Research Article

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Impact of Nanoclay on the Mechanical and Structural Properties of Alkali-treated *Abutilon indicum* Fiber-reinforced Epoxy Nanocomposites

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ABSTRACT

This research examines the effect of nanoclay (Cloisite 25A) on the mechanical and structural properties of treated *Abutilon indicum* fiber-reinforced epoxy nanocomposites. The nanoclay content ranged from 0 wt.% to 4 wt.%, with consistent ratios of epoxy resin and hardener maintained throughout. Composite laminates were produced utilising a hand layup technique and subsequently subjected to compression moulding. The evaluation of mechanical properties, including tensile, flexural, impact, and compressive strengths, was conducted by ASTM standards. The incorporation of nanoclay markedly improved the mechanical properties of the nanocomposite. The tensile strength rose from 39.63 MPa (0% nanoclay) to a maximum of 45.92 MPa at 2 wt.% loading, indicating a 15.87% enhancement. Flexural, impact and compressive strengths exhibited improvements, with impact strength attaining a peak of 0.85 J at 2 wt.% nanoclay, representing a 66.67 % increase. Nevertheless, beyond 2 to 3 wt.% nanoclay loading, a slight reduction in tensile and flexural properties was noted, presumably attributable to nanoparticle agglomeration. Structural morphology was examined using scanning electron microscopy (SEM), revealing improved interfacial bonding and reduced fiber pull-out at lower nanoclay concentrations, which contributed to the enhanced mechanical properties. SEM images also confirmed the agglomeration of nanoclay at 4 wt.% loading. Overall, the study confirms that nanoclay addition up to an optimal level (2 to 3 wt.%) effectively enhances both the mechanical and structural integrity of *Abutilon indicum* fiber epoxy nanocomposites.

Keywords: Nanoclay; *Abutilon indicum* fiber; Mechanical properties; Nanocomposites; Cloisite 25A.

1. INTRODUCTION

In recent years, the global pursuit of sustainable technologies and environmentally benign materials has led to a significant surge in research dedicated to bio-based composites. This growing interest is primarily fueled by concerns over environmental pollution, depletion of fossil resources, and the ecological impact of synthetic fiber-reinforced composites (Mylsamy *et al*. 2019). As industries seek alternatives that align with principles of circular economy and sustainable development, natural fiber-reinforced polymer composites (NFRPCs) have emerged as a compelling option. These materials integrate naturally sourced fibers into polymer matrices, offering several key advantages, including low density, biodegradability, renewability, cost-effectiveness, and favourable specific mechanical properties (Puttaswamygowda *et al*. 2024). Such characteristics make NFRPCs suitable for use in various industrial sectors, including automotive, aerospace, construction, packaging, and consumer goods. Despite the considerable promise of NFRPCs, their widespread adoption is often constrained by several intrinsic limitations. Natural fibers, being hydrophilic due to the presence of hydroxyl groups, exhibit poor compatibility with most hydrophobic polymer matrices (Jeyakumar *et al*. 2017). This results in weak fiber/matrix interfacial bonding, leading to inadequate load transfer efficiency and inferior mechanical performance. Additionally, natural fibers are susceptible to moisture uptake, which compromises dimensional stability and long-term durability. Overcoming these challenges is essential to realise the full potential of natural fiber composites for structural and high-performance applications (Mohan and Kanny, 2019).

Among the variety of natural fibers being investigated, *Abutilon indicum*, a fast-growing climbing plant native to tropical regions, has received limited attention in composite research. The fiber derived from the stem of *Abutilon indicum* is a lignocellulosic material composed mainly of cellulose, hemicellulose, and lignin. Its ease of extraction, local availability, and biodegradability make it an attractive and underexplored reinforcement candidate for green composites (Kumar *et al*. 2010). Additionally, this fiber presents numerous benefits such as easy cultivation, accessibility in tropical areas, rapid growth and higher cellulose levels. The surface roughness after alkali treatment enhances interfacial bonding, rendering it appropriate for load-bearing applications. In comparison to other fibers such as jute or hemp, it remains not fully utilised however illustrates superior mechanical properties following treatment (Mohanraj *et al*. 2023; Krishnudu *et al*. 2023). However, like most lignocellulosic fibers, *Abutilon indicum* fiber (CIF) inherently possesses drawbacks such as low interfacial compatibility with polymer matrices, poor wettability, and moderate thermal resistance. These disadvantages necessitate the development of effective strategies to enhance its interfacial interaction and overall composite performance (Ho *et al*. 2006).

To address these concerns, surface modification of natural fibers and the inclusion of nanoscale fillers into the matrix has proven to be effective. Among various nanofillers, organomodified montmorillonite (OMMT) nanoclay. Specifically, Cloisite 25A has garnered considerable attention (Merzah *et al*. 2022) . Cloisite 25A is a type of layered silicate modified with a quaternary ammonium compound, making it more compatible with hydrophobic polymers such as epoxy resins. Nanoclay has a high aspect ratio and extremely large surface area, enabling it to intercalate or exfoliate within the matrix, forming a well-dispersed nanostructure (Ahmad *et al*. 2024). This dispersion contributes to improved stress transfer, reduced crack propagation, increased barrier properties, and restricted polymer chain mobility. Consequently, the mechanical, thermal, and moisture resistance properties of the composite are significantly enhanced (Chowdhury *et al*. 2007).

The effectiveness of nanoclay in composite systems is largely dependent on its concentration and dispersion quality. At lower concentrations (typically between 1–3 wt.%), nanoclay tends to disperse uniformly, resulting in enhanced reinforcement and interfacial bonding (Tareq *et al*. 2019) . However, at higher loadings, nanoclay particles are prone to agglomeration due to Van der Waals forces, leading to micro defects, voids, and stress concentration points. This can adversely affect the mechanical integrity of the composite, highlighting the importance of optimising nanoclay content (Miyagawa *et al*. 2004).

Epoxy resin systems are frequently used in structural composites due to their excellent mechanical properties, chemical resistance, and low shrinkage. However, their inherent brittleness and poor impact resistance can be mitigated through the inclusion of flexible fillers and reinforcement agents (Ambekar *et al*. 2023). In the present study, a bio-based reinforcement strategy is proposed by incorporating alkali-treated *Abutilon indicum* fiber into an epoxy matrix, further modified with varying concentrations of Cloisite 25A nanoclay (Manickaraj *et al*. 2024).

Alkali treatment of natural fibers is a recognised method that improves surface roughness, eliminates non-cellulosic components (including hemicellulose, lignin, pectin, and waxes), and reveals additional cellulose, facilitating enhanced mechanical interlocking with the matrix (Alamri and Low, 2013). This treatment enhances adhesion between the fiber and matrix, leading to improved tensile and flexural properties. This study aims to investigate the combined effects of chemically treated *Abutilon indicum* fiber and Cloisite 25A nanoclay on the mechanical and structural properties of epoxy composites (Shelly *et al*. 2023). Nanoclay is introduced in incremental weight percentages of 0 wt.%, 1 wt.%, 2 wt.%, 3 wt.%, and 4 wt.% to determine the optimal concentration that maximises mechanical enhancement while avoiding agglomeration effects. The composite samples undergo mechanical characterisation, which includes tensile strength, flexural strength, impact resistance, and compressive strength, by relevant ASTM standards (N. V. Chithra *et al*. 2024). Scanning Electron Microscopy (SEM) is utilised to examine the morphology of fracture surfaces and to assess fiber/matrix interfacial bonding, fiber pull-out behaviour, void content, and the dispersion state of nanoclay (Chinnasamy *et al*. 2020).

This work presents a novel approach by utilising *Abutilon indicum* fiber, an unexplored natural fiber along with Cloisite 25A nanoclay within an epoxy matrix. This study investigates the synergistic effects of alkali-treated *Abutilon indicum* fiber combined with nanoclay reinforcement, showcasing enhancements in mechanical and morphological performance, in contrast to previous research that examined Cloisite 25A with other natural fibers such as coir, jute, or flax.

Through this multi-scale approach, the study aims to provide insights into the structure-property relationships in nanoclay-modified natural fiber nanocomposites. The results are expected to establish a pathway for developing cost-effective, sustainable, and high-performance

composite materials using underutilised natural fibers and nanomaterials (Withers *et al*. 2015). The successful optimisation of such bio-composites could open paths for their use in load-bearing applications, thereby supporting the transition toward greener material solutions in industries (Zabihi *et al*. 2018).

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 *Abutilon indicum* Fiber

Fibers from *Abutilon indicum* (Fig. 1(a), (b)) were manually extracted from the mature stems of this tropical vine, which is abundant in lignocellulosic material. The fibers underwent alkali treatment with a 5% sodium hydroxide (NaOH) solution for 4 hours to eliminate hemicellulose, lignin, waxes, and surface impurities (Ahmad *et al*. 2024). The treatment increased the surface roughness of the fiber, thereby enhancing mechanical interlocking with the epoxy matrix. Following chemical treatment, the fibers were extensively washed with distilled water until a neutral pH was attained. The fibers were subsequently dried in a hot air oven at 60°C for 24 hours to remove residual moisture, which could otherwise result in voids or weak bonding within the composite. The dried fibers were sectioned into uniform lengths of approximately 30 mm, appropriate for reinforcement purposes. This preprocessing enhances matrix dispersion and increases stress transfer efficiency during loading.

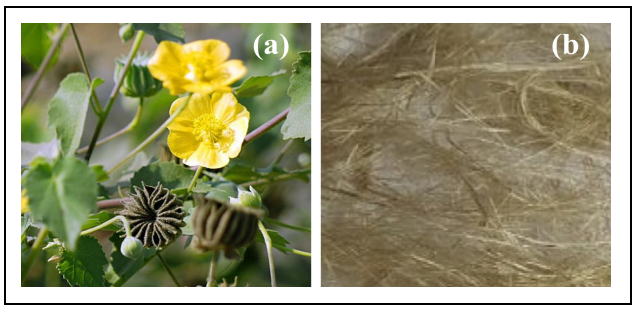


Fig. 1: (a) *Abutilon indicum* plant and (b) Extracted fiber

2.2 Matrix/Epoxy Resin System

The matrix system consisted of LY556 epoxy resin and HY951 hardener, used in a weight ratio of 10:1 as recommended by the supplier. LY556 is a bisphenol-A-based thermoset resin known for its excellent adhesion, dimensional stability, and chemical resistance. The hardener HY951, an aliphatic amine, promotes crosslinking by opening the epoxy rings, leading to a rigid and durable 3D polymer network. This matrix serves as the continuous phase, encapsulating both the fibers and the nanoclay particles (Zunjarrao *et al*. 2006). The role of the matrix is crucial in stress distribution and load transfer, as well as in protecting the fibers from environmental degradation. Proper mixing and degassing of the resin hardener mixture were performed to minimise voids and ensure a uniform cure.

2.3 Cloisite 25A Nanoclay

Cloisite 25A, commercial organomodified montmorillonite (OMMT) nanoclay, was selected as the nanofiller due to its compatibility with organic polymers like epoxy. Cloisite 25A nanoclay was selected due to its compatibility nature with epoxy matrix. Also, it has enhanced interfacial interaction resulting from its organo modification. In comparison to other MMT nanoclay, Cloisite 25A demonstrates superior dispersion in epoxy resins and has been confirmed to significantly improve mechanical properties (Senthil *et al*. 2015; 2018).

The structure of Cloisite 25A is shown in Fig. 2. It consists of montmorillonite (MMT) clay modified with a quaternary ammonium salt (Table 1), improving its dispersion within hydrophobic matrices (Aruchamy *et al*. 2024).

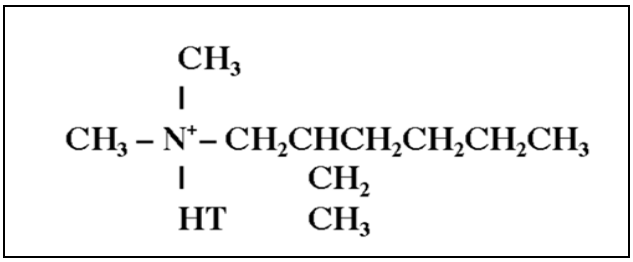


Fig. 2: Structure of Cloisite 25A nanoclay

Table 1. Properties of Cloisite 25A nanoclay

Organic Modifier	Modifier Concentration	% Moisture	% Weight Loss on Ignition	Density g/cc
2MHTL8 (dimethyl, dehydrogenated tallow, 2-ethylhexyl quaternary ammonium)	95 meq/100g clay	< 2%	34%	1.87

The nanoclay was added in varying weight percentages (0 wt.%, 1 wt.%, 2 wt.%, 3 wt.% and 4 wt.%) to study its effect on composite performance. The required amount of nanoclay was first mechanically stirred into the epoxy resin and then ultrasonicated for 30 minutes to aid

exfoliation and prevent agglomeration. Nanoclay improves interfacial bonding, enhances stiffness, reduces moisture permeability, and acts as a crack-arresting agent by creating a tortuous path. The even dispersion of nanoclay is essential to achieving optimal improvements in mechanical and thermal properties.

2.4 Composite Fabrication

Composites were produced through a hand layup technique and subsequently subjected to compression moulding. Nanoclay was dispersed in epoxy resin at varying weight percentages (0 wt.%, 1 wt.%, 2 wt.%, 3 wt.% and 4 wt.%) through mechanical stirring and ultrasonication to achieve uniform dispersion. The *Abutilon indicum* fibers, after treatment, were incorporated into the resin clay mixture, subsequently followed by the addition of the hardener (Gurusamy *et al*. 2024). The mixture was subsequently poured into a mould and subjected to constant pressure for compression. The matrix composition was regulated to maintain a consistent total mass of 200 grams for each formulation, as outlined in Table 2. All samples that were cut to 30 mm had a consistent 35% fiber content (Mohanraj *et al*. 2023). Previous studies that showed optimal reinforcement occurs within the range of 1-4 wt.%, before the beginning of agglomeration affects properties (Wong *et al*. 2021).

Table 2. Details of nanoclay modified matrix

Cloisite 25A (%)	Cloisite 25A (g)	Epoxy Resin (g)	Hardener (g)	Total Weight (g)
0	0	180	20	200
2	4	178.2	17.8	200
4	8	174.5	17.5	200
6	12	170.9	17.1	200
8	16	167.3	16.7	200
10	20	163.6	16.4	200

3. MATERIAL CHARACTERISATION DETAILS

3.1 Mechanical Testing

The mechanical properties of the fabricated composites were evaluated using standard ASTM procedures to ensure accuracy and reproducibility. Tensile testing was conducted following ASTM D638 standards utilising a universal testing machine (Fig. 3). Dumbbell-shaped specimens were fabricated, and the testing procedure was executed at a crosshead speed of 2 mm/min. The tensile strength is determined by dividing the maximum load by the cross-sectional area of the specimen. Flexural testing followed ASTM D790, using a three-point bending setup. Rectangular specimens were tested with a span-to-depth ratio of 16:1, and loading was applied at the midpoint until fracture. Flexural strength was computed from the maximum bending load using standard formulae. Charpy impact tests were carried out according to ASTM D256 to assess the energy absorption capacity under sudden loading. Notched specimens were used, and the impact strength was expressed in joules per meter. Compressive strength was measured using ASTM D695, where cylindrical or cuboidal specimens were compressed axially in a UTM. The maximum compressive load before deformation or failure was used to determine the compressive strength. Each mechanical test was conducted with at least five specimens per sample group, and average values were reported along with standard deviations to ensure reliability and repeatability.



Fig. 3: Computerised universal testing machine

3.2 Morphological Analysis (SEM)

Scanning Electron Microscopy (SEM) was performed on the fractured surfaces of the composites to analyse the fiber/matrix interface and the mechanisms of failure. The analysis offered insights into the dispersion characteristics of nanoclay and the quality of interfacial bonding. Gold sputter coating was utilized to enhance surface conductivity and image clarity. Treated fibers demonstrated enhanced adhesion with the epoxy matrix, while composites containing optimal nanoclay content exhibited more uniform dispersion and a reduction in structural defects. The observations corroborated the improved mechanical properties noted in the experimental results.

4. RESULTS AND DISCUSSION

4.1 Tensile Strength

Fig. 4 indicates the tensile strength of nanoclay-loaded epoxy natural fiber-reinforced nanocomposites. The results of tensile strength tests showed a significant enhancement with the addition of nanoclay at a concentration of up to 2 wt.%. The composite without nanoclay demonstrated a tensile strength of 39.63 MPa. The incorporation of 1 wt.% Cloisite 25A resulted in a tensile strength of 42.76 MPa, reflecting a 7.89% increase. The maximum tensile strength observed was 45.92 MPa with the addition of 2 wt.% nanoclay, indicating a 15.87% improvement. The enhancement observed can be linked to the increased interfacial adhesion between the treated *Abutilon indicum* fibers and the epoxy matrix, which is a result of improved load transfer enabled by the nanoclay. Well-dispersed nanoclay particles effectively fill microvoids, resulting in a more rigid matrix structure that enhances resistance to tensile stress.

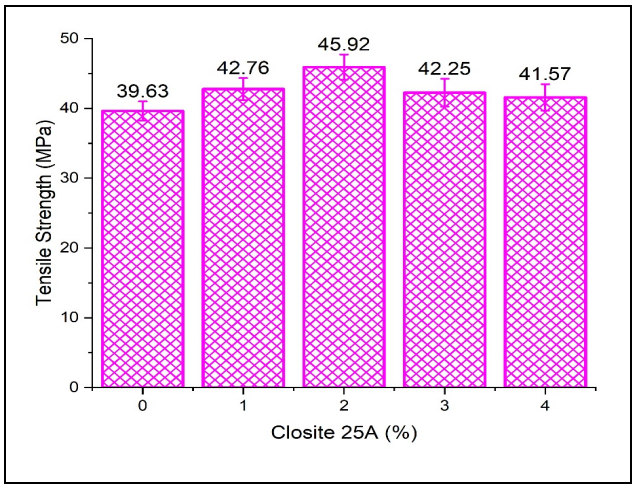


Fig.4: Tensile strength of nanoclay loaded composites

The platelet-like morphology of Cloisite 25A establishes a complex pathway for crack propagation, which enhances the resistance of composite to failure when subjected to tensile loading. The uniform dispersion of nanoclay results in stress delocalisation, thereby reducing localised deformation. At 2 wt.%, the equilibrium between nanoclay exfoliation and interfacial bonding is optimal, facilitating effective matrix stiffening while maintaining ductility. Exceeding a concentration of 2 wt.% nanoclay results in agglomeration driven by Vander Waals forces. This phenomenon leads to the formation of weak regions that serve as sites for crack initiation when subjected to load. This analysis elucidates the minor reduction in tensile strength noted at 3 wt.% and 4 wt.%, thereby supporting the conclusion that 2 wt.% nanoclay serves as the optimal reinforcement threshold for enhancing tensile performance within this system.

4.2 Flexural Strength

Fig. 5 indicates the flexural strength of nanoclay-loaded epoxy natural fiber-reinforced nanocomposites. Similar to the tensile behaviour, flexural strength also exhibited an increasing trend with nanoclay addition of up to 2 wt.%, followed by a mild reduction. The control specimen without nanoclay recorded a flexural strength of 62.29 MPa. The addition of 1 wt.% and wt. 2% nanoclay resulted in strengths of 65.82 MPa (5.67% gain) and 68.34 MPa (9.71% gain), respectively. These enhancements are due to the improved stiffness and rigidity of the matrix imparted by the well-dispersed nanoclay platelets, which act as barriers to deformation under bending loads. The increased surface interaction among fibers, matrix, and nanoclay helps delay crack initiation and propagation during bending.

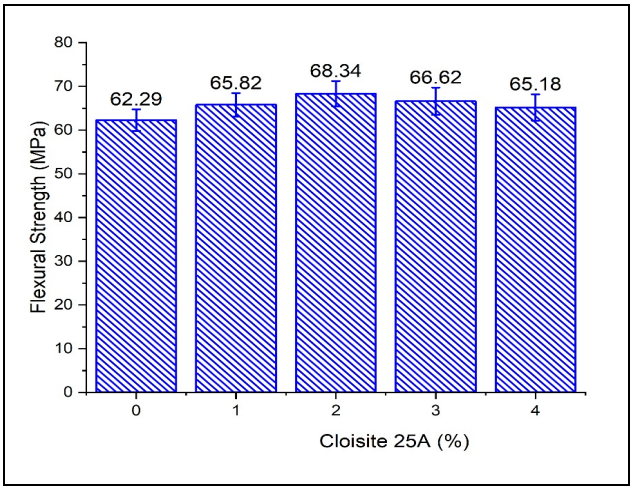


Fig. 5: Flexural strength of nanoclay loaded composites

Nanoclay particles create a reinforcing network that limits plastic deformation by increasing crosslinking density and restricting polymer chain mobility in the epoxy matrix. This stiffening effect is especially beneficial during flexural loading, where the outer surface experiences high tensile and compressive stresses. The fine dispersion of Cloisite 25A ensures uniform stress distribution across the cross-section, minimising stress concentrations. However, with 3 wt.% and 4 wt.% nanoclay, platelet agglomeration was likely, leading to the formation of stress-raising defects and slight declines in flexural strength. Therefore, a 2 wt.% nanoclay loading emerges as the most effective formulation, offering a synergistic balance between stiffness, ductility, and interfacial cohesion in flexural conditions.

4.3 Impact Strength

Fig. 6 indicates the impact strength of nanoclay-loaded epoxy natural fiber-reinforced nanocomposites. The impact strength of the fabricated composites demonstrated a consistent improvement with the incremental addition of Cloisite 25A nanoclay across the tested range of 0 to 4 wt.%. The unreinforced control composite exhibited an impact energy absorption of 0.51 J, indicating limited resistance to sudden or dynamic loading. Upon the inclusion of 1 wt.% nanoclay, the impact strength increased to 0.65 J, reflecting a 27.45% gain. The strength peaked at 0.85 J for the 2 wt.% nanoclay composites, corresponding to a 66.67% enhancement. This behaviour indicates that nanoclay serves as an effective energy-dissipating component within the composite matrix.

The improvement in impact resistance is attributed to the ability of nanoclay platelets to arrest and deflect propagating cracks through a combination of mechanisms, including crack tip blunting, interfacial friction, and matrix shear banding. The presence of well-dispersed nanoclay particles introduces tortuous pathways that absorb fracture energy and delay catastrophic failure. Additionally, the chemically treated *Abutilon indicum* fibers contribute to mechanisms like fiber pull-out, crack bridging and frictional sliding.

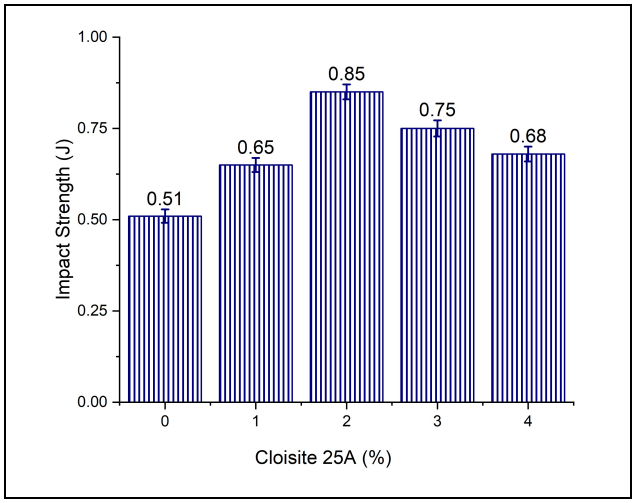


Fig. 6: Impact strength of nanoclay loaded composites

Interestingly, even at higher nanoclay contents of 3 wt.% and 4 wt.%, the impact strength remained relatively stable at 0.75 J and 0.68 J, respectively. Unlike tensile and flexural properties, which are sensitive to nanoclay agglomeration at higher loadings, the impact properties showed resilience, possibly due to increased matrix density and the formation of microcrack shielding zones around agglomerates. These findings indicate that the hybrid composite system maintains adequate dynamic toughness even at elevated nanoclay concentrations, making it suitable for applications subjected to sudden, cyclic, or impact loading conditions, such as in automotive interior panels, enclosures, or protective casings.

Overall, the integration of nanoclay enhances energy absorption by activating multi-scale fracture processes, and the composite retains favourable impact characteristics across all nanoclay levels tested, with optimal performance observed at 2 wt.%.

4.4 Compressive Strength

Fig. 7 indicates the compressive strength of nanoclay-loaded epoxy natural fiber-reinforced nanocomposites. The effect of nanoclay on the compressive strength of *Abutilon indicum* fiber-reinforced epoxy nanocomposites was particularly prominent, showing a consistent and significant increase with rising nanoclay content. The baseline compressive strength of the control composite (without nanoclay) was 47.24 MPa. With the incremental addition of 1 wt.%, 2 wt.%, 3 wt.% and 4 wt.% Cloisite 25A nanoclay, the compressive strength increased progressively to 52.87 MPa (11.92% gain), 66.25 MPa (40.24% gain), 72.94 MPa (54.40% gain) and 68.51 MPa (45.03% gain), respectively. These results indicate a nearly linear enhancement in load-bearing capacity under axial loading conditions.

This trend is largely attributed to the microstructural refinement caused by nanoclay addition, where exfoliated or intercalated nanoclay platelets occupy voids and interstitial spaces within the matrix and around the fiber surfaces. The nanoclay acts as a micro reinforcement, reducing resin shrinkage, impeding crack initiation, and increasing the modulus of elasticity of the matrix phase. Moreover, the rigid layered structure of Cloisite 25A offers resistance against compressive strains by limiting plastic deformation and restraining fiber micro buckling, which is a common failure mode under compression.

Unlike tensile and flexural properties, compressive strength appears to benefit more directly from nanoclay-induced densification, and the issue of agglomeration at higher filler contents does not adversely affect compressive performance. This is likely because compressive loads are more forgiving of local stress concentrations when the overall matrix stiffness and constraint against lateral movement are improved. Thus, for structural applications where compressive resistance is critical, such as load-bearing panels, brackets, or frames, a nanoclay loading of up to 4 wt.% is both effective and advantageous. Matrix stiffness is also an important

parameter in determining compressive strength. Higher stiffness and better packing help to achieve better load-carrying capacity under compressive load but decrease tensile as well as flexural properties by causing stress concentration. The comparison of mechanical properties of various nanocomposites is available in the Table 3.

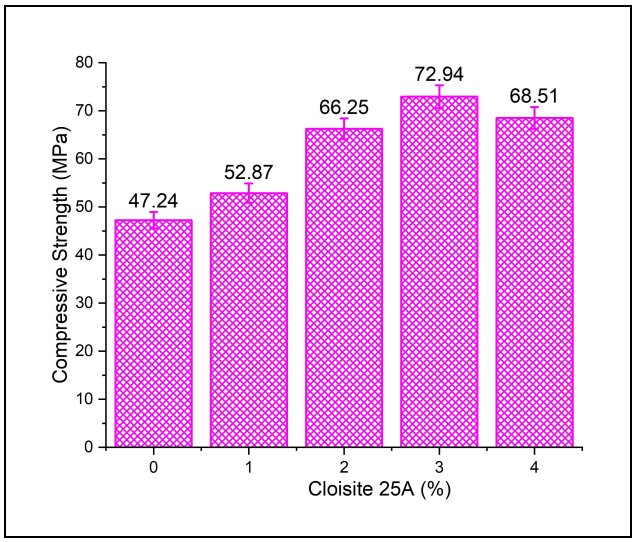


Fig. 7: Compression strength of nanoclay loaded composites

4.5 SEM Analysis

Scanning electron microscopy (SEM) was performed on the fracture surfaces of the tensile-tested specimens to examine the fiber/matrix interface, crack propagation, and nanoclay dispersion (Fig. 8). The control composite (0 wt.% nanoclay) displayed clear signs of fiber pull-out, large interfacial gaps, and smooth fiber surfaces indicative of weak adhesion between the untreated fiber and epoxy matrix. Matrix cracking and voids were also observed, which contributed to premature failure and lower mechanical strength. In contrast, the 1 wt.% and 2 wt.% nanoclay-modified nanocomposites exhibited significant improvements in interfacial adhesion. SEM micrographs showed rougher fiber surfaces embedded firmly in the matrix, with minimal gaps and reduced pull-out. The well-dispersed nanoclay platelets contributed to matrix densification, restricting crack growth and enhancing load transfer. The 2 wt.% nanoclay sample, which showed the highest tensile and flexural strength, also demonstrated uniform nanoclay dispersion and fewer voids, confirming the synergy between fiber treatment and nanoclay reinforcement. At higher loadings (3 wt.% and 4 wt.%), however, SEM images revealed localised agglomeration of nanoclay particles.

Table 3. Comparison of mechanical properties of various nanocomposites

Material	Properties	Values	Ref.
Kevlar/Cocos nucifera sheath/Graphene nanoplatelets/Epoxy	Tensile strength (MPa)	350-48	(Naveen *et al.* 2019)
	Tensile modulus (GPa)	7.9-4.8	
	Flexural strength (MPa)	251-52	
	Flexural modulus (GPa)	25-5.1	
	Impact strength (kJ/m^2)	120-8	
Poly(methyl methacrylate)/Reduced graphene oxide/Hematite nanoparticles	Tensile strength (MPa)	36.0–73.9	(Haq *et al.* 2020)
	Tensile modulus (GPa)	2.0 - 4.4	
Poly(ε-caprolactone)/Poly (lactic acid)/ Montmorillonite nanoclay	Tensile strength (MPa)	38.6	(Zhu *et al.* 2019)
	Tensile modulus (GPa)	1.18	
Kenaf/Epoxy/ Montmorillonite nanoclay	Tensile strength (MPa)	42.5-19.5	(Shen *et al.* 2018)
	Tensile modulus (GPa)	1.1-0.3	
Kenaf/Epoxy/ Montmorillonite nanoclay/ Hexamethylene Diisocyanate	Tensile strength (MPa)	47-24	
	Tensile modulus (GPa)	1.59-0.57	
Polyester/ hydroxyapatite nanowires	Tensile strength (MPa)	15-68	(Zuliahani *et al.* 2011)
	Tensile modulus (GPa)	0.73-1.47	
High density polyethylene/ Montmorillonite nanoclay/Rice husk	Tensile strength (MPa)	29.83-27.71	(Kord, 2011)
	Tensile modulus (GPa)	3.2-3.1	
	Impact strength (MPa)	17.82-16.89	
Polycarbonate/Boron nitride nanotubes	Tensile strength (MPa)	34.7-62.0	(Guan *et al.* 2019)
	Tensile modulus (GPa)	2.32-2.80	
Abutilon indicum Fiber/Epoxy /Montmorillonite nanoclay	Tensile strength (MPa)	45.92-41.57	Current Study
	Flexural strength (MPa)	68.34-65.18	
	Compressive strength (MPa)	72.94-52.87	
	Impact strength (J)	0.85-0.65	

These agglomerates acted as stress concentration sites, promoting microcrack initiation and interfacial debonding. At the same time, compressive strength continued to improve due to increased matrix rigidity and tensile and flexural performance plateaued or declined due to these defects. Overall, SEM analysis validated the

mechanical test results by highlighting the morphological changes brought about by nanoclay addition. Optimal nanoclay content (2 wt.%) provided a well-integrated microstructure with strong interfacial bonding, minimal defects, and enhanced energy dissipation mechanisms under mechanical loading.

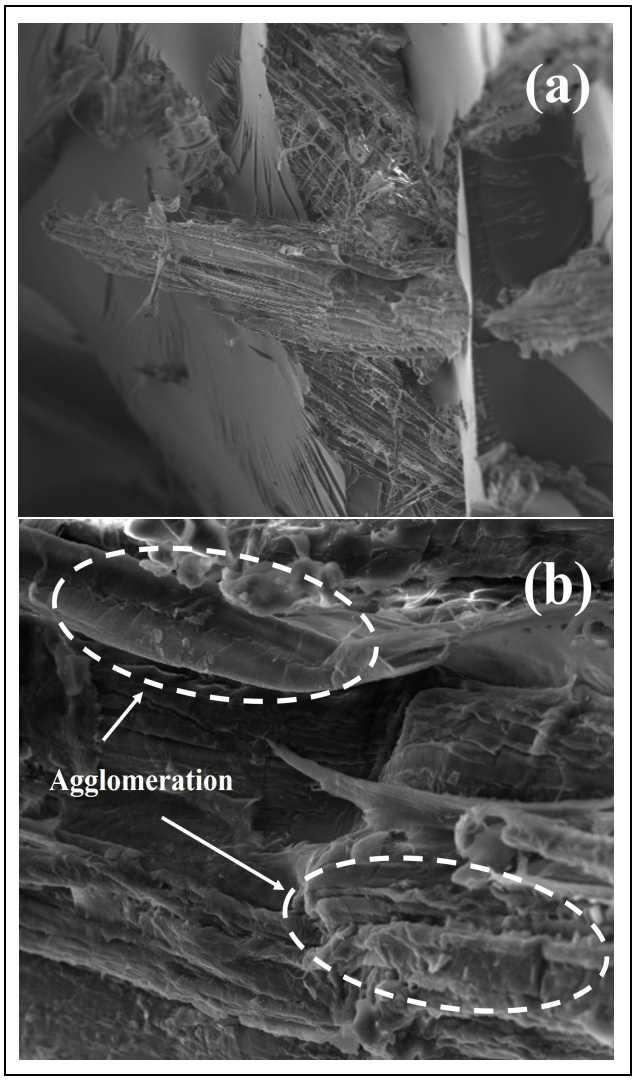


Fig. 8: SEM images of tensile fracture surfaces of nanoclay loaded composites, (a) 0 wt.% (b) 4 wt.%

5. CONCLUSION

The present research work investigated the influence of Cloisite 25A nanoclay on the mechanical and structural characteristics of epoxy nanocomposites reinforced with alkali-treated *Abutilon indicum* fibers. LY556 epoxy combined with HY951 hardener in a 10:1 ratio served as the matrix.

Fibers underwent treatment with 5% NaOH to enhance surface roughness and adhesion. The nanoclay content ranged from 0 to 4 wt.%. It was dispersed in the epoxy through mechanical stirring and ultrasonication to achieve uniform distribution before the moulding process. Mechanical testing indicated that the incorporation of nanoclay resulted in notable enhancements across all properties. At a concentration of 2 wt.% nanoclay, the nanocomposite demonstrated peak tensile strength of 45.92 MPa, an increase of 15.87%, flexural strength of 68.34 MPa, reflecting a 9.71% enhancement, and impact strength of 0.85 J, which corresponds to a 66.77% rise. The compressive strength exhibited a continuous increase with the addition of nanoclay, reaching a maximum at 3 wt.% (72.94 MPa), which corresponds to a 54.50% improvement compared to the control sample. The observed enhancements result from optimised load transfer at the fiber/matrix interface, along with the reinforcing influence of nanoclay particles that limited matrix mobility and postponed crack propagation.

The analysis of fractured specimens using SEM validated these findings. At 0 wt.% nanoclay, the micrographs indicated the presence of fiber pull-out, voids, and inadequate adhesion. At elevated nanoclay concentrations (4 wt.%), SEM images showed the presence of localised agglomeration of nanoclay platelets and microcracking. This phenomenon was associated with minor reductions in tensile and flexural strength, attributed to the formation of stress concentration zones. The optimal nanoclay content for maximizing mechanical performance while preserving microstructural integrity has been determined to be 2 wt.%. The combination of treated *Abutilon indicum* fiber and nanoclay within epoxy resin produces a hybrid nanocomposite characterized by enhanced mechanical properties, effective interfacial bonding, and optimized morphology. Sustainable composites present significant potential for lightweight structural applications across the automotive, construction, and packaging sectors, providing an environmentally friendly alternative to synthetic fiber reinforced materials.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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