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# Optimization of Mechanical Properties in *Nypa fruticans* Composite Boards with Varying Additive Loadings

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***Abstract*—The optimisation of mechanical properties in composite materials is essential for advancing sustainable material utilisation of non-wood fibres, which often exhibit inferior mechanical performance compared to conventional wood-based composite boards. This study investigates the influence of varying nano-titanium dioxide ($TiO_2$) loadings on the mechanical performance of *Nypa fruticans*-based composite boards. Epoxy resin was employed as the binding matrix, with nano-$TiO_2$ incorporated at loading levels of 0%, 1%, 3%, 5% and 7% by weight. Key mechanical properties were evaluated through modulus of rupture (MOR), modulus of elasticity (MOE), and tensile strength testing. The results revealed a pronounced effect of nano-$TiO_2$ incorporation on the composite's mechanical performance, with improvements observed up to an optimal loading of 3 wt%. Beyond this critical threshold, the reinforcing efficiency of the nanoparticle declined, primarily due to agglomeration. This phenomenon was substantiated by scanning electron microscopy (SEM), which confirmed the microstructural changes and non-uniform nanoparticle distribution at higher loadings. Overall, the optimised composite board containing 3 wt% nano-$TiO_2$ satisfied the ISO and ASTM standard requirements for both bending and tensile strength, demonstrating the viability of *N. fruticans* fibre as a sustainable alternative material for indoor application.**

***Keywords*—*Tensile strength, Agglomeration, Nipah, Nanoparticles, Sarawak.***

## I. INTRODUCTION

Epoxy-based composites are widely utilized across numerous industrial sectors due to their excellent mechanical strength [1] and chemical resistance [2]. These materials are commonly applied in automotive body panels, aerospace components, wind turbine blades, marine structures, sports equipment, and furniture manufacturing, where high performance and durability are critical. The mechanical performance of these composites is largely influenced by the type of reinforcing fibre used. Conventional reinforcement fibres include glass fibres, known for their high tensile strength and cost-effectiveness [3], carbon fibres, which offer superior stiffness and strength but at significantly higher cost [4] and natural fibres such as jute, flax, and hemp, which are biodegradable, lightweight, and derived from renewable sources [5]. Overall, natural fibres present a more sustainable alternative compared to synthetic counterparts.

Among the many types of natural fibres, *Nypa fruticans* (commonly known as the Nipah palm) presents a locally abundant and sustainable option, particularly in Southeast Asia, where it grows extensively in mangrove ecosystems. This species predominantly thrives in intertidal zones characterized by brackish, muddy waters, where it plays a pivotal ecological role in shoreline stabilisation, sediment retention, and biodiversity conservation [6]. Distinct from conventional palm species, *N. fruticans* lacks a conventional above-ground trunk. Instead, its fronds emerge directly from a rhizomatous root system, a morphological adaptation that enables resilience to fluctuating tidal conditions. Submerged fronds often develop spongy, buoyant tissues for floatation, while aerial fronds exhibit structural rigidity, facilitating mechanical stability in dynamic environments [7].

In the Sarawak River region of Malaysia, *N. fruticans* are locally referred to as *pokok apong*, is abundant and holds substantial cultural and economic significance. Its sap is traditionally harvested and processed into *gula apong*, a highly valued natural



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sweetener in regional cuisines. Furthermore, the young fronds are widely utilised in traditional handicrafts, thatching, food wrapping, and cigarette packaging industries. However, mature fronds, characterised by increased lignification, are typically regarded as agricultural waste and are often discarded through environmentally detrimental practices such as open burning or landfilling. These disposal methods contribute to air pollution and ecosystem disruption [8].

Sarawak's mangrove forests encompass approximately 90,000 hectares, providing a significant and underutilised resource base for *N. fruticans* biomass volarization. Although comprehensive population data remain limited, cultivated *N. fruticans* in tidal zones demonstrate favourable growth dynamics, with specimens attaining an average height of 1.78 meters within 16 months under optimal conditions [9, 10]. These attributes position *N. fruticans* as a promising sustainable feedstock for diverse industrial applications, particularly in the development of bio-composites and environmentally friendly materials.

Despite its ecological and cultural value, *N. fruticans* possesses relatively low mechanical properties compared to conventional reinforcement materials. Although there is no current study conducted that tests the strength of *N. fruticans* fibre, it is widely known that natural fibres typically exhibit lower mechanical strength and stiffness than synthetic fibres, due to their inherent biological structure and material composition. Unlike glass or carbon fibres, which are composed of homogenous and highly ordered crystalline or amorphous materials [11], natural fibres are composed of complex, heterogeneous assemblies of cellulose, hemicellulose, lignin, pectin, and waxes. The cellulose microfibrils in natural fibres are embedded within an amorphous matrix of lignin and hemicellulose, limits the alignment and crystallinity required for optimal tensile performance [12].

Furthermore, the presence of defects such as lumen voids, kink bands, and surface impurities in natural fibres contributes to stress concentration and early failure under load [13]. Natural fibres also exhibit hydrophilic behaviour due to hydroxyl groups in cellulose, which leads to moisture absorption, swelling, and a decline in interfacial adhesion with hydrophobic polymer matrices [14]. In contrast, glass and carbon fibres are chemically engineered for high uniformity, surface smoothness, and moisture resistance, resulting in superior tensile strengths.

Nevertheless, the inherent mechanical performance of natural fibres can be enhanced through strategic material modifications, including optimization of particle geometry (size and aspect ratio) [15], integration of natural reinforcements [16], refinement of processing parameters [8], and the incorporation of functional additives.

Recent advancements in nanotechnology have demonstrated the potential of nanoparticles as highly effective additives for improving composite properties. Various nanoparticles, including nano-silicon dioxide ($SiO_2$), nano-aluminium oxide ($Al_2O_3$), nano-zinc oxide (ZnO), and nano-calcium carbonate ($CaSiCO_3$), have been extensively explored for their reinforcing capabilities, owing to their distinctive chemical and physical properties. Nanoparticles exist in diverse forms, including metal oxides, synthetic polymers, micelles, and large biomolecular assemblies [17].

Numerous studies have highlighted the beneficial effects of nanoparticles on composite mechanical properties. For example, the addition of nano-$SiO_2$ and nano-copper (Cu) to urea-formaldehyde (UF) resins has been reported to enhance screw withdrawal resistance and surface hardness. These improvements are attributed to superior heat transfer during the curing process and the formation of additional interfacial bonds within the matrix [18]. Similarly, nano-ZnO has been shown to significantly improve both the modulus of elasticity (MOE) and modulus of rupture (MOR), particularly in wet conditions, due to its ability to facilitate more uniform temperature distribution during hot pressing [16, 19].

Titanium dioxide ($TiO_2$) nanoparticles offer several advantageous properties as additives in composite board production, especially in non-wood fibre applications. Despite their potential, nano-$TiO_2$ remains relatively underexplored within this context. Previous studies have demonstrated that nano-$TiO_2$ can enhance mechanical properties such as compressive, tensile and flexural strength, primarily through its strong interfacial interaction with polymer matrices. This interaction improves stress transfer across the matrix-filler interface, thereby increasing the load-bearing capacity and reducing wear and deformation rates under mechanical stress [20 - 22]. Additionally, nano-$TiO_2$ improves composite board durability by enhancing resistance to chemical degradation, thermal fluctuations, and abrasion. These functional advantages are ascribed to its nanoscale dimensions, large surface area, and high chemical stability under varying environmental conditions [23, 24].

In composite manufacturing, the incorporation of additive is typically limited to concentrations below 5 wt%, as higher loadings can lead to undesirable effects. While low concentrations of nanoparticles are effective in enhancing tensile, flexural, impact strength [25, 26], excessive additive content often promotes nanoparticle agglomeration. This phenomenon results in stress concentration points and compromises the mechanical integrity within the composite structure [27].

Accordingly, this study aims to investigate the optimal loading of nano-$TiO_2$ for enhancing the mechanical properties of *N. fruticans*-based composite boards. Mechanical characterisation focused on evaluating key performance metrics, including MOR, MOE, and tensile strength. Morphological analysis was conducted using a scanning electron microscope

(SEM) to assess the dispersion and integration of nano-$TiO_2$ within the composite matrix, thereby providing structural insights that corroborate the mechanical performance outcomes. This research seeks to optimise composite board fabrication using underutilised biomass resources, contributing to the growing body of knowledge on nanoparticle-enhanced composites, particularly in the context of sustainable non-wood fibre applications.

## II. METHODOLOGY

### *A. Material*

The composite board in this study was fabricated using three primary components: epoxy resin as the polymer matrix, *N. fruticans* particles as the reinforcing filler, and nano-$TiO_2$ as the inorganic additives. The *N. fruticans* were sourced from Kampung Saai, Daro, Sarawak. The epoxy resin, procured from a local supplier, was utilised in its as-received condition without any further purification or modification. Nano-$TiO_2$ powder, with an average primary particle size of 21 nm, was obtained from Sigma-Aldrich Co., ensuring high purity and consistent quality suitable for composite applications.

### *B. Composite Board Fabrication*

The fabrication process involved blending *N. fruticans* particles (80 wt%) with an aqueous epoxy resin solution (20 wt%). The resin-to-hardener ratio was maintained at 3:1 by weight to facilitate optimal curing kinetics. Nano-$TiO_2$ was incorporated into the mixture at varying loadings of 0%, 1%, 3%, 5% and 7% by weight relative to the total composite mass. The blended mixture was subjected to continuous mechanical stirring for 10 minutes to promote homogenous dispersion of both *N. fruticans* particles and nano-$TiO_2$ within the resin matrix.

The target density for the composite board was designed at 1000 g/m³ to ensure structural consistency and facilitate performance comparisons. The prepared mixture was evenly distributed into a steel mould with internal dimensions of 320 × 320 × 5 mm. To aid in demoulding and prevent surface defects, a releasing agent was applied, and baking paper was placed within the mould. Hot pressing was conducted at a pressure of 10 MPa for 8 minutes at 120 ºC to achieve effective consolidation and curing of the material.

Following the hot-pressing process, the composite boards were demoulded and subsequently cut into standardised test specimens in accordance with the Japanese Industrial Standards (JIS) and American Society for Testing and Materials (ASTM).

### *C. Mechanical Testing of Composite Board*

The mechanical performance of the fabricated composite boards was evaluated through a series of standardised tests to determine their structural integrity and suitability for practical applications. The bending strength properties, specifically the MOR and MOE, were assessed following the guidelines stipulated in JIS A 5908:2003. The bending test configuration is illustrated in Fig. 1.

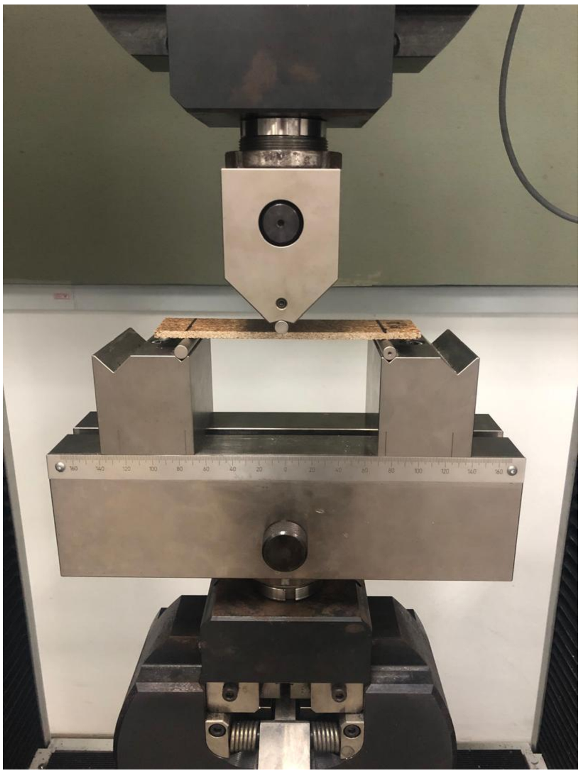

Fig. 1. The bending test setup.

In addition, tensile property evaluations were performed in accordance with ASTM D1037 standards to ensure methodological consistency and accuracy. Post-testing analysis of fractured samples provided insights into the failure mechanisms, as shown in Fig. 2. All mechanical tests were carried out using an Inspekt 300-1 universal testing machine, ensuring precise load application and data acquisition.

Fig. 2. The fractured tensile test sample.

### *D. Morphology Analysis*

To elucidate the microstructural characteristics and dispersion behaviour of nano-$TiO_2$ within the composite matrix, SEM analysis was conducted using a JEOL 6000 system. Small specimens (10 mm x 10 mm x 5 mm) were sectioned from the tensile test samples. Prior to imaging, the specimens were oven-dried at 105ºC to remove residual moisture and stored in contamination-free conditions.

To enhance electrical conductivity and image clarity, the samples were sputter-coated with a thin gold layer approximately 20 nm thick. High-resolution SEM micrographs were captured from multiple viewing angles, with the most representative images selected for detailed examination and discussion.

## III. RESULTS AND DISCUSSION

### A. *Mechanical Properties of N. fruticans Composite Boards*

Figure 3 illustrates the variation in MOR of *N. fruticans*-based composite boards as a function of different nano-$TiO_2$ loading levels (0%, 1%, 3%, 5%, and 7% by weight). A progressive enhancement in MOR was observed with increasing nano-$TiO_2$ content up to 3 wt%, beyond which the mechanical performance exhibited a declining trend.

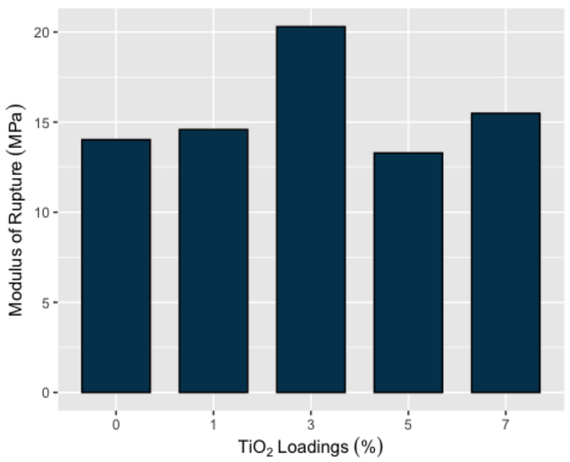


Fig. 3. MOR of *N. fruticans* composite board at different nano-$TiO_2$ loading.

The initial improvement in MOR is attributed to the effective dispersion of nano-$TiO_2$ particles within the epoxy matrix, which facilitates enhanced interfacial bonding between *N. fruticans* particles and the resin. The well-dispersed nano-$TiO_2$ acts as stress transfer bridges, enabling better load distribution across the matrix and improving the flexural strength of the composite.

Yalçin [28] demonstrated that $TiO_2$ nanoparticles enhance the bonding strength between particles and UF adhesive by increasing surface area and promoting better dispersion within the adhesive matrix. This mechanism results in a more homogeneous stress distribution and strengthens the load-bearing capacity of composite board. Additionally, nano-$TiO_2$ contributes to structural integrity by filling voids and reducing defects, thereby resulting in a denser and more cohesive structure [29].

However, when the nano-$TiO_2$ loading exceeded 3 wt%, MOR values declined. This reduction is primarily due to the agglomeration of $TiO_2$ nanoparticles at higher concentrations, leading to the formation of stress concentration sites and microstructural defects [28, 30]. Agglomerated nanoparticles act as weak points, interrupting stress transfer and reducing mechanical performance. Furthermore, an excessive concentration of rigid nanoparticles may increase the brittleness of the composite, which decreases its flexibility and promotes crack initiation under stress [28].

The optimal MOR was recorded at 3 wt% nano-$TiO_2$ loading, achieving a maximum value of 20.3 MPa which is a 45% enhancement over the unreinforced sample. This value surpassed the minimum MOR requirement of 18 MPa specified in JIS A 5908:2003, demonstrating the structural suitability of the composite for practical applications.

Analysis of variance (ANOVA) confirmed that nano-$TiO_2$ loading had a significant effect on MOR ($p \leq 0.05$) as shown in Table I. Further analysis using Tukey's post-hoc test identified significant differences between the MOR of the 3 wt% nano-$TiO_2$-reinforced samples and both the control and 5 wt% samples, supporting the observed performance trend.

Table I. Two-way ANOVA results of the mechanical properties of the *N. fruticans* composite board at different nano-$TiO_2$ loading.

| | ***MOR*** | ***MOE*** | ***Tensile strength*** |
|---|---|---|---|
| Nano-$TiO_2$ loading | 0.050* | 0.5698 | 0.090 |

Note: *significant at 0.05

Figure 4 illustrates the variation in the MOE of *N. fruticans*-based composite boards as a function of nano-$TiO_2$ loading levels (0%, 1%, 3%, 5%, and 7% by weight). The results exhibit a distinct trend: MOE increases progressively with nano-$TiO_2$ addition up to an optimum level of 3 wt%, beyond which a gradual decline is observed at higher loading levels.

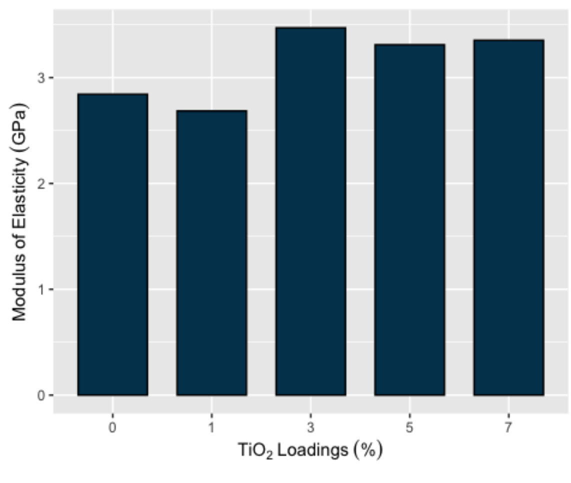


Fig. 4. MOE of *N. fruticans* composite board at different nano-$TiO_2$ loading.

The initial enhancement in MOE from 0% to 3 wt% nano-$TiO_2$ is primarily attributed to the homogenous dispersion of $TiO_2$ nanoparticles within the epoxy matrix. The nano-$TiO_2$ particles, characterised by a high surface area and excellent intrinsic mechanical properties, facilitate efficient stress transfer between the *N. fruticans* particles and the matrix [31]. This results in improved interfacial adhesion, leading to a denser and more rigid composite structure capable of sustaining greater elastic deformation under applied load.

Conversely, further increases in nano-$TiO_2$ content beyond 3 wt% resulted in a marked reduction in MOE. This reduction is ascribed to nanoparticles agglomeration at higher loadings, which promotes the formation of stress concentration zones and micro-defects within the matrix. These agglomerates hinder effective stress distribution and compromise the structural integrity of the composite, increasing its vulnerability to microcracking under elastic loading. Moreover, excessive nanoparticle content may induce phase separation and heterogeneity, further deteriorating the stiffness of the composite [32].

Overall, the incorporation of nano-$TiO_2$ up to 3 wt% was found to significantly enhance the MOE of *N. fruticans*-based composite boards, with the maximum MOE recorded at 3 wt%, representing an improvement of approximately 22% over the unreinforced control sample. These findings align with the study by Lei *et al.* [33], who reported that a 3% addition of nano-$SiO_2$ improved both MOE and MOR in gypsum particleboards. Similarly, the current study demonstrates that 3% nano-$TiO_2$ serves as the optimal loading level to improve the MOE of *N. fruticans* composite board.

Furthermore, according to the JIS A 5908:2003, the minimum MOE requirement is 2.00 GPa. All composite boards produced in this study, regardless of $TiO_2$ loading, satisfied this criterion, indicating their suitability for indoor application.

However, ANOVA analysis (Table I) revealed no statistically significant differences ($p > 0.05$) in MOE values among the different nano-$TiO_2$ loading levels. This suggests that despite observable variations in MOE, all reinforced and unreinforced *N. fruticans* composite boards exhibited comparable structural performance within the acceptable standard range.

Figure 5 illustrates the variation in tensile strength of *N. fruticans*-based composite boards as a function of nano-$TiO_2$ loading levels (0%, 1%, 3%, 5%, and 7% by weight). The tensile strength displayed a non-linear response to increasing nano-$TiO_2$ content, with a marked improvement at lower concentrations, peaking at 3 wt%, followed by a gradual reduction at higher loadings (5 wt% and 7 wt%).

Despite these variations, all boards produced in this study satisfied the minimum tensile strength requirement for high-density composite board, as stipulated by ASTM 1037, which mandates a minimum tensile strength of 0.50 MPa.

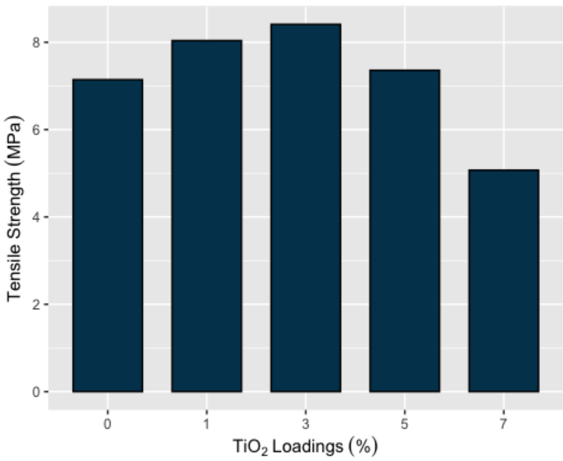


Fig. 5. Tensile strength of *N. fruticans* composite board at different nano$TiO_2$ loading.

The enhancement in tensile strength observed up to 3 wt% nano-$TiO_2$ can be attributed to the effective dispersion of nanoparticles within the epoxy matrix. The well-dispersed $TiO_2$ nanoparticles fill micro-voids and reduce defects, promoting a denser, compact composite structure with enhanced load-bearing capacity [34]. The nanoparticles act as reinforcement agents, improving stress transfer efficiency across the matrix and the *N. fruticans* particles.

However, beyond the optimal loading of 3 wt%, a notable decrease in tensile strength was observed. This reduction is primarily ascribed to nanoparticle agglomeration at higher concentrations. As nano-$TiO_2$ loading exceeds the critical threshold, the particles tend to cluster due to high surface energy, leading to a reduction in the available specific surface area for matrix bonding [35]. This agglomeration results in weaker interfacial adhesion and poor stress transfer, thus undermining the mechanical integrity of the composite.

These findings align with previous research by Ashraf *et al.* [36], Raichman *et al.* [37], and Zare *et al.* [38], who reported that excessive nanoparticle loading reduces the specific effective volume fraction and specific surface area critical for strong interfacial binding. When nanoparticles aggregate, they behave similarly to larger particles, contributing minimally to reinforcement and stress concentration zones that facilitate microcrack initiation and propagation.

Furthermore, ANOVA analysis (Table I) indicated no statistically significant difference in tensile strength across the various nano-$TiO_2$ loadings. This suggests that, despite observable trends in tensile performance, all reinforced and unreinforced *N. fruticans*-based composite boards exhibited comparable tensile strength values within the acceptable range specified by the ASTM D1037 standard.

Due to the statistically insignificant findings for MOE and tensile strength across different $TiO_2$ loading levels, additional analysis was conducted using 95% confidence intervals (CI). This approach is important because it provides a clearer picture of the precision and reliability of the mean estimates, even when p-values do not indicate statistical significance. CI allows the visualisation of overlapping or distinct trends between groups and can highlight practically meaningful differences that may not reach significance due to sample size limitations or natural variability in composite boards.

Figures. 6 and 7 show the CI for MOE and tensile strength of *N. fruticans*-based composite boards as a function of nano-$TiO_2$ loading levels (0%, 1%, 3%, 5%, and 7% by weight).

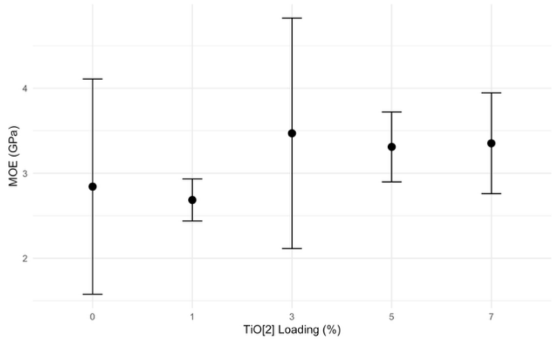


Fig. 6. CI of MOE for *N. fruticans* composite board at different nano$TiO_2$ loading.

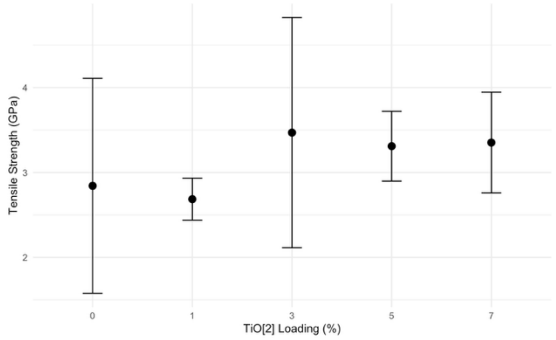


Fig. 7. CI of tensile strength for *N. fruticans* composite board at different nano$TiO_2$ loading.

As visualised in Figs. 6 and 7, the plotted 95% confidence intervals for both MOE and tensile strength demonstrate a clear peak in performance at 3 wt% $TiO_2$ loading. The narrower confidence bands at this level suggest greater measurement consistency and reduced variability, indicating a more stable mechanical response. While some overlap exists between groups, the overall directional trend and central tendency strongly support a mechanical enhancement at this concentration. These statistical observations will be further validated by the morphological analysis.

*B. Morphology Analysis of N. fruticans Composite Board*

Figures 8 to 12 present SEM images of *N. fruticans*-based composite boards with varying nano-$TiO_2$ loadings, offering critical insights into the morphological characteristics and their correlation with the mechanical performance of the composites.

The SEM micrographs of unreinforced *N. fructicans* composite board (Fig. 8) reveal the presence of discernible voids and microcavities within the composite matrix. These structural defects act as stress concentration sites and are likely responsible for the relatively lower mechanical properties observed in the unreinforced composite, particularly in terms of MOR, MOE, and tensile strength. The occurrence of these voids suggests that while the adhesive effectively coats the fibres, it alone is insufficient to significantly improve the load-bearing capacity of the composite in the absence of reinforcement.

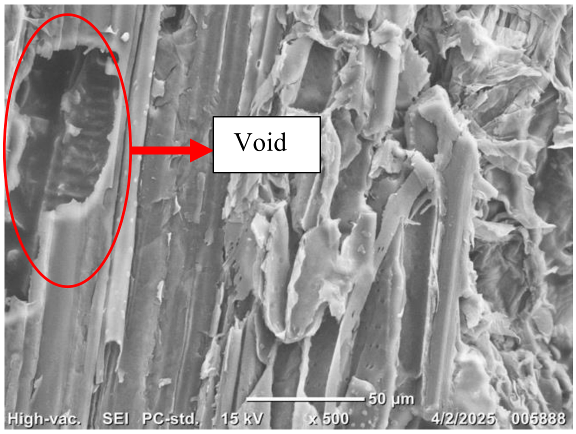


Fig. 8. SEM image of unreinforced *N. fruticans* composite board.

The SEM micrographs of the *N. fruticans* composite board reinforced with 1 wt% nano-$TiO_2$ (Fig. 9) highlight the presence of $TiO_2$ nanoparticles. However, their distribution within the epoxy matrix appears suboptimal. Rather than achieving uniform dispersion, the nanoparticles predominantly localise on the resin surface, displaying limited interfacial interaction with the surrounding matrix. This morphological observation suggests that the nanoparticles function more as discrete foreign inclusions rather than as integral components of the load-bearing structure.

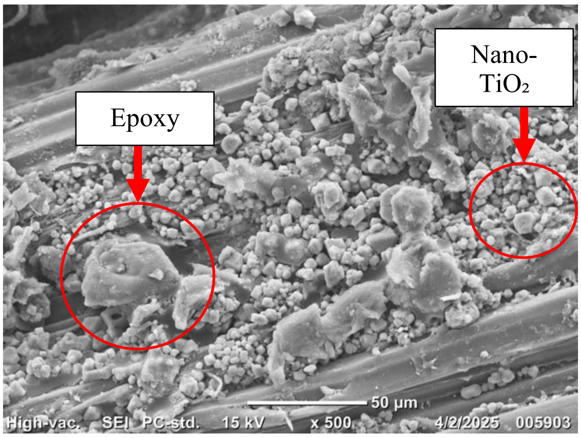


Fig. 9. SEM image of *N. fruticans* composite board reinforced with 1% nano-$TiO_2$.

The insufficient nanoparticle-matrix integration at this loading level is likely a contributing factor to the reduction in mechanical properties observed at 1 wt% nano-$TiO_2$, as reported in the preceding mechanical analysis. In particular, the failure of nano-$TiO_2$ to disperse homogeneously and establish interfacial bonding restricts its capacity to transfer stress effectively, thereby compromising the reinforcing potential of the composite.

The SEM micrographs of the *N. fruticans* composite board reinforced with 3 wt% nano-$TiO_2$ (Fig. 10) reveal a markedly enhanced dispersion of nanoparticles within the epoxy matrix. In contrast to the lower nanoparticle loading, the $TiO_2$ nanoparticles at concentration are well integrated into the matrix, effectively filling micro-voids and contributing to a denser and more homogeneous composite microstructure.

This uniform distribution is indicative of improved nanoparticle-matrix compatibility, facilitating better interfacial adhesion and more efficient stress transfer mechanisms under mechanical loading. The ability of the well-dispersed nano-$TiO_2$ to bridge microstructural defects and reinforce the resin-fibre interface is likely responsible for the substantial enhancement in mechanical properties observed at this loading level.

Specifically, the superior MOR, MOE, and tensile strength recorded for the 3 wt% nano-$TiO_2$ composite reflect an optimal balance between strength and flexibility. Notably, the MOR exhibited an impressive 45% increase relative to the unreinforced board, underscoring the effectiveness of the nano-$TiO_2$ in reinforcing the composite at this concentration. These findings are consistent with the established role of nanoparticles in improving load-bearing capacity through void-filling, crack-bridging, and stress distribution mechanisms when appropriate dispersion and interfacial bonding are achieved.

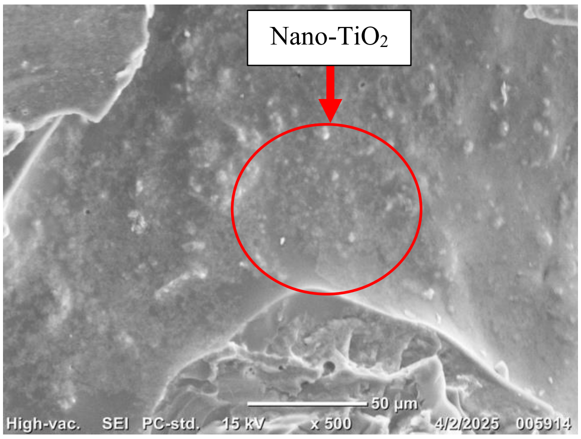


Fig. 10. SEM image of *N. fruticans* composite board reinforced with 3% nano-$TiO_2$.

The SEM micrograph of the *N. fruticans* composite board reinforced with 5 wt% nano-$TiO_2$ (Fig. 11) reveals pronounced nanoparticle agglomeration, signifying a critical threshold beyond which effective nanoparticle dispersion within the epoxy matrix is compromised. At this loading level, the $TiO_2$ nanoparticles exhibit a strong tendency to cluster, forming large aggregates rather than distributing uniformly throughout the matrix.

These agglomerates not only fail to occupy micro-voids but also introduce new structural discontinuities, acting as stress concentrators and potential crack initiation sites. Such morphological defects severely hinder the efficiency of stress transfer between the matrix and reinforcement phases, thereby reducing the overall structural integrity and cohesion of the composite board.

Consequently, the mechanical performance of the 5 wt% nano-$TiO_2$-reinforced composite board, particularly the MOR and tensile strength, deteriorates relative to the optimal 3 wt% formulation. This observed decline is consistent with prior studies by Liu and Yalçin [29], which have reported that excessive nanoparticle loading beyond the dispersion limit often leads to agglomeration-induced weakening. These findings highlight the critical importance of maintaining optimal nanoparticle dispersion to maximise reinforcement efficiency in polymeric composite systems.

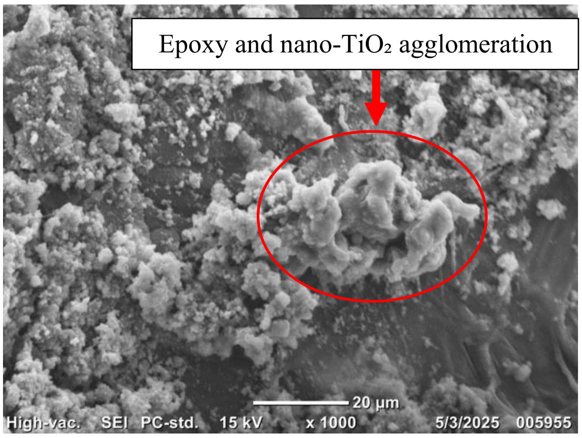


Fig. 11. SEM image of *N. fruticans* composite board reinforced with 5% nano-$TiO_2$.

The SEM micrograph of the N. fruticans composite board reinforced with 7 wt% nano-$TiO_2$ (Fig. 12) demonstrates a marginal improvement in nanoparticle dispersion relative to the 5 wt% formulation. In this sample, the $TiO_2$ nanoparticles exhibit a moderately enhanced distribution within the epoxy matrix, suggesting that higher shear forces during processing or increased particle-matrix interactions may have facilitated a more uniform integration compared to the lower dispersion quality observed at 5 wt%.

This improved dispersion likely contributes to the moderate recovery of mechanical performance, with the 7 wt% nano-$TiO_2$-reinforced composite board exhibiting higher MOR and tensile strength values than its 5 wt% counterpart. Nevertheless, the overall mechanical properties remain inferior to those of the 3 wt% $TiO_2$-reinforced composite, reaffirming that optimal reinforcement is achieved within a limited nanoparticle loading range.

Despite the partial improvement in particle-matrix interaction at 7 wt%, the presence of localised agglomerates persists, potentially leading to stress concentration sites and increased brittleness. This observation underscores the well-documented phenomenon wherein excessive nanoparticle loading, beyond the percolation threshold, induces diminishing returns in mechanical enhancement due to particle clustering and suboptimal stress transfer.

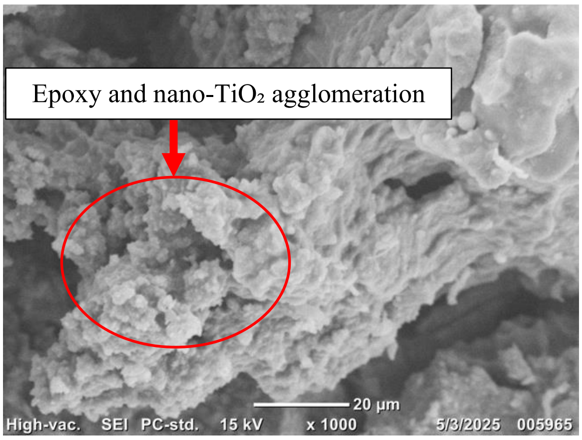


Fig. 12. SEM image of *N. fruticans* composite board reinforced with 7% nano-$TiO_2$.

### C. Environmental Considerations

While the incorporation of nano-$TiO_2$ offers tangible enhancements in the mechanical performance of bio-composite materials, its environmental implications warrant careful consideration. Nano-$TiO_2$, due to their nanoscale size and high surface reactivity, pose potential ecological risks including toxicity to aquatic organisms, persistence in soil and water systems, and uncertainties surrounding end-of-life degradation or recyclability of nano-enabled products [39]. These risks are exacerbated when nanoparticles are released during manufacturing, use, or disposal, potentially accumulating in ecosystems with long-term effects that are not yet fully understood.

However, the environmental impact of nano-$TiO_2$ must be weighed against the significant sustainability benefits conferred by the use of *N. fruticans* fibres, which are locally abundant, biodegradable, and typically considered agricultural waste. By valorising this underutilised biomass, the composite system reduces reliance on energy-intensive synthetic fibres and diverts waste from environmentally harmful disposal practices such as open burning or landfilling. Therefore, future research should focus on developing safer-by-design nano formulations and establishing clear guidelines for the lifecycle assessment of nanoparticle-reinforced composite boards.

## IV. CONCLUSION

Bending and tensile strength are fundamental performance parameters for composite boards fabricated from renewable biomaterials, as they directly govern structural integrity and suitability for diverse engineering applications. The incorporation of nanotechnology into composite systems offers promising avenues for enhancing these mechanical attributes, particularly through the strategic use of nanomaterial reinforcement. Accordingly, this study sought to develop an innovative *N. fruticans*-based composite board with improved mechanical performance via nano-$TiO_2$ reinforcement across varying loading levels.

The experimental findings of this research unequivocally demonstrate that nano-reinforcement exerts a profound influence on the mechanical behaviour of *N. fruticans* composite boards. Among the evaluated formulations, the composite board reinforced with 3 wt% nano-$TiO_2$ emerged as the most effective, fulfilling the minimum MOR requirement stipulated by ISO standards. In contrast, while all $TiO_2$-reinforced formulations satisfied the ISO and ASTM minimum thresholds for MOE and tensile strength, only the 3 wt% formulation simultaneously met the stringent MOR criterion. These mechanical enhancements were corroborated by SEM microstructural analyses, which revealed that the 3 wt% $TiO_2$ loading facilitated optimal nanoparticle dispersion and interfacial bonding within the epoxy matrix which are key factors contributing to the improved load transfer efficiency and structural cohesion of the composite board.

Importantly, the results of this study are consistent with the widely recognised principle that the mechanical reinforcement efficacy of nanoparticles in polymeric composites is maximised within a limited concentration window, typically below 5 wt%. Excessive nanoparticle incorporation often induces agglomeration, leading to the formation of microstructural defects that compromise stress transfer pathways and reduce mechanical performance. This phenomenon was evident in the current study, where $TiO_2$ loadings beyond 3 wt% resulted in diminished MOR values due to particle clustering and increased material brittleness. Conversely, at lower loadings (1 wt%), inadequate nanoparticle dispersion and weak interfacial bonding limited the reinforcing contribution of $TiO_2$ to the composite matrix.

In conclusion, this study establishes 3 wt% nano-$TiO_2$ as the optimal reinforcement concentration for *N. fruticans*-based composite boards, effectively meeting the ISO and ASTM standards for both physical and mechanical properties. To maximise the benefits of nano reinforcement while mitigating the deleterious effects associated with nanoparticle agglomeration, it is recommended that TiO2 loading in such composite systems does not exceed 3 wt%. These findings reinforce industry best practices advocating for nanoparticle incorporation below 5 wt% in composite boards applications. Furthermore, the study underscores the viability of *N. fruticans* as a sustainable and alternative raw material for engineered wood products, contributing to the advancement of environmentally friendly and high-performance composites boards for non-structural applications.

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