



Impact of Montmorillonite Nanoclay on the Performance of Alkali-treated Agave/Epoxy Biocomposites

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ABSTRACT

This study investigates the influence of montmorillonite nanoclay (MMT) filler on the mechanical and structural performance of alkali-treated *Agave sisalana* fiber-reinforced epoxy composites. Six composite formulations (AM1–AM6) were fabricated with constant epoxy content (60 wt.%) and varying fiber and nanoclay percentages. Composites AM1 to AM5 incorporated MMT filler (1.5–7.5 wt.%) along with agave fiber (32.5–38.5 wt.%), while AM6 served as the control sample without nanoclay. Mechanical tests, including tensile, flexural, impact, and Shore D hardness measurements, were conducted. Water absorption characteristics and morphological analysis using scanning electron microscopy (SEM) were also evaluated. The AM4 composite (3 wt.% MMT, 37 wt.% fiber) exhibited the highest tensile strength (68.4 MPa), flexural strength (110.1 MPa), hardness (88.7 Shore D), and impact strength (36.8 J), along with the lowest water uptake (10%). SEM micrographs confirmed superior fiber–matrix adhesion and uniform nanoclay dispersion at the optimal filler loading. Excessive nanoclay loading (AM1, 7.5 wt.%) caused particle agglomeration, leading to performance deterioration. Overall, 3 wt.% MMT was identified as the optimum filler concentration, highlighting the synergistic role of nanoclay and treated natural fibers in enhancing epoxy composite performance.

Keywords: Nanomaterial; Montmorillonite nanoclay; *Agave sisalana* fiber; Epoxy; Biocomposites.

1. INTRODUCTION

The global shift towards sustainable and eco-friendly materials has generated considerable interest in natural fiber-reinforced polymer composites (NFRPCs) in recent years. These composites are being recognized as viable alternatives to synthetic fiber-based systems, attributed to their biodegradability, cost-effectiveness, lightweight nature, and diminished environmental impact (Campo *et al.* 2020). Natural fibers, including jute, flax, hemp, kenaf, coir, and agave, are extensively utilized in polymer composites for both structural and semi-structural applications. These applications span automotive components, construction materials, packaging, and consumer goods (Martínez *et al.* 2022).

Agave sisalana, referred to as sisal, is a notable natural fiber characterized by its high availability, superior specific strength, and advantageous mechanical properties. Sisal, classified as a lignocellulosic fiber, is predominantly composed of cellulose, hemicellulose, and lignin, where cellulose plays a critical role in providing tensile strength. Cultivation of this crop is prevalent in countries including Brazil, India, Mexico, and Kenya. The fibers are derived from the leaves of the agave plant and are distinguished by their considerable

length, elevated aspect ratio, and rigidity, rendering them appropriate reinforcements in thermoset and thermoplastic matrices (Gudapati *et al.* 2020).

The primary drawback of utilizing sisal and other natural fibers in polymer composites is their hydrophilic characteristics, which result in inadequate compatibility with hydrophobic polymer matrices like epoxy (Kıranşan *et al.* 2014). The discrepancy at the fiber–matrix interface results in inadequate adhesion, which in turn causes ineffective stress transfer, diminished mechanical properties, and potential long-term durability challenges, particularly when exposed to moisture. The fiber surface is characterized by the presence of hydroxyl groups, which readily engage in hydrogen bonding with water molecules. This interaction increases water uptake and contributes to dimensional instability in composite applications (Kenned *et al.* 2021).

Surface treatments are utilized to chemically or physically modify the fiber surface to resolve the issue of interfacial adhesion. Alkali treatment, referred to as mercerization, represents a widely utilized and efficient technique. The procedure entails submerging the fibers in a sodium hydroxide (NaOH) solution, facilitating the

removal of amorphous components, including hemicellulose, pectin, waxes, and oils (Campo *et al.* 2020). Consequently, there is an increase in cellulose content, resulting in a rougher fiber surface and an enhancement in the number of active sites available for matrix bonding. The treatment results in a reduction of fiber diameter, which increases the aspect ratio and improves mechanical interlocking with the matrix. Numerous studies have validated the effectiveness of alkali treatment in enhancing tensile strength, interfacial shear strength, and moisture resistance of natural fiber composites (Navin *et al.* 2025).

Fiber treatment alone may not provide adequate performance for demanding applications. Researchers have increasingly incorporated nanofillers into the matrix to further enhance the mechanical, thermal, and barrier properties of natural fiber composites (Manickaraj *et al.* 2025). Nanofillers exhibit remarkably high surface area-to-volume ratios and distinct physicochemical properties, which contribute to their effectiveness in reinforcing polymer matrices even at minimal loading levels. Montmorillonite nanoclay (MMT) is recognized as one of the most effective and extensively researched types of nanofillers among the various options available (Arumugam *et al.* 2024).

Montmorillonite is a naturally occurring smectite clay mineral with a layered silicate structure. When exfoliated or intercalated in the polymer matrix, MMT can form a percolated network that significantly enhances stiffness, thermal stability, flame resistance, barrier performance, and in some cases, mechanical strength (Achachlouei and Zahedi, 2018). The high aspect ratio and platelet-like morphology of MMT particles create tortuous paths for gas and moisture diffusion, thereby reducing permeability and improving the long-term durability of the composites. Furthermore, MMT can interact at the molecular level with the polymer matrix, modifying the rheological behavior and enhancing load-bearing capabilities (Achachlouei and Zahedi, 2018).

In fiber-reinforced composites, nanoclay plays a dual role. First, it reinforces the polymer matrix, improving its inherent mechanical properties. Second, it contributes to a better stress transfer at the fiber–matrix interface by enhancing matrix stiffness and reducing the mobility of polymer chains around the fiber surface. When combined with alkali-treated natural fibers, nanoclay has been shown to produce a synergistic effect, resulting in superior composite performance compared to composites reinforced with either nanoclay or treated fibers alone (Wang *et al.* 2021).

The challenge, however, lies in optimizing the nanoclay content. While small amounts of MMT can be beneficial, excessive filler loading can lead to particle agglomeration, poor dispersion, increased viscosity

during processing, and reduced mechanical performance. Therefore, determining the optimal concentration of MMT is crucial to maximize its reinforcing effect without compromising processability and composite integrity (Idumah *et al.* 2022).

This study systematically investigates the impact of different MMT nanoclay content on the mechanical, physical, and structural properties of alkali-treated *Agave sisalana* fiber-reinforced epoxy composites. Epoxy resin was chosen as the matrix because of its superior mechanical properties, resistance to chemicals, and broad applicability in structural composites (Archibong *et al.* 2023). A series of thorough tests was performed to assess the tensile strength, flexural strength, impact strength, and Shore D hardness of the composites. Furthermore, water absorption tests were conducted to evaluate the hydrophobic performance of the nanoclay-modified systems. SEM analysis was conducted on fractured surfaces to investigate the interfacial morphology and filler dispersion (Torres *et al.* 2022).

This research provides significant insights into the development of hybrid natural fiber nanocomposites, focusing on improved structural integrity and durability. The findings indicate significant implications for the design of eco-friendly composites across various sectors, including automotive, construction, consumer goods, and packaging, where there is a growing demand for lightweight and sustainable materials (Anamika *et al.* 2021). The integration of alkali-treated natural fibers with optimized nanoclay content signifies a viable approach for enhancing the performance of green composites. The results provide a basis for subsequent investigations into hybridization, surface compatibilizers, and multi-scale modelling to fully realize the potential of nanomaterial-enhanced natural fiber composites (Santhosh and Anand, 2023).

2. MATERIALS

2.1 *Agave Sisalana* Fiber

Agave sisalana fibers were procured in raw form and used as the primary natural reinforcement in this study. The fibers were manually cleaned to remove residual dust, dirt, and surface impurities. Due to their naturally hydrophilic surface, further chemical modifications were carried out (Gurusamy *et al.* 2025). *Agave sisalana* fibers are shown in Fig. 1.

2.2 Epoxy Resin

A commercially available epoxy resin based on bisphenol-A and an amine-based hardener was used as the matrix material, mixed in a weight ratio of 10:1. Epoxy was chosen due to its superior dimensional stability, mechanical strength, and chemical resistance

(Hasan *et al.* 2020). The epoxy content remained constant at 60 wt.% in all composite formulations.



Fig. 1: *Agave sisalana* fibers

2.3. Montmorillonite Nanoclay

Montmorillonite nanoclay was used as the nanoscale filler in this study due to its layered silicate structure, high surface area, and superior interfacial interaction with polymer matrices. The nanoclay was procured from Intelligent Materials Private Limited, Punjab, India, and used without further surface modification. Before mixing, it was dried to remove moisture. The nanoclay content was varied from 1.5 to 7.5 wt.% in the composites (Karuppusamy *et al.* 2025). Fig. 2 shows the montmorillonite nanoclay powder.



Fig. 2: Montmorillonite nanoclay powder

2.4 Chemical Treatment of Fibers

A chemical alkali treatment was conducted to enhance the compatibility between the hydrophilic *Agave sisalana* fibers and the hydrophobic epoxy matrix. The raw fibers underwent immersion in a 5 wt.% NaOH aqueous solution for 4 h at room temperature, with continuous stirring. The mercerization process effectively eliminated amorphous constituents, including hemicellulose, lignin, pectin, and surface waxes. This action resulted in the exposure of a greater amount of

cellulose and an increase in the surface roughness of the fibers. Following the treatment process, the fibers were subjected to a comprehensive washing procedure using distilled water. The fibers that were treated underwent a drying process at room temperature for 24 h (Balaji *et al.* 2020).

2.5 Composite Fabrication

The composites were produced through a hand lay-up process, subsequently followed by compression molding. Nanoclay was incorporated into epoxy resin through mechanical stirring for a duration of 20 min, followed by ultrasonication for 30 min. The resulting mixture was then combined with a hardener at a ratio of 10:1. Agave fibers, treated with alkali, were systematically arranged within the mold and subsequently impregnated with the epoxy mixture. The lay-up underwent compaction and curing at a pressure of 10–15 MPa at room temperature for 24 h, followed by post-curing at 80 °C for 2 h. Subsequently, the laminates were demolded, trimmed, and conditioned for 48 h before testing (Martínez *et al.* 2022).

2.6 Composite Designations

Six different composite formulations were developed by varying the fiber and nanoclay contents while keeping the epoxy percentage constant (Aravinth *et al.* 2023). The designations and corresponding compositions are listed in Table 1.

Table 1. Composite designations and compositions

S. No.	<i>Agave Sisalana</i> Fibers (%)	Montmorillonite Nanoclay (%)	Epoxy Resin (%)	Composite Designation
1	32.5	7.5	60	AM1
2	34	6	60	AM2
3	35.5	4.5	60	AM3
4	37	3	60	AM4
5	38.5	1.5	60	AM5
6	40	0	60	AM6 (Without nanoclay)

2.7 Testing Standards and Characterization Methods

The mechanical and physical performances of the fabricated agave fiber/nanoclay-reinforced epoxy composites were evaluated by adhering to standard testing procedures in accordance with the guidelines set forth by the American Society for Testing and Materials (ASTM) (Fonseca *et al.* 2024).

2.7.1 Tensile Properties

Tensile testing was conducted in accordance with ASTM D638, which specifies the procedure for

assessing the tensile strength and tensile modulus of polymer matrix composites. Specimens were fabricated in accordance with the standard Type I dumbbell configuration, adhering to the specified dimensions outlined in the standard. Testing was performed using a universal testing machine (UTM) at a crosshead speed of 2 mm/min in ambient conditions. The tensile strength and Young's modulus were determined from the stress-strain characteristics of the composites (Hossain *et al.* 2023).

2.7.2 Flexural Properties

Flexural strength was evaluated using ASTM D790's three-point bending technique. Rectangular specimens underwent testing with a span-to-depth ratio of 16:1, utilizing a crosshead speed of 1.3 mm/min. The maximum flexural stress and the corresponding strain were measured to determine the flexural strength and modulus (Thirumalaisamy *et al.* 2023).

2.7.3 Impact Strength

Impact resistance was evaluated using the Izod impact test as per ASTM D256. Notched specimens were tested using a pendulum impact tester, and the impact energy absorbed during fracture was measured in joules. This test assesses the composite's toughness and its ability to absorb energy under sudden loading (Sifuentes-Nieves *et al.* 2021).

2.7.4 Hardness (Shore D)

The measurement of surface hardness for the composites was conducted utilizing a Shore D durometer, following the guidelines established by ASTM D2240. The indenter was applied vertically to the surface of the specimens, and the hardness value was documented following a 15-second application period. For each sample, five readings were recorded to ensure consistency (Gomez *et al.* 2024).

2.7.5 Water Absorption

The water absorption behavior was evaluated in accordance with ASTM D570, which outlines the procedure for determining the moisture uptake of plastics. Specimens were initially subjected to drying in an oven at a temperature of 50 °C until a constant weight was achieved. Subsequently, they were immersed in distilled water at room temperature for 24 h. The samples were extracted, dried thoroughly, and measured for weight. The calculation of the percentage increase in weight was performed to quantify the water absorption capacity, which indicates the hydrophilicity and durability of the composite in moist environments (Smith *et al.* 2020).

2.8 SEM Analysis

SEM analysis was conducted on the fractured surfaces of the composite specimens to investigate the morphological characteristics and interfacial bonding between the agave fibers, nanoclay, and the epoxy matrix

(Natrayan *et al.* 2022). SEM images were obtained from the fractured surfaces resulting from tensile testing. These regions are critical for analyzing failure modes, fiber pull-out, matrix cracking, nanoclay dispersion, and fiber-matrix adhesion.

3. RESULTS AND DISCUSSION

3.1 Tensile Strength Analysis

The tensile strength values exhibit a distinct trend in relation to the changes in nanoclay and fiber content. Among the evaluated specimens, AM4, which comprises 3 wt.% MMT nanoclay and 37 wt.% agave fiber demonstrated the highest tensile strength recorded at 68.4 MPa. This indicates a 14.4% enhancement compared to the control sample AM6, with a recorded tensile strength of 59.8 MPa. The observed enhancement results from the synergistic interaction between alkali-treated agave fibers and the optimal dispersion of montmorillonite nanoclay. The alkali treatment enhances interfacial adhesion through increased surface roughness and the removal of impurities. Concurrently, the nanoclay facilitates stress transfer within the matrix by establishing a pseudo-network that limits matrix mobility and strengthens the interphase. At a concentration of 3 wt.%, nanoclay demonstrated effective dispersion and uniform distribution, leading to enhanced stress distribution across the composite (Atmakuri *et al.* 2020). In the range of AM1 to AM3, characterized by a higher nanoclay content of 4.5–7.5 wt.% and a lower fiber content of 32.5–35.5 wt.%, a progressive increase in tensile strength was noted, rising from 61.1 MPa to 64.7 MPa. The increase is not linear for concentrations exceeding 3 wt.% nanoclay. The tensile strength exhibits a plateau or decline in AM1 and AM2, which is attributable to the agglomeration of excess nanoclay particles. The agglomerates function as stress concentrators, compromising the continuity of the local matrix and consequently diminishing the effectiveness of the reinforcement. Conversely, AM5 exhibits the highest fiber content at 38.5 wt.%, yet contains only 1.5 wt.% nanoclay, resulting in a minor reduction in tensile strength, measured at 60.3 MPa, when compared to AM4. This suggests that a minimal nanoclay content is inadequate for establishing a continuous intercalated structure within the epoxy, while an excessive fiber content may result in suboptimal wetting and the formation of voids during processing (Krishnadev *et al.* 2021). The control sample AM6, comprising 40 wt.% agave fibers and devoid of nanoclay, exhibited the lowest tensile strength at 59.8 MPa. The incorporation of nanoclay, even in small quantities, significantly enhances the load-bearing capability of the hybrid composite system by improving interfacial interactions and minimizing microstructural defects. The tensile behavior of the composites demonstrates that a nanoclay content of 3 wt.% achieves optimal dispersion within the epoxy matrix, enhances fiber-matrix interfacial bonding, and

results in a significant improvement in mechanical strength. Excessive loading of nanoclay results in agglomeration, creating sites of stress concentration and reducing the effectiveness of reinforcement (Hosseini, 2020). On the other hand, insufficient nanoclay or an excessively high fiber content may impede adequate matrix wetting and resin flow, leading to compromised interfacial adhesion and diminished tensile performance. The findings underscore the significance of optimizing nanofillers in the design of high-performance natural fiber-reinforced composites. Fig. 3 illustrates the tensile properties of the six composite designations.

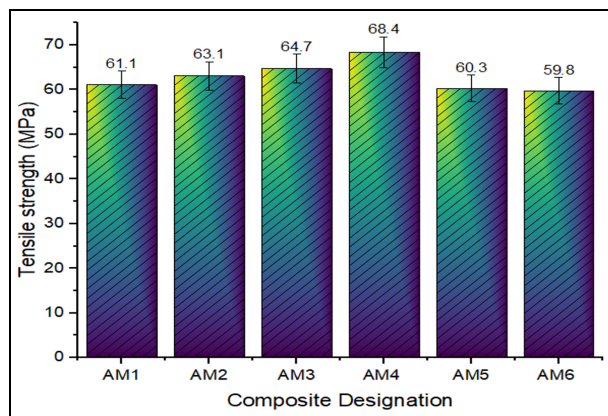


Fig. 3: Tensile strength of the composites

3.2 Flexural Strength Analysis

Flexural strength is a critical mechanical property used to assess the bending performance and stiffness of fiber-reinforced composites, particularly in scenarios where the material experiences transverse loads. As evident from Fig. 4, the addition of montmorillonite nanoclay substantially enhances the flexural performance of agave fiber-reinforced epoxy composites. The composite AM4, comprising 3 wt.% nanoclay and 37 wt.% agave fiber, demonstrated a maximum flexural strength of 110.1 MPa, surpassing the control sample AM6 by roughly 14.9%. The enhancement of flexural strength resulting from the incorporation of nanoclay can be explained by the development of a complex network of clay platelets within the matrix. This network limits the mobility of polymer chains and enhances resistance to deformation. Additionally, uniformly distributed nanoclay serves as a supplementary reinforcement that increases the stiffness of the matrix, thereby effectively supporting the applied bending loads and enhancing the stress transfer between the matrix and fibers. The tensile behavior exhibits a comparable trend in this context: the data from AM1 to AM3 indicate a progressive increase in flexural strength as the nanoclay content decreases from 7.5 to 4.5 wt.%. However, beyond the optimal 3 wt.% (AM4), a decline is observed in AM5 (1.5 wt.% nanoclay) and AM6 (no nanoclay). The decrease in AM5 can be linked to inadequate nanoclay loading, which does not create a

reinforcing network. In contrast, the reduction in AM6 is due to the complete lack of nanoclay, rendering it solely reliant on fiber–matrix bonding. Conversely, AM1 and AM2, which contain higher nanoclay concentrations of 7.5 wt.% and 6 wt.%, respectively, demonstrate only a moderate enhancement compared to the control. The observed underperformance relative to AM4 can be attributed to the agglomeration of nanoclay, which may function as stress concentrators when subjected to bending loads, thereby initiating microcracks and localized failure (Ortíz *et al.* 2021). The optimal performance of AM4 suggests that a filler concentration of 3 wt.% nanoclay achieves an effective balance among dispersion quality, interfacial adhesion, and matrix stiffening within this system. This formulation achieves optimal fiber wetting, utilizes nanoclay–matrix synergy, and incorporates interfacial stress transfer mechanisms, all of which contribute to enhanced flexural behavior. The flexural results corroborate the findings from tensile testing, indicating that the addition of moderate nanoclay (specifically 3 wt.%) enhances the structural integrity of the composite when subjected to multi-axial loading conditions (Gillela *et al.* 2024).

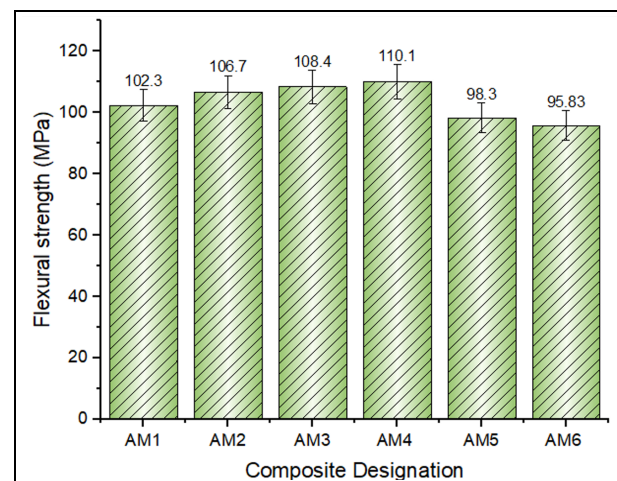


Fig. 4: Flexural strength of the composites

3.3 Impact Strength Analysis

The impact strength of a composite material indicates its capacity to absorb and dissipate energy when subjected to sudden or shock loading, thereby preventing catastrophic failure. The impact strength of agave fiber-reinforced epoxy composites was assessed using the Izod method in accordance with ASTM D256. The findings indicate a positive influence of integrating montmorillonite nanoclay with alkali-treated agave fibers on the impact resistance of the composite laminates. AM4, comprising 3 wt.% nanoclay and 37 wt.% agave fiber, demonstrated the highest impact strength, measured at 36.8 J (Fig. 5). This demonstrates a notable enhancement in energy absorption capacity relative to the control sample AM6, which exhibited the lowest impact strength of 26.5 J. The improvement in

AM4 results from the effective distribution of nanoclay within the epoxy matrix, which enhances the energy dissipation mechanism *via* crack deflection, matrix toughening, and increased fiber–matrix interfacial adhesion (Turki *et al.* 2023). A consistent rise in impact strength is noted from AM1 to AM4 as the nanoclay content diminishes from 7.5 to 3 wt.%. AM1 and AM2 exhibited impact strengths of 31.5 J and 34.2 J, respectively, whereas AM3 achieved an impact strength of 35.1 J. The observed trend indicates that the incorporation of moderate nanoclay loading enhances impact resistance by inhibiting micro-crack formation and improving the toughness of the composite structure. The nanoclay is expected to establish a pseudo-network within the matrix, contributing to the reduction of crack propagation and enhancing the absorption of impact energy. In AM5, with a further reduction of nanoclay content to 1.5 wt.%, the impact strength decreased to 30.4 J. The observed decline can be attributed to inadequate nanoclay reinforcement, potentially resulting in a less cohesive network within the epoxy matrix. The fiber content in AM5 is marginally elevated; however, the lack of sufficient nanoclay support leads to diminished energy absorption capabilities and reduced toughness. The minimum value observed in AM6 underscores the significance of nanoclay as an essential factor influencing the impact performance of the composite. The control sample, lacking nanoclay, exhibits diminished fiber–matrix interlocking and a more brittle matrix response when subjected to impact loading (Sathiamurthi *et al.* 2021). The analysis of impact strength data indicates that a loading level of 3 wt.% MMT nanoclay is optimal for enhancing impact resistance in alkali-treated agave fiber/epoxy composites. Exceeding this threshold results in agglomeration, whereas an inadequate amount of nanoclay does not provide substantial reinforcement to the matrix, consequently diminishing the effectiveness of energy dissipation during fracture (Mendoza *et al.* 2019).

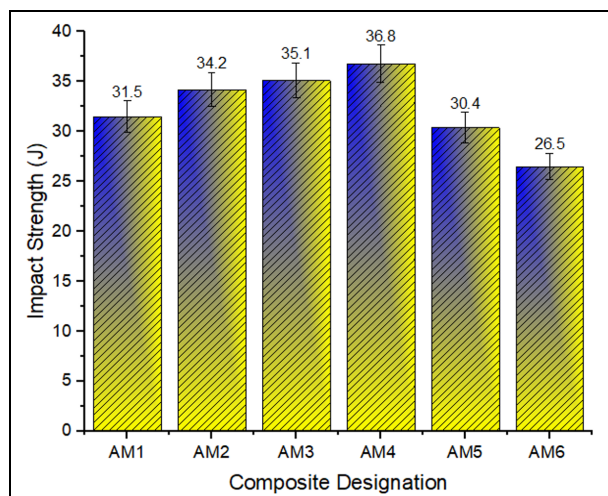


Fig. 5: Impact strength of the composites

3.4 Hardness Analysis

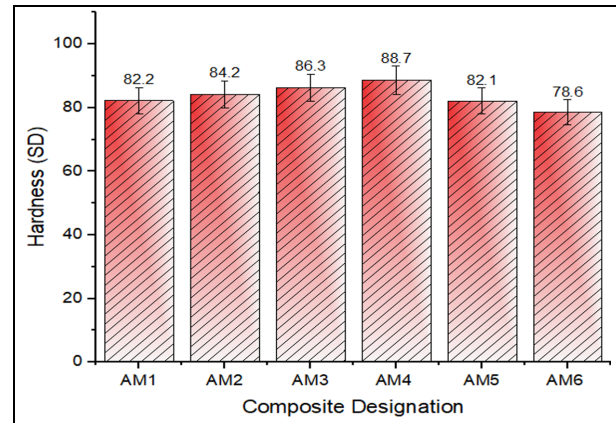


Fig. 6: Hardness of the composites

The findings indicate a significant enhancement in hardness with the addition of nanoclay to the epoxy matrix, especially at an optimal loading of 3 wt.% (AM4). The maximum hardness value recorded was 88.7 Shore D for AM4, which also aligned with its highest performance in other mechanical properties, including tensile, flexural, and impact strength. The enhancement observed is due to the stiffening effect provided by well-dispersed MMT nanoclay, which increases the matrix's resistance to deformation (Olivares *et al.* 2019). The incorporation of rigid silicate layers from the nanoclay enhances the reinforcement of the polymer structure, resulting in increased resistance to indentation on the surface. The observed progression from AM1 (82.2) to AM4 (88.7) demonstrates that moderate concentrations of nanoclay enhance interfacial bonding and matrix rigidity, resulting in improved surface hardness. The incorporation of nanoclay limits the movement of polymer chains and offers reinforcement at the microstructural scale, leading to improved surface resistance. At lower nanoclay loading levels, specifically AM5 at 1.5 wt.% and the control sample AM6 at 0 wt.%, the observed hardness values are 82.1 and 78.6, respectively. The reduced hardness observed in AM5 indicates that the inadequate presence of nanoclay does not effectively enhance matrix reinforcement. Conversely, AM6, which lacks nanoclay entirely, exhibits the lowest hardness across all formulations. This statement verifies that nanoclay serves as a crucial element in enhancing the surface characteristics of the composite. The observed slight reduction in hardness in AM1, which contains the highest nanoclay content of 7.5 wt.%, compared to AM4, indicates that an excess of nanoclay may result in particle agglomeration. This agglomeration can decrease the uniformity of the composite and create localized weak zones, ultimately leading to a reduction in overall hardness. In conclusion, the hardness data indicate that a balanced nanoclay loading of approximately 3 wt.% provides optimal surface reinforcement. Deviations from this loading,

whether through underloading or overloading, negatively impact the surface resistance of the composite (Ramesh *et al.* 2025). This behavior aligns with trends noted in tensile, flexural, and impact testing, thereby reinforcing AM4 as the preferred formulation for multifunctional mechanical performance. Fig. 6 illustrates the Shore D hardness test results.

3.5 Water Absorption Analysis

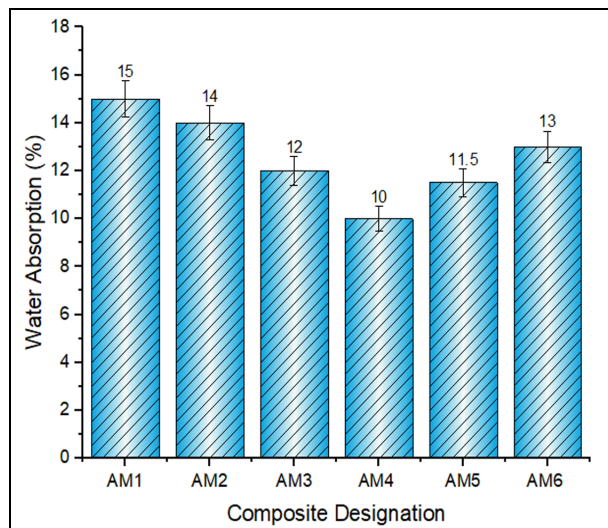


Fig. 7: Water absorption of the composites

The water absorption behavior of the composites during a one-week immersion period demonstrated a significant impact of nanoclay content on the moisture resistance of the agave fiber–epoxy system. As evident from Fig. 7, among the samples, AM4 demonstrated the lowest water absorption at 10%, signifying improved interfacial sealing and decreased permeability. The observed enhancement can be ascribed to the effective dispersion of nanoclay, which presumably established a complex pathway for water molecules and improved fiber–matrix interaction by minimizing microvoids (Venkatram *et al.* 2016). AM1 and AM2, which contain higher nanoclay contents of 7.5 wt.% and 6 wt.%, respectively, exhibited increased moisture absorption rates of 15% and 14%. This indicates that the presence of excessive filler contributed to agglomeration, leading to the formation of voids and microcracks that allowed for water ingress. AM3 (4.5 wt.% nanoclay) exhibited a moderate water absorption rate of 12%. In contrast, AM5, which included only 1.5 wt.% nanoclay, absorbed 11.5%. This suggests that an insufficient amount of nanoclay does not deliver an adequate barrier effect, even with an increase in fiber loading. The control sample, AM6, exhibited a water uptake of 13%, thereby underscoring the significance of nanoclay in enhancing the moisture resistance of the composite. The results indicate that a balanced formulation, specifically containing 3 wt.% nanoclay, enhances mechanical performance and

significantly improves environmental durability by restricting water diffusion (Selvi *et al.* 2023).

3.6 SEM Analysis

The SEM micrographs of the fractured tensile surfaces demonstrated distinct variations in fiber–matrix interaction, nanoclay dispersion, and failure mechanisms throughout the composite series. In the control sample, the absence of nanoclay resulted in notable fiber pull-out, smooth fiber surfaces, and interfacial gaps, which suggest inadequate adhesion between the alkali-treated agave fibers and the epoxy matrix, leading to suboptimal stress transfer as evidenced by the reduced mechanical performance. The composite AM4, containing 3 wt.% nanoclay, exhibited a significantly cohesive fracture surface characterized by well-embedded fibers, a reduction in voids, and consistent matrix continuity surrounding the fibers (Rangel *et al.* 2022). The inclusion of exfoliated nanoclay platelets at this concentration resulted in enhanced matrix packing and improved fiber wetting, thereby facilitating better stress transfer and mechanical integrity. AM1 and AM2, which contain higher nanoclay loadings of 7.5 wt.% and 6 wt.%, respectively, exhibited areas of nanoclay agglomeration and sites for microcrack initiation. This phenomenon is likely attributed to inadequate dispersion and stress concentration surrounding the clusters (Nair *et al.* 2021). In contrast, AM5 and AM3 demonstrated a moderate enhancement in bonding compared to the control, yet their structural integration remained inferior to that of AM4. SEM analysis demonstrated that optimized nanoclay loading significantly enhances fiber–matrix adhesion, decreases void content, and produces a more uniform fracture morphology, which aligns closely with the mechanical and water absorption outcomes. Fig. 8 shows the SEM micrograph of AM4 composite.

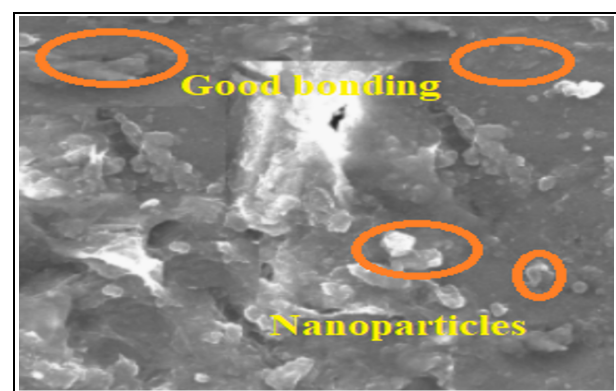


Fig. 8: SEM image of AM4

4. CONCLUSION

This research examined the influence of montmorillonite nanoclay loading on the mechanical, physical, and morphological properties of alkali-treated *Agave sisalana* fiber-reinforced epoxy composites. The

findings indicate that the addition of nanoclay markedly improves tensile, flexural, impact, and hardness characteristics, with peak performance observed at 3 wt.% nanoclay (AM4). The formulation demonstrated the highest tensile strength of 68.4 MPa, flexural strength of 110.1 MPa, impact strength of 36.8 J, and Shore D hardness of 88.7. In addition, it exhibited the lowest water absorption rate of 10% compared to all tested composites. SEM analysis confirmed enhanced fiber–matrix adhesion, minimized voids, and consistent fracture morphology in AM4, which can be attributed to the effective dispersion and interaction of nanoclay within the matrix. Excessive nanoclay content, specifically in the range of 6–7.5 wt.%, resulted in particle agglomeration and the introduction of microstructural defects, which adversely impacted performance. In a similar manner, inadequate nanoclay (1.5 wt.%) did not succeed in establishing a reinforcing network. The results highlighted the importance of fiber surface treatment and nanofiller optimization in improving the mechanical integrity and durability of natural fiber composites. The hybrid composite containing 3 wt.% nanoclay provides a balanced and sustainable material solution for structural and semi-structural applications that demand enhanced strength, toughness, and environmental resistance.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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