nano fibers restricts polymer chain mobility and enhances the rigidity of the composite system. However, further fiber addition caused a slight reduction in modulus, with values dropping to 1782.349 MPa and 1658.714 MPa at 7 wt% and 9 wt%, respectively (Ogunleye *et al.* 2022; Salama *et al.* 2022). This reduction can be linked to fiber clustering and poor resin continuity, which limits the effective stress distribution and disrupts the homogeneous stiffness of the composite. Overall, these findings confirm that optimum flexural properties are achieved at 5 wt% reinforcement, where efficient fiber–matrix bonding and uniform dispersion are attained. Beyond this threshold, the benefits of reinforcement are counteracted by microstructural irregularities, demonstrating the importance of controlling fiber loading to balance strength, stiffness, and processing uniformity.

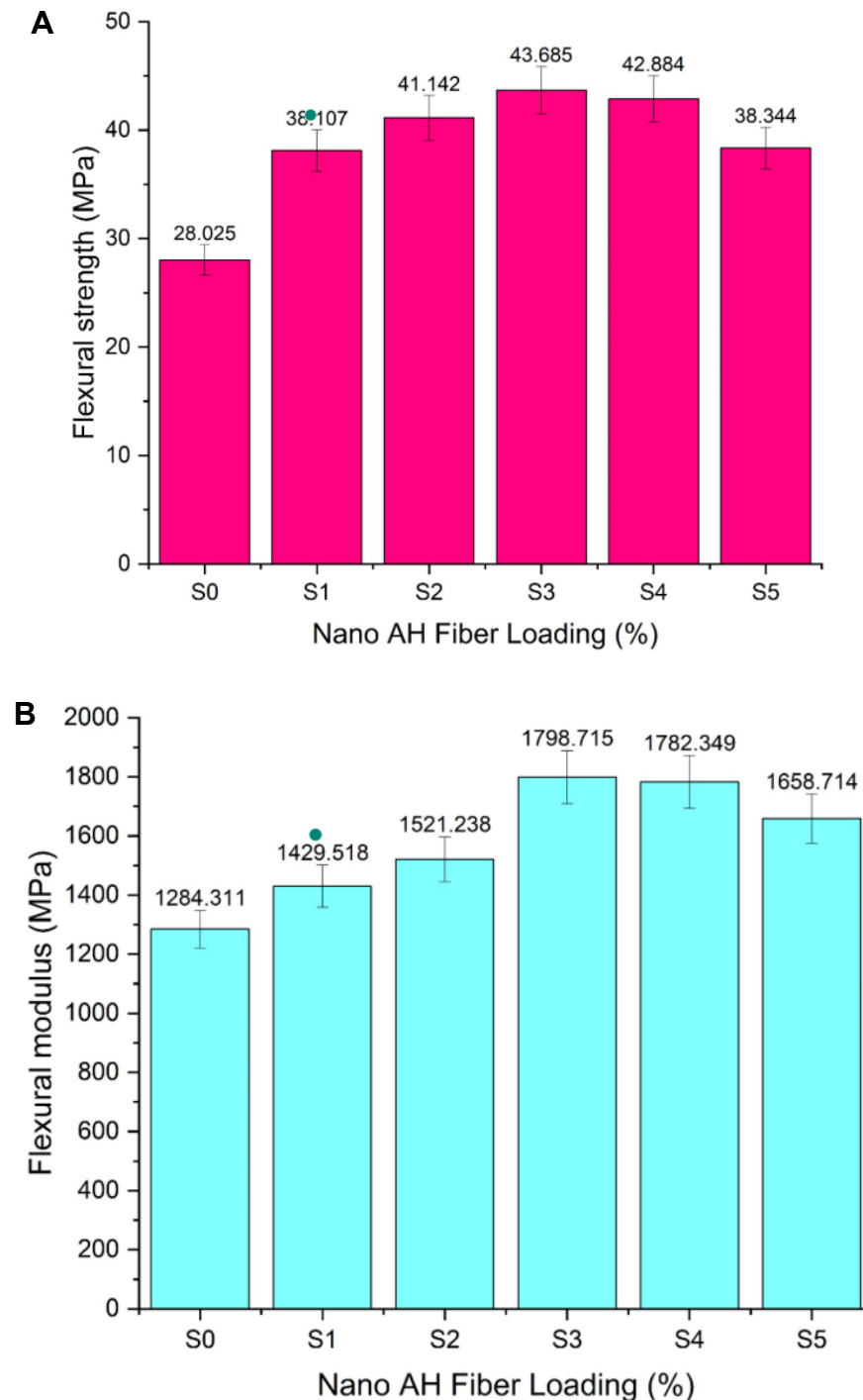


Fig. 9. Effect of fiber loading with respect **A.** flexural strength and **B.** flexural modulus

Impact Strength

The Charpy impact test (Fig. 7C) was employed to evaluate the energy absorption capacity of the composites under sudden loading conditions, thereby providing critical insights into their toughness, crack initiation resistance, and ability to dissipate dynamic stresses (Liang 2002; Faruk *et al.* 2014; Prasad *et al.* 2023). The neat polyester composite exhibited a relatively low impact strength of 1.45 KJ/m², which is characteristic of the

inherently brittle behavior of unreinforced thermoset resins, where crack propagation occurs with minimal energy absorption. Upon the incorporation of *Aristida hystrix* nano fibers, a progressive enhancement in impact performance was observed. At 1 wt% fiber loading, the impact strength improved to 1.57 KJ/m², indicating that even a small amount of reinforcement was sufficient to introduce localized toughening mechanisms such as crack pinning and limited fiber bridging. At 3 wt% loading, the impact strength further increased to 1.79 KJ/m², demonstrating the increasing role of fiber–matrix interaction in arresting crack propagation and dissipating impact energy. The maximum performance was achieved at 5 wt% fiber loading, with an impact strength of 1.87 KJ/m² (Fig. 10), corresponding to an enhancement of nearly 29% compared to neat polyester. This notable improvement is attributed to the homogeneous dispersion of nano fibers, which provided multiple crack-bridging sites and facilitated deflection of crack paths. Such mechanisms not only prolonged the crack propagation route but also required higher energy input for fracture, thereby significantly improving the overall toughness of the composite (Ikubanni *et al.* 2017; Padmanabhan *et al.* 2024). SEM observations further corroborated this explanation, revealing a well-integrated morphology at 5 wt% fiber loading. The micrographs displayed reduced voids, effective resin wetting, and uniform fiber distribution, all of which are essential for achieving strong interfacial adhesion and efficient stress transfer. The microstructural integrity at this loading created a synergistic effect between the resin and fibers, where the matrix restricted fiber pull-out while the fibers acted as barriers to crack advancement. This synergy effectively enhanced energy absorption under sudden loading, explaining the peak performance at this concentration.

However, beyond the optimal threshold, a deterioration in impact strength was observed. At 7 wt% and 9 wt% fiber loadings, the values dropped to 1.36 KJ/m² and 1.30 KJ/m², respectively. This decline can be explained by the agglomeration of fibers at higher concentrations, which disrupted uniform stress distribution within the matrix. The fiber clusters acted as stress concentrators and micro-defect sites, reducing the efficiency of load transfer and providing easy routes for crack initiation. Additionally, excessive fibers reduced the availability of resin for proper wetting and encapsulation, thereby weakening the fiber–matrix interface. The poor interfacial adhesion facilitated premature crack initiation and accelerated crack propagation under impact loading (Vivek and Kanthavel 2019; Yang *et al.* 2020). Thus, while the incorporation of *Aristida hystrix* nano fibers was effective in enhancing the impact toughness of polyester composites up to an optimum level, exceeding this reinforcement limit resulted in compromised structural integrity. This behavior underscores the critical importance of controlling fiber loading and dispersion to balance toughness, adhesion, and energy absorption capacity in polymer nanocomposites.

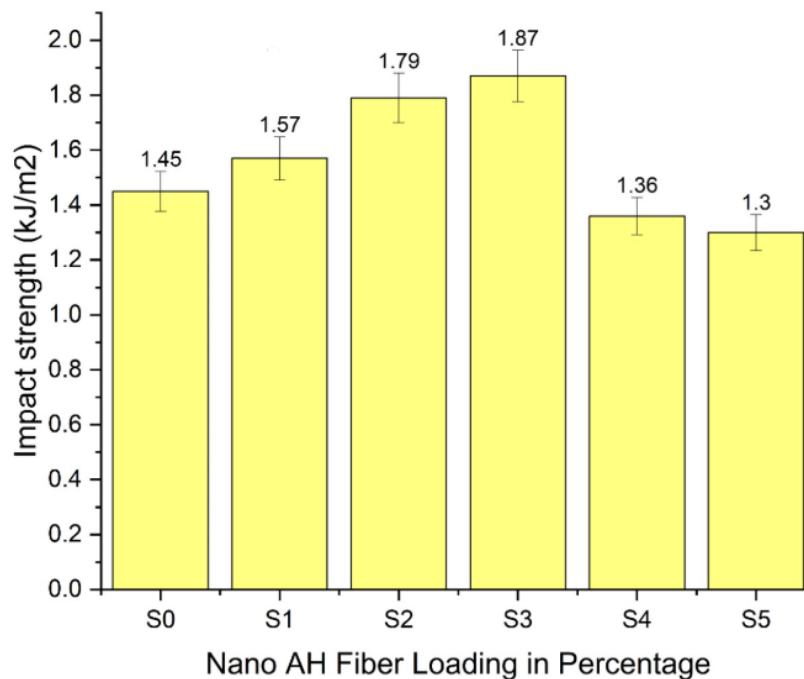


Fig. 10. Effect of fiber loading with respect impact strength

Water Absorption

The water absorption behavior of nano *Aristida hystrix* fiber-reinforced polyester composites was systematically examined over a 24-h immersion period (Fig. 11). The results revealed a clear correlation between fiber loading and water uptake, with higher fiber incorporation consistently leading to increased moisture absorption (Sanjeevi *et al.* 2021; Prasad *et al.* 2023). The neat polyester resin (0 wt% fiber) exhibited the lowest absorption value of 0.8%, reflecting the inherent hydrophobicity of the polyester matrix, which resists moisture ingress. Upon addition of nano fibers, a gradual increase in water uptake was observed. At 1 wt% and 3 wt%, the absorption values rose modestly to 0.86% and 0.95%, respectively. This minor rise can be attributed to the limited hydrophilic sites introduced by the small fraction of fibers, which slightly enhanced the capillary pathways for water diffusion (Gurunathan *et al.* 2022).

At higher fiber loadings, however, the effect became much more pronounced. The water absorption values reached 1.46% at 5 wt%, 1.78% at 7 wt%, and 2.12% at 9 wt%. These increments are primarily due to two key factors: (i) the increased volume fraction of hydrophilic cellulose-rich fibers, which readily form hydrogen bonds with water molecules, and (ii) the higher probability of microvoid formation at elevated fiber contents, which provides additional free pathways for water ingress (Lu *et al.* 2022). SEM analysis further corroborated this, as composites with 7 to 9 wt% loadings exhibited visible fiber pull-outs and microcracks, acting as channels for moisture penetration. The observed trend highlights the classic strength–durability trade-off encountered in natural fiber-reinforced composites. While the inclusion of nano fibers significantly improves mechanical performance, it simultaneously elevates water absorption, which could compromise long-term stability in humid or aqueous service conditions. To ensure long-term performance in applications requiring dimensional stability and environmental resistance, moisture mitigation strategies become essential. Thus, although *A. hystrix* nano fibers enhanced the

overall mechanical characteristics of polyester composites, their hydrophilic nature inevitably elevated water absorption, underscoring the importance of optimizing fiber surface chemistry and composite design for real-world applications.

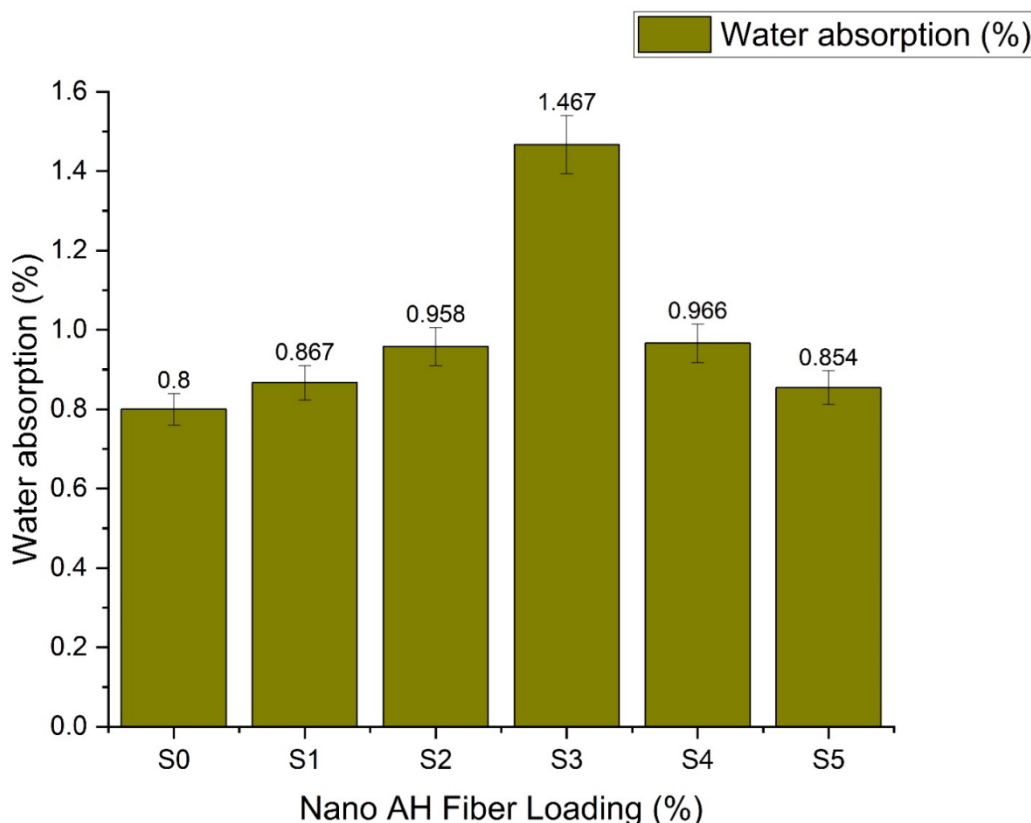


Fig. 11. Effect of fibre loading with respect to Water uptake behaviour for 12 h

Scanning Electron Microscopy

The interfacial behaviour of the fiber-matrix interaction in the fractured surfaces of tensile-tested specimens was analysed using scanning electron microscopy (SEM) to elucidate the failure mechanisms. Figure 12 (A through F) displays the SEM images of composites featuring varying fibre loadings, offering insights into the fracture behaviour (Sharma *et al.* 2021; Palanisamy *et al.* 2022). Figure 12(A) illustrates the fractured surface of the 0 wt% fibre composite, characterised by a rough and uneven morphology. This observation suggests brittle failure, a common trait of pure resin composites. The lack of reinforcing fibres leads to reduced energy absorption and sudden fracture when subjected to tensile loading (Kathirselvam *et al.* 2019; Vinod *et al.* 2021).

The addition of 1 wt% and 3 wt% nano fibre particles, as illustrated in Figs. 12(B) and 12(C), results in fractured surfaces that exhibit enhanced smoothness, indicating a potential improvement in the ductile behaviour of the composites. The incorporation of fibre reinforcement facilitates improved stress distribution, mitigates brittleness, and enhances the composite's capacity for plastic deformation prior to failure (Bay and Eryildiz 2024). At 5 wt% fibre loading, which demonstrated the highest mechanical performance, the SEM image in Fig. 12(D) shows a more uniform fracture surface characterised by smooth regions interspersed with minor irregularities. This demonstrates optimal fibre

dispersion and robust interfacial adhesion, which efficiently transferred the applied load from the fibre to the matrix. The increased elongation at break noted in this composition further indicates the enhanced toughness and ductility of the composite (Raju *et al.* 2021; Palanisamy *et al.* 2022; Shiferaw *et al.* 2023).

As the fibre content increased to 7 wt% and 9 wt%, Figs. 12(E) and 12(F) illustrate rough and highly fractured surfaces, indicating a return to brittle failure. The high fibre content resulted in fibre agglomeration and inadequate interfacial bonding, which caused stress concentration points within the composite (Pandit *et al.* 2017; Bledzki *et al.* 2021; Palanisamy *et al.* 2021). The tensile properties were compromised, as the fibres could not adequately support load-bearing, resulting in early failure. The SEM analysis indicates that fibre loading has a significant impact on the fracture behaviour of composites. Moderate fibre reinforcement at 5 wt% improves ductility and mechanical strength. However, an excessive fibre content of 7 wt% or more negatively affects interfacial bonding, resulting in brittleness and diminished performance.

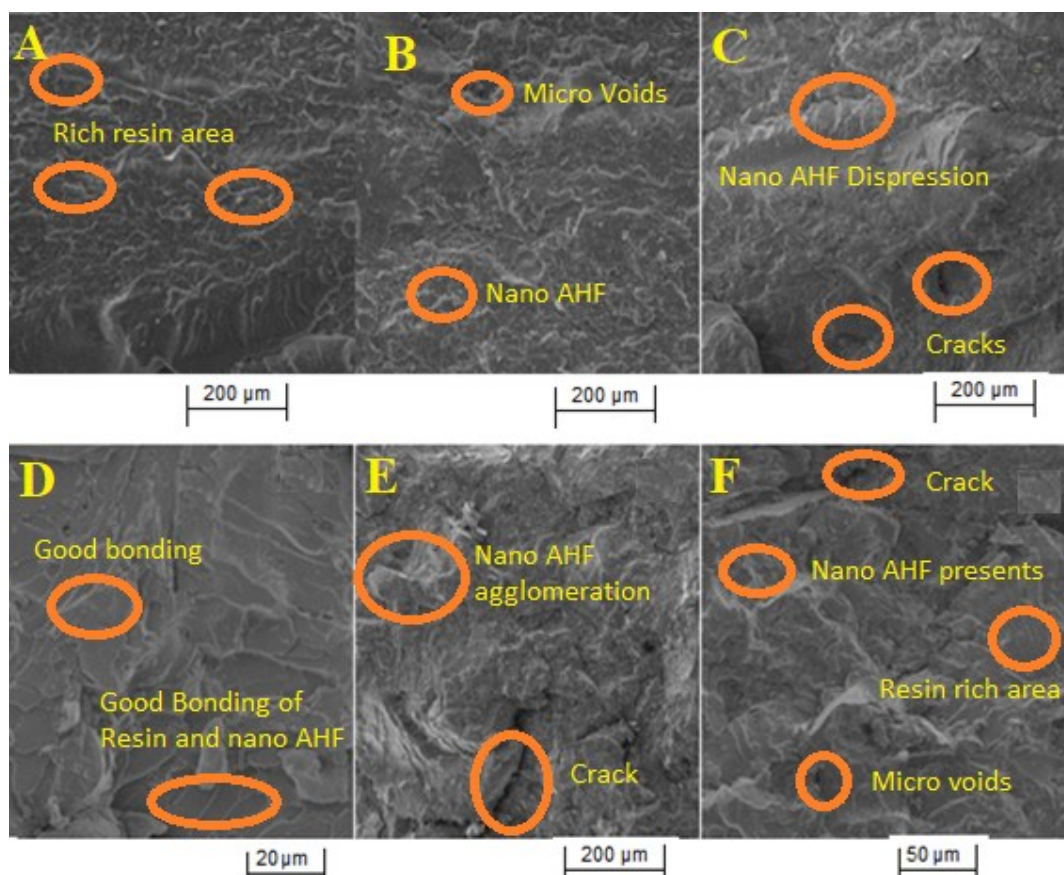


Fig. 12. Morphological analysis of tensile tested fractured specimen to: **A-** 0 wt%; **B-** 1 wt%; **C-** 3 wt%; **D-** 5 wt%; **E-** 7 wt%; **F-** 9 wt% composites

CONCLUSIONS

Aristida hystrix (AH) nano fiber-reinforced polyester composites were tested for mechanical qualities using ASTM standards. The investigation showed that composites reinforced with 5 wt% nano AH fibres performed better than others. Morphological

research confirmed high fiber-matrix adhesion as the enhancer.

1. Tensile, flexural, and impact strengths of 5 wt% nano fibre composites were measured at 30.13 MPa, 43.685 MPa, and 1.87 KJ/m², respectively. The values are 2.3, 1.5, and 1.29 times higher than pure polyester composites. Tensile and flexural moduli for 5 wt% fibre loading were 1106.442 MPa and 1798.715 MPa, respectively, suggesting increased stiffness compared to composites with lower and higher fibre concentrations. The 5 wt% composite had a maximum elongation of 3.2%, balancing strength and ductility.
2. Nano fibre particles in polyester matrix increased moisture uptake in water absorption tests. This trend shows that nano fibres increase mechanical capabilities but also introduce hydrophilic features that must be considered in moisture-resistant applications.
3. SEM revealed fibre dispersion and interfacial bonding. At 5 wt% fibre loading, nano fibres were evenly distributed in the matrix, enabling stress transmission. Increased fibre content over 5 wt% caused aggregation and poor fiber-matrix adherence, reducing mechanical performance. These composites have voids and weak surfaces, confirming the negative impact of high fibre content.
4. Experimental results show that nano-sized *Aristida hystrix* fibre particles may strengthen polymer composites. Mechanical qualities improve with 5 wt%, making them suitable for lightweight, high-performance composites. Nano natural fibres may be used to make sustainable composites for automotive, aerospace, and construction applications, according to this research.

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Data Availability Statement

Data are available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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