



Influence Of Non-Mercerized Banana Fibers Architectures On Mechanical Properties Of Pva Composites For Lightweight Structural Biodegradable Applications

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ABSTRACT : Natural fibre composites are gaining attention as eco-friendly alternatives to synthetic materials, yet challenges such as inconsistent mechanical strength and high moisture absorption limit their broader application. This study investigates the influence of non-mercerized banana fibers architectures on mechanical properties of PVA composites for lightweight structural biodegradable applications, focusing on woven (plain and twill) and nonwoven (mat and multidirectional) fibre configurations. Banana fibers were mechanically extracted, processed, and fabricated into composite boards using PVA as the matrix. Standard tests, tensile, flexural, impact, compressive strength, and microstructural analyses, including SEM, FTIR, EDX, and XRD, were conducted. Results showed that plain weave composites had the highest tensile (20.03 N/mm²) and flexural (42.52 N/mm²) strengths, while nonwoven composites exhibited superior impact resistance (1.3 J). All composites displayed high water absorption due to the amorphous nature of the fibres, confirmed by FTIR and XRD, indicating limited durability in humid environments. SEM revealed surface irregularities that may hinder fibre–matrix bonding, and EDX highlighted a high silicon content, potentially due to soil contamination. This study highlights the viability of banana fibre composites for indoor applications and biodegradable packaging, while recommending surface treatments to improve water resistance. These findings have practical, environmental, and policy implications for advancing natural fibre materials in sustainable development.

KEYWORDS: Banana fibre, PVA composites, Fiber architecture, Mechanical properties, Impact strength, Biodegradable Materials.

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I. INTRODUCTION

1. Introduction

Natural fibre-reinforced composites have emerged as sustainable alternatives to conventional synthetic materials in applications such as construction, automotive components, and packaging (Okoronkwo et al. 2025). Among these, banana fibre offers notable advantages due to its renewability, biodegradability, and mechanical potential. In Ghana, banana cultivation generates a substantial volume of pseudo-stem waste, yet this resource remains underutilized. Leveraging banana fibre as a reinforcement material not only supports environmental sustainability but also presents economic opportunities through value-added applications (Okoronkwo et al. 2019). Banana fibres, extracted from the pseudo-stems of banana plants, possess desirable mechanical characteristics that make them suitable for use in polymer composites. When combined with polyvinyl alcohol (PVA), a biodegradable matrix with excellent film-forming properties, water solubility, and biocompatibility, the result is an eco-friendly composite material. The integration of banana fiber into PVA matrices has been explored for diverse applications, including automotive components, construction materials, furniture, and biodegradable packaging, (Okoronkwo et al. 2022), (Okoronkwo et al. 2021), (Madu et al. 2019), (Madu et al. 2020) and (Ezeokpube et al. 2021)).

A critical factor influencing the mechanical performance of natural fibre composites is the fibre architecture (Okoronkwo et al. 2024). Woven and non-woven reinforcement structures exhibit distinct mechanical behaviors. Woven fabrics, composed of interlaced warp and weft yarns, typically provide higher mechanical stability, improved load distribution, and better dimensional integrity ((Okoronkwo et al. 2025), (Okoronkwo et al. 2024), (Okoronkwo et al. 2022)). In contrast, non-woven fabrics, with randomly oriented fibers bonded chemically or mechanically, offer advantages such as flexibility, better drapeability, and cost-effectiveness ((Okoronkwo et al. 2019), (Madu et al. 2019), (Madu et al. 2020) and (Ezeokpube et al. 2021)). While previous studies have investigated the general use of banana fibre in composites, few have directly compared woven and non-woven banana fibre composites under standardized mechanical testing conditions (Nguyen et al. 2022). Moreover, the influence of non-alkali treatment on fiber–matrix interaction and adhesion remains inadequately explored (Ezeokpube et al. 2021). This is significant given the increasing shift toward environmentally conscious production practices that reduce the reliance on chemical treatments.

This study addresses these gaps by analyzing the mechanical performance of woven and non-woven banana fibre-reinforced PVA composites. It examines how different fibre configurations influence tensile, flexural, impact, and compressive properties, and evaluates the effects of non-alkaline fibre treatment on composite performance. The findings aim to inform the development of high-performance, sustainable composites suitable for use in lightweight structural, packaging, and impact-resisting applications.

2. Empirical review

Given recent developments in natural fibre composites, studies have highlighted the differences in mechanical performance between woven and non-woven banana fibre-reinforced polymers. According to (Rana et al. 2020), woven banana fibre-reinforced polyvinyl alcohol (PVA) composites exhibit relatively lower mechanical strength, with reported tensile and flexural strengths of 18.57 MPa and 10.2 MPa, respectively. In contrast, as indicated by (Okoronkwo et al. 2021), non-woven banana fiber epoxy composites demonstrate significantly enhanced mechanical performance, achieving tensile strength of 65.6 MPa and flexural strength of 38.1 MPa at optimal fiber loading. Furthermore, as revealed by (Murugan et al. 2021), the mechanical behaviour of non-woven composites is greatly influenced by fibre length and volume fraction. Optimal performance was observed with a fibre length of 6 cm and a volume fraction of 30 %, contributing to improved durability and elasticity. Collectively, these findings suggest that non-woven banana fibre composites outperform their woven counterparts, particularly in strength and resilience, making them more viable for demanding engineering applications.

Research on banana fibre-reinforced composites has revealed notable distinctions in mechanical performance between woven and non-woven configurations. As noted by (Okoronkwo et al. 2021), woven banana fibre composites exhibit superior flexural and impact strengths, which are attributed to their structured interlacing and higher cellulose content. This suggests that woven structures provide greater load-bearing stability and energy absorption capacity, making them suitable for applications requiring enhanced structural integrity. In contrast, non-woven banana fibre composites have shown significant improvements in tensile and flexural properties when optimized for fibre content. As reported by (Gairola et al. 2020), maximum tensile and flexural strengths of 65.6 MPa and 38.1 MPa, respectively, were achieved at 30 wt.% fiber loading. This highlights the potential of non-woven composites for tailoring mechanical performance through strategic material formulation, offering flexibility in design for lightweight and moderately stressed components.

Additionally, fibre surface treatments play a critical role in enhancing composite performance. According to (Yuan et al. 2021), alkali and enzymatic modifications improved the tensile strength of banana/polypropylene composites by 24–69%, alongside marked gains in impact resistance. These findings underscore the importance of chemical modifications in enhancing fibre–matrix adhesion, which is essential for improving durability in practical applications. While woven composites generally outperform non-woven types in terms of inherent mechanical strength, the latter can be engineered through fibre treatment and loading strategies to achieve comparable performance. As emphasized by (Okoronkwo et al. 2024), this adaptability of non-woven composites offers promising avenues for cost-effective, sustainable alternatives in engineering and manufacturing contexts.

In a related study, (Madu et al. 2020) examined chemically treated woven banana fabrics, noting enhanced mechanical properties, although specific numerical values were not provided. This suggests that chemical modification can play a crucial role in enhancing the structural performance of fibre-based composites, which is essential for applications requiring improved durability under handling and storage conditions. Furthermore, as demonstrated by (Chatterjee et al. 2023), a non-woven viscose–PVA composite achieved a remarkable 100 – 300% increase in tensile strength compared to pure PVA. This substantial improvement reinforces the potential of blended natural and synthetic biodegradable fibres for use in flexible and durable packaging solutions. As reported by (Madu et al. 2020), incorporating 40 % untreated banana fibers into polyester matrices led to a 20 % increase in tensile strength and an exceptional 341 % increase in impact strength. This substantial improvement indicates the potential of banana fibre to significantly enhance energy absorption, making such composites suitable for impact-sensitive applications.

Comparative studies on woven and non-woven fibre structures in composite materials reveal that performance outcomes vary significantly based on the fibre type, matrix system, and intended application. According to (Okoronkwo et al. 2024), non-woven laminates in carbon fibre-reinforced plastics (CFRP) generally outperform woven configurations in terms of static and fatigue performance. This suggests that non-woven architectures may offer better stress distribution and energy dissipation in high-cycle applications such as aerospace components. In the context of natural fibers, (Okoronkwo et al. 2024) found that woven kenaf fiber-reinforced polyester composites, particularly those using plain and twill weaves, achieved higher tensile strength and elastic modulus than their non-woven counterparts. These findings underscore the effectiveness of woven configurations in enhancing stiffness and load-bearing capacity in bio-composites, making them suitable for structural applications. Meanwhile, (Okoronkwo et al. 2019) reported that non-woven glass fibre composites, fabricated using needle-punching techniques, exhibited improved mechanical properties due to enhanced fibre entanglement. These non-woven structures displayed more isotropic behaviour and significantly better inter-laminar fracture toughness than woven laminates, suggesting their utility in impact-prone or multi-directional load-bearing environments. This study uniquely compares woven and non-woven banana fiber architectures in PVA composites under identical processing conditions, providing new insights into structure–property relationships in biodegradable materials.

III. MATERIALS AND METHODS

3.1. Materials

The primary materials used in this study were banana fibres and polyvinyl alcohol (PVA) as the polymer matrix. Banana fibres were sourced from local agricultural waste, supporting sustainability and cost-effectiveness (Akrofi et al. 2023). The fibers were extracted from the pseudo-stems of *Musa acuminata* using mechanical methods and subsequently washed with warm water to remove impurities while retaining their natural structural integrity and mechanical strength. PVA, locally available as glue in Nigeria, was selected for its strong adhesion, film-forming ability, and biodegradability. The PVA matrix was prepared by mixing PVA with water in a 1:1 ratio by volume.

3.2. Material preparation

Banana fibers were collected from the local Agricultural and food market at Owerri, Imo State. Mechanical extraction was employed using a manual decortication machine (Akrofi et al. 2023). The extracted fibers were washed in warm water to remove non-cellulosic components and air-dried under controlled conditions. Dried fibres were either combed and arranged for non-woven mat fabrication or twisted to form yarns for weaving [16].

3.3. Composite fabrication

3.3.1. Woven composites

Woven fabrics were prepared using a tri-loom setup, with both warp and weft yarns derived from twisted banana fibres. Each bundle contained 50 yarns with an approximate thickness of 1.2 mm. Plain and twill weaves were produced (Figure 1).

The woven fabrics were arranged in four layers, each layer uniformly coated with the PVA solution. The stacked layers were then compressed and left to air-dry for 3 – 5 days.

3.3.2. Non-woven composites

Non-woven banana fibre composites were fabricated by manually arranging untreated fibres in two orientations: mat and multi-directional. The fibres were evenly coated with PVA and compressed using a hydraulic press. The composites were air-dried at room temperature for 3 – 5 days and subsequently cured at 120 °C to ensure adequate polymerization. Figure 2 below depicts that.

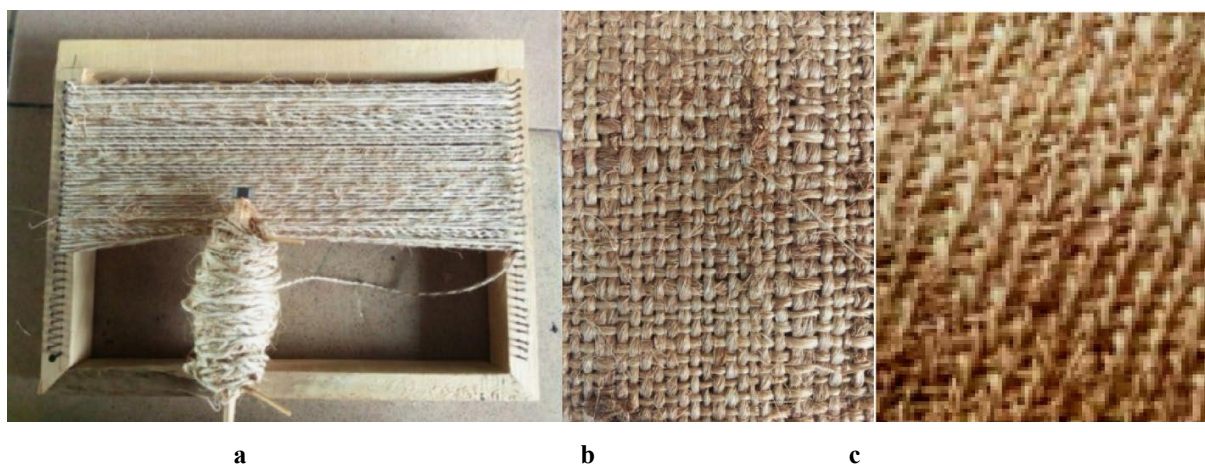


Figure 1: a (Tri-Loom), b (Plain weave) and c (twill weave) Banana fibre woven fabrics.

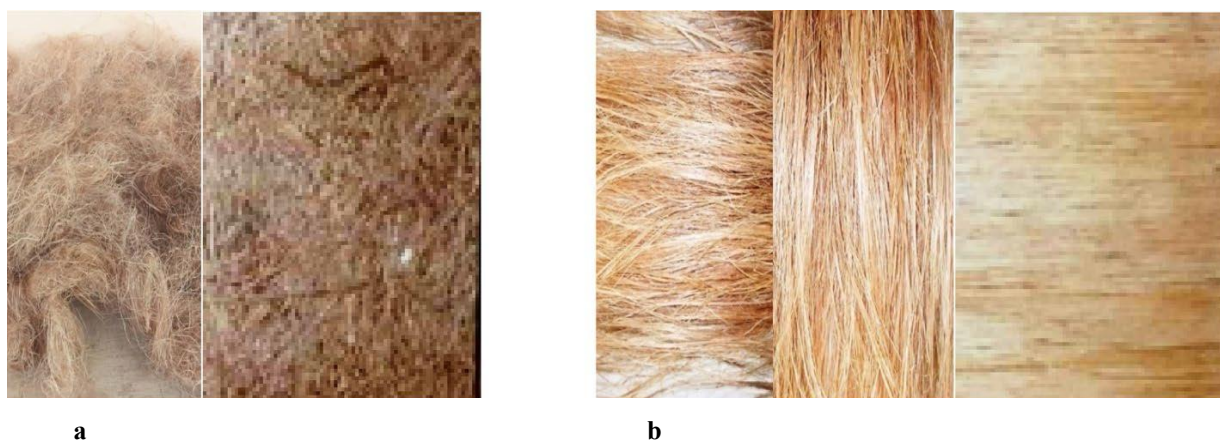


Figure 2: a (Matt) and b (multi-directional) banana fibre non-woven fabric orientation.



Figure 3: PVA application and compression process.

3.3.3. Reinforcement and final processing

For both woven and non-woven composites, reinforcement was achieved by saturating fibre structures with the PVA matrix. Four layers of woven fabric and stacked non-woven fibres were pressed to remove excess adhesive. The composites were allowed to dry at room temperature for 3 – 5 days, depending on ambient conditions. A final hot pressing step was performed at 120 °C for 1 min under constant pressure to enhance compactness, before sample trimming and mechanical testing. Figures 3, 4, and 5 depicted that.

3.3.4. Mechanical testing

Mechanical testing of the composite samples was performed in accordance with relevant ASTM and ISO standards to evaluate their structural performance. Five samples were tested for each sample type to ensure statistical reliability. Tensile strength was determined following ASTM D 638 using a MARK-10 ESM 301L universal strength tester, where dog-bone samples were subjected to uniaxial tension at a strain rate of 2 mm/min under controlled environmental conditions of 23 °C and 50 % relative humidity. Flexural strength was assessed through three-point bending tests in accordance with ASTM D 790 to evaluate the material's resistance to bending. Impact strength was measured using Charpy impact tests based on ASTM D 256, employing an HSM 55 Pendulum

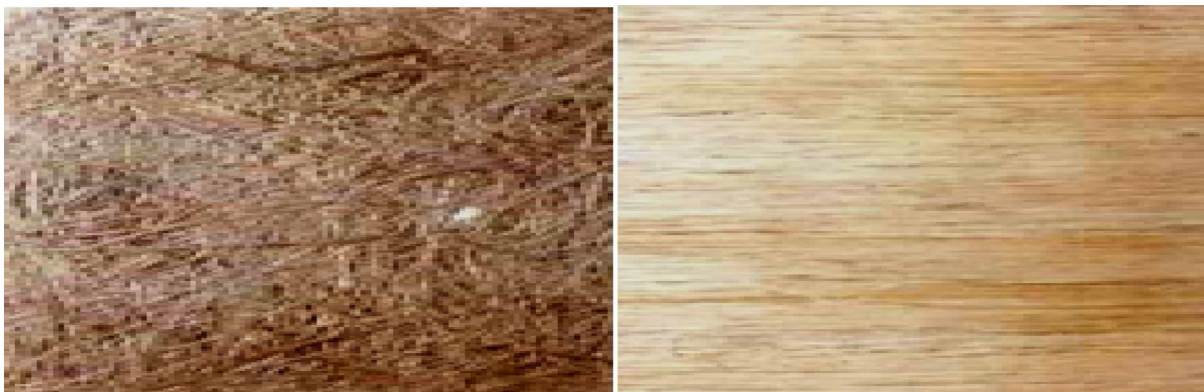


Figure 4: BFC non-woven fabric board sample



Figure 5: BFC woven fabric board sample.

impact Tester (300 J) to determine the energy absorbed during sudden impact. Water absorption was examined following ASTM D 570, where samples were immersed in distilled water at 23 °C for 24 h, and the percentage increase in mass was recorded to assess moisture uptake. Finally, compressive deformation was evaluated according to ASTM D 695 using the MARK-10 ESM 301L tester, with samples compressed between parallel plates at a constant loading rate to determine their resistance to compressive stress.

3.3.5. Microstructural analysis

Microstructural analysis of the composite samples was carried out using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) to examine morphological features and chemical interactions. SEM analysis was performed with a ZEISS EVO MA15 scanning electron microscope, equipped with energy-dispersive X-ray spectroscopy (EDX) for elemental analysis. This enabled high-resolution imaging and automated measurement of fibre structures to assess fibre-matrix interfacial bonding and surface morphology. FTIR analysis was conducted using an Alpha Platinum FTIR spectrometer to identify the functional groups present and to evaluate possible chemical interactions between the banana fibres and the polyvinyl alcohol (PVA) matrix, providing insights into the compatibility and bonding characteristics of the composite material.

3.4. Statistical analysis

Mechanical test data were statistically analyzed using Analysis of Variance (ANOVA) at a 95 % confidence level ($P < 0.05$) to determine significant differences among the various composite types. The analysis was performed using MATLAB version R2007b, and comparisons of mean performance values were used to evaluate the effect of fibre structure and orientation on the mechanical properties of the composites (Gairola et al. 2020).

IV. RESULTS AND DISCUSSION

4.1. Physical properties of banana fibres

The physical characteristics of banana fibres play a critical role in determining their suitability for composite applications. In this study, fibres were extracted from banana pseudo stems sourced from mixed fields, resulting in variability in plant size and maturity. Although the specific cultivar and maturity stage could not be established due to inter-sourcing, the harvested stems exhibited substantial dimensional diversity, with diameters ranging from 18 to 30 inches and heights between 60 and 125 inches. This variation may influence fibre structure, cellulose content, and moisture retention capacity factors known to affect composite behavior. The fibres were obtained through mechanical extraction, followed by manual scraping to remove residual pith and non-cellulosic components. This method preserved the natural morphology of the fibres while minimizing structural damage. All fibres were subsequently washed and combed to prevent entanglement and ensure uniformity during composite processing.

Each banana fibre strand is composed of a bundle of micro-fibrils held together by lignin, as observed in Figure 6. These natural lignin bonds contribute to the mechanical integrity of the fibre but can also hinder optimal fibre-matrix interaction if not sufficiently disrupted. The hierarchical fibre structure, which includes a coarse outer layer and a more flexible inner core, may influence fibre wettability, porosity, and bonding with hydrophilic matrices like polyvinyl alcohol (PVA). The presence of natural nodal joints or "nods" along the fibre surface, shown in the micrograph, introduces potential discontinuities that can act as stress concentrators

under tensile loading. However, these nodes may also enhance mechanical interlocking with the matrix when properly embedded.



Figure 6: Digital optical microscopic view single (200 \times); showing nod along the fibre axis.

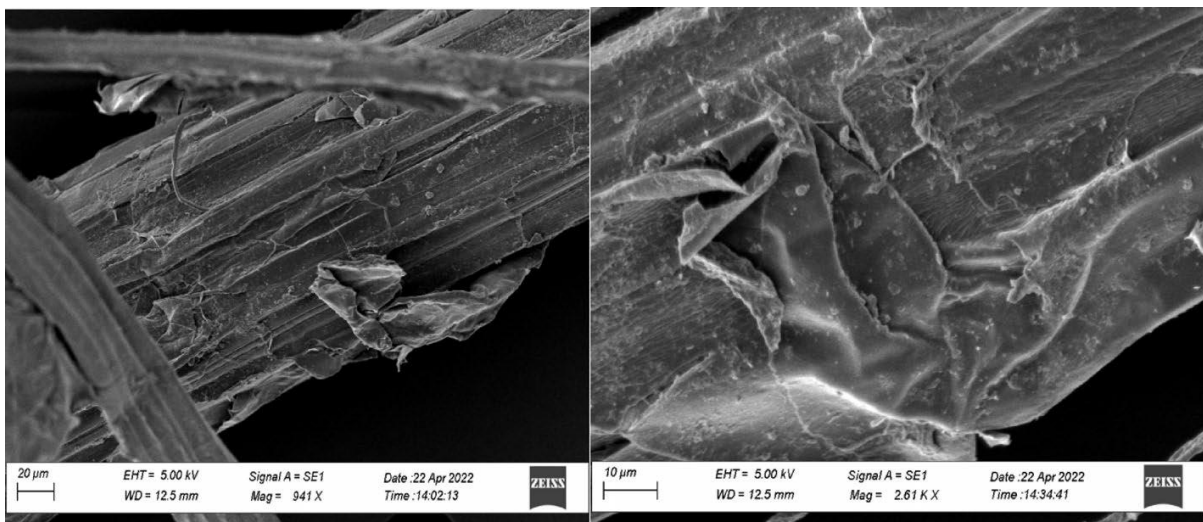


Figure 7: SEM imaging of mechanically extracted banana fibers (941 \times / 261 \times).

4.2. Scanning electron microscopic examination of the banana fibres

The surface morphology of the untreated banana fibres was examined using Scanning Electron Microscopy (SEM) to evaluate their structural characteristics after mechanical extraction and to determine their suitability for effective interfacial bonding with the PVA matrix. SEM imaging was performed at magnifications of 393 \times and 1.11 k \times under an accelerating voltage of 15 kV and a working distance of 10 mm. Before imaging, the fibre samples were mounted on aluminium stubs and sputter-coated with a thin layer of gold to improve surface conductivity and enhance image clarity.

As shown in Figure 7, the fiber surfaces exhibit significant roughness and fractured regions, likely resulting from the manual mechanical extraction and scraping process. The image at 393 \times magnification reveals surface grooves, disoriented fibrils, and micro-cracks, while the image at 1.11 k \times highlights localized surface ruptures and detachment of fibre bundles. Such damage could be attributed to the shearing forces during extraction, which may disrupt the natural alignment of cellulose micro-fibrils.

These surface features play a critical role in fibre-matrix adhesion. The observed roughness and fibrillation may enhance mechanical interlocking with the PVA matrix, thereby potentially improving tensile and flexural properties of the resulting composites. However, the presence of surface micro-cracks and exposed voids may also serve as initiation points for crack propagation under stress, especially if matrix infiltration is incomplete. Furthermore, the irregular fibre surface may lead to non-uniform stress transfer along the fibre-matrix interface, which could compromise the composite's durability under cyclic or impact loading. Therefore, while untreated

fibres retain a certain degree of natural roughness beneficial for mechanical anchoring, their inconsistent surface morphology necessitates further consideration in terms of pretreatment or surface modification to balance adhesion and structural integrity.

4.3. Energy dispersive x-ray spectroscopy (EDS)

Energy Dispersive X-ray Spectroscopy (EDS) analysis was carried out to determine the elemental composition of the untreated banana fibre surfaces. Using the ZEISS EVO MA15 SEM-EDS system, operated at an accelerating voltage of 20 kV and a working distance of 10 mm, the system achieved a spatial resolution of 1.23 μm , enabling detailed examination of the fibre surface morphology and composition. The analysis revealed that the predominant elements present were oxygen (O), carbon (C), and silicon (Si), with corresponding weight percentages of 40.64%, 6.59%, and 26.42%, respectively. The presence of oxygen and carbon reflects the organic nature of the banana fibres, primarily composed of cellulose, hemicellulose, and lignin, while the silicon content indicates traces of inorganic constituents possibly retained from the plant's growth environment. These elemental characteristics provide insight into the surface chemistry and purity of the fibres, which are critical factors influencing their interfacial bonding with the PVA matrix as presented in Table 1.

The high oxygen and carbon content is typical of lingo-cellulosic fibres, which are composed predominantly of cellulose, hemicellulose, and lignin. These polymers are rich in hydroxyl and ether functional groups, contributing to the fibre's polarity and affinity for hydrophilic matrices such as polyvinyl alcohol (PVA). The presence of carbon and oxygen is consistent with findings from other studies on natural fibres, including banana, flax, and hemp.

However, the relatively high silicon content observed on the banana fibre surface is unusual for untreated lingo-cellulosic fibres. This may be attributed to several factors. First, banana plants are known to accumulate silica in the form of phytoliths, which are inorganic deposits found in monocot species. Second, the mechanical extraction process and environmental exposure during harvesting and processing may introduce surface contamination from soil or dust particles, contributing to elevated silicon readings (Okoronkwo et al. 2025). Additionally, tooling abrasion during fibre processing could result in residual silicate deposits.

The implications of these elements are significant. While carbon and oxygen support interfacial adhesion due to their compatibility with polar matrices, excessive silicon may hinder matrix wetting and stress transfer. Silica-rich surfaces tend to be chemically inert and non-polar, which can reduce fibre-matrix bonding efficiency in polymer composites (Okoronkwo et al. 2024). This suggests that surface treatment or additional cleaning steps may be necessary to enhance fibre performance in composite applications.

Table 1: EDS data on a strand of banana fibre.

Element	At. No	Netto	Mass [%]	Mass Norm. [%]	Atom [%]	abs. error [%](1 sigma)	rel. error [%](1 sigma)
Carbon	6	297	6.59	8.95	13.62	2.21	33.59
Oxygen	8	8486	40.64	55.18	63.03	5.85	14.4
Silicon	14	27681	26.42	35.87	23.34	1.17	4.44
SUM			73.65	100	99.99		

4.4. FTIR test analysis

Fourier-transform infrared spectroscopy (FTIR) was conducted to identify the functional groups present in the banana fibre and to understand the chemical structure relevant to fibre-matrix interactions. The FTIR spectrum (Figure 8) reveals characteristic absorption bands associated with lingo-cellulosic constituents, confirming the presence of cellulose, hemicellulose, and lignin, major components of banana fibre.

The broad absorption band observed at approximately 3586 cm^{-1} corresponds to the stretching vibration of hydroxyl (-OH) groups. This peak is indicative of the abundant hydrogen bonding present in the cellulose and hemicellulose fractions of the fiber (Arumugam et al. 2021). The intensity of this peak suggests strong hydrophilicity, which influences water absorption behaviour and has implications for composite matrix compatibility, particularly with polar polymers like PVA. A notable peak at 1712 cm^{-1} is attributed to the

stretching vibration of the carbonyl group ($C=O$), which may be associated with ester linkages in hemicellulose or absorbed water molecules. The band at 1272 cm^{-1} is linked to the $O-H$ bending vibration in phenolic structures found in lignin. Additionally, the band near 1013 cm^{-1} corresponds to the $C-O-C$ stretching vibration, characteristic of the ether linkages in cellulose and hemicellulose backbones. The presence and positioning of these peaks are consistent with prior studies on banana and other lingo-cellulosic fibres, although slight spectral shifts ($\pm 150\text{ cm}^{-1}$) may occur due to differences in fibre maturity, processing conditions, or environmental exposure ((Arumugam et al. 2021), (Okoronkwo et al. 2024), (Okoronkwo et al. 2024)). These spectral features confirm that the banana fibres retain their natural chemical functionality, which is crucial for forming hydrogen bonds with hydrophilic polymer matrices such as PVA. The high hydroxyl content also suggests that untreated fibres may exhibit significant moisture uptake, which could influence the dimensional stability and mechanical performance of the resulting composites. Consequently, while the natural chemical groups present in the fibre are beneficial for interfacial bonding with polar matrices, surface modification may be necessary to enhance water resistance and thermal stability for specific applications.

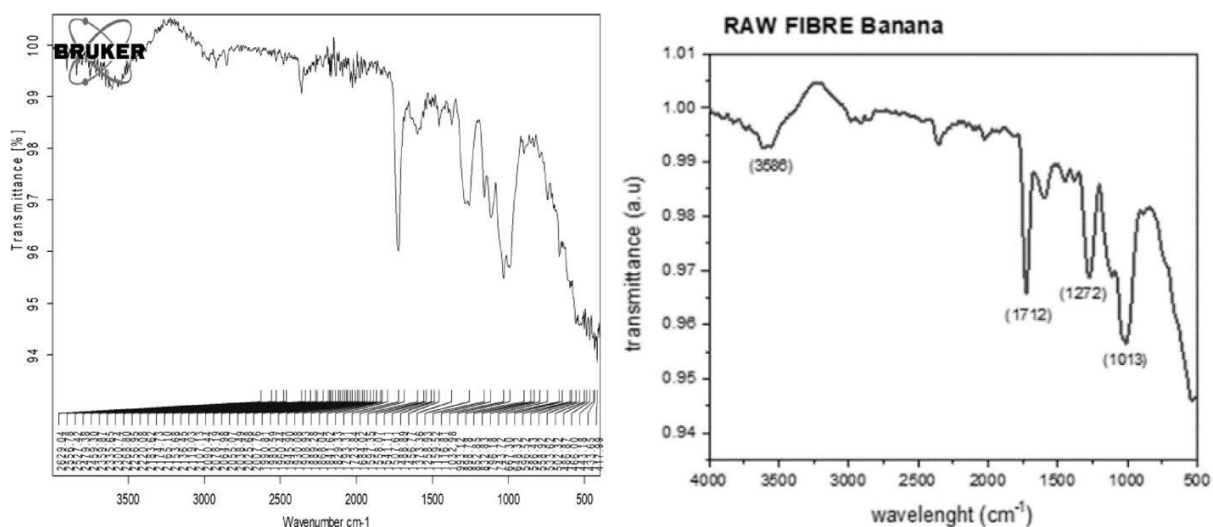


Figure 8: Graphical representation of the FTIR test on raw banana fibre.

Table 2: Peak points of XRD test on banana fibre.

Pos. [$^{\circ}2\theta$]	Height [cts]	FWHM Left [$^{\circ}2\theta$]	d-spacing [\AA]	Rel. Int. [%]
22.8258	10,325.13	2.1323	3.89603	100.00
35.5813	879.29	0.7754	2.52320	8.52

Table 3: Water absorption property of banana fibres.

Time	Dry wt	10 min	30 min	60 min	24 h
The difference in the rates of absorption -Weight (grams)	0.29	0.81	0.88	0.90	0.92

4.5. XRD test analysis

X-ray diffraction (XRD) was performed to characterize the crystalline structure of the untreated banana fibres. The diffraction pattern (Table 2) displayed broad and low-intensity peaks, indicating a predominance of amorphous regions. The main peak at 22.83° , corresponding to the (002) plane of cellulose I, and a minor peak at 35.58° suggest limited molecular order within the cellulose micro-fibrils. The broadness of these peaks confirms the low crystallinity typical of untreated lingo-cellulosic fibres.

Previous studies have reported crystallinity indices of 50.8 – 53.3 % for untreated banana fibres ((Madhushani et al. 2022), (Manimaran et al. 2020)), consistent with the 52 % had also been reported. These values affirm the

coexistence of crystalline and amorphous phases within the fibre structure. The amorphous domains contribute to water absorption, weakening fiber-matrix adhesion and tensile strength (Okoronkwo et al. 2024) and (Okoronkwo et al. 2025)). Chemical treatments such as alkali and bleaching are known to enhance crystallinity by removing hemicellulose and lignin [6], with crystallinity indices increasing to 61.7 % or higher (Madhushani et al. 2022). Thus, while the untreated banana fibres exhibit low crystallinity, processing and modification methods can significantly improve their structural order and composite performance.

4.5.1. Water absorption property of banana fibres

The water absorption behaviour of untreated banana fibres was evaluated over a 24 h immersion period to assess their hydrophilicity and moisture uptake capacity. Table 3 presents the weight gain and percentage increase in fibre mass at different time intervals. The results revealed a rapid increase in weight within the first 10 min of immersion, indicating a strong affinity for water due to the presence of hydroxyl groups in cellulose and hemicellulose. The absorption rate gradually stabilized after 60 min, with only marginal changes observed between 60 min and 24 h, suggesting that the fibres reached their fiber saturation point (FSP) within the first hour of exposure.

This finding aligns with previous studies on the moisture behavior of cellulosic materials. (Okoronkwo et al. 2025) defined the FSP as the level at which water becomes chemically bound to cellulose and related wood constituents, forming a “solid solution” distinct from free water. Using FTIR spectroscopy, (Okoronkwo et al. 2022) further demonstrated that water adsorption occurs simultaneously at multiple sorption sites, with molecules aggregating into clusters. Similarly, (Okoronkwo et al. 2019) reported that kenaf fiber composites exhibit Fickian water diffusion behavior, with absorption rates increasing proportionally to cellulose content, while (Madu et al. 2020) observed that hemp-based composites show rapid initial absorption followed by stabilization, consistent with the pattern recorded in this study.

Table 4: Single-strand tensile strength test of banana fibre

Fibre type	Diameter (mm)	Area (mm ²)	Ultimate force (N/mm ²)	Ultimate stress (N/mm ²)	Breaking distance (mm)
Banana	0.10	0.01	2.01	250.85	13.94

Table 5: Descriptive statistics for tensile strength level among bundle components for banana fibre.

No. of bundles	10	20	30	40	50
Mean	538.50	425.60	322.60	193.00	160.65
SE Mean	34.80	16.40	26.00	12.30	9.16
St. Dev	173.90	81.90	129.80	61.30	45.79
Coef. Var	32.29	19.25	40.23	31.78	28.50
Minimum	269.70	313.70	149.00	72.50	95.64
Q1	421.70	357.90	214.80	148.00	126.93
Median	520.90	402.70	309.80	203.00	158.40
Q3	625.50	492.40	422.10	241.10	177.56
Maximum	952.20	567.30	573.10	327.40	290.02
IQR	203.80	134.50	207.30	93.10	50.63
Skewness	0.74	0.18	0.50	0.04	1.04
95% CI (Pooled St. Dev. = 109.224)	(495.2, 581.7)	(382.3, 468.8)	(279.4, 365.9)	(149.8, 236.3)	(117.40, 203.90)
Grouping (Tukey pairwise comparisons)	A	B			

C

D

D

The high moisture uptake of untreated banana fibres, although beneficial for bonding with polar matrices such as PVA, may compromise dimensional stability and promote microbial degradation under humid conditions. For practical composite applications, it is therefore essential to minimise water absorption through matrix encapsulation or surface modification techniques such as alkali or silane treatment to enhance fibre durability and interfacial performance.

4.6. Tensile strength test on raw banana fibre cords/yarns

The tensile properties of raw banana fibres were evaluated at both single-strand and yarn bundle levels to determine their mechanical suitability for reinforcement in polymer composites. The performance of individual fibres and twisted yarns plays a crucial role in defining the strength, flexibility, and durability of woven structures. The tensile test on a single banana fibre strand yielded an ultimate tensile stress of 250.85 N/mm^2 with a cross-sectional area of 0.01 mm^2 and a breaking elongation of 13.94 mm (Table 4). This value is comparable to those reported for other bast fibers such as sisal and hemp, reinforcing the potential of banana fibre as an effective reinforcement material.

To assess the effect of fiber bundling, the fibers were twisted into yarns comprising 10, 20, 30, 40, and 50 bundles, and their tensile performance was evaluated (Table 5). An inverse relationship was observed between bundle size and tensile strength: smaller yarn bundles exhibited higher strength values, with the 10-bundle yarns recording 538.50 N/mm^2 , while the 50-bundle yarns showed a reduced tensile strength of 160.65 N/mm^2 . This decline is attributed to uneven stress distribution, slippage between fibres, and the presence of inter-bundle voids, which collectively weaken load transfer efficiency within thicker yarns.

These findings are consistent with previous research on banana fibre-reinforced composites. (Okoronkwo et al. 2021) reported tensile strengths of $62.3 \pm 0.67 \text{ MPa}$ and elastic moduli of $8.72 \pm 1.12 \text{ GPa}$ for banana fibre/epoxy composites tested under ASTM D 3039 standards. Similarly, (Kavitha et al. 2022) demonstrated that tensile properties are strongly influenced by fibre volume fraction and orientation, with optimal performance achieved at balanced fibre-to-epoxy ratios and alignment along the 0° direction. Further research confirmed that tensile strength increases with fibre diameter, with maximum stress occurring when the load is applied parallel to the fibre direction.

The decline in tensile strength with increasing bundle size may be attributed to internal slippage between fibres, non-uniform twist distribution, and increased void formation. Smaller bundles exhibit more uniform stress distribution and better alignment, resulting in higher load-bearing capacity.

Statistical analysis using one-way ANOVA and Tukey's pairwise comparison (Table 6) confirmed that the differences in tensile strength across the various yarn bundle sizes were statistically significant ($P < 0.05$), with R^2 value of 63.60% , indicating a moderately strong model fit. The grouping matrix revealed that the 10-, 20-, and 30-bundle yarns each formed distinct strength groups (A, B, and C, respectively), while the 40- and 50-bundle yarns were not statistically different, suggesting a threshold effect at higher bundle counts where additional bundles no longer contribute to significant strength gains.

Despite their comparatively lower tensile strength, the 50-bundle yarns were selected for fabric weaving because of their superior handling properties, flexibility, and compatibility with weaving operations. This practical selection aligns with empirical findings by (Ezeokpube et al. 2021), who note that factors such as flexibility, drapeability, and processability are equally vital in textile and composite fabrication involving natural fibres. Faruk et al. [16] further highlight that finer fibres or yarns with reduced tensile strength can produce smoother textures and improved weaving quality, enhancing the structural uniformity of woven composites.

These observations indicate that tensile strength alone does not solely determine the suitability of fibres for composite weaving. Parameters such as bundle diameter, fibre alignment, twist uniformity, and inter-fibre cohesion play important roles in defining overall performance. In practical applications, yarns with higher bundle counts often exhibit better workability and conformability, especially under tight weave patterns or when a uniform fabric texture is desired.

Statistical approaches have long been applied in analyzing fiber and yarn strength behavior. (Ezeokpube et al. 2021) demonstrated that Weibull distributions effectively describe the statistical strength of yarns and cables,

emphasizing that variability in fibre strength strongly influence median tensile performance. Similarly, (Gheribi et al. 2024) applied ANOVA to assess *Strelitzia juncea* fibre strength across gauge lengths ranging from 10 to 50 mm, finding tensile values between 270 and 731 MPa with significant statistical variation. (Belaadi, et al. 2022) used a combination of ANOVA and Weibull modelling to examine *Yucca treculeana* fibers (10 – 40 mm gauge lengths), confirming the large natural dispersion typical of such materials. Furthermore, researchers utilized statistical bundle theory and Weibull distributions fitted through maximum likelihood estimation to predict the tensile strength of woven fabrics, illustrating how fibre interactions and load-sharing mechanisms influence mechanical performance.

Table 6 : Summary of tensile strength level among bundle components for banana fibre.

S	R-sq	R-sq(adj)	R-sq(pred)	F-Value	P-Value
109.224	63.60%	62.39%	60.51%	52.42	0.000

4.7. Mechanical analysis of non-woven banana fibre composites

The mechanical behaviour of non-woven banana fibre composites is closely influenced by fibre arrangement, bonding quality, and structural consistency. In this study, non-woven fabrics were manually constructed using hand-laid fibre mats in two configurations: multi-directional and mat-oriented. These arrangements were bonded with a polyvinyl alcohol (PVA) matrix to ensure cohesion in the absence of traditional interlacing or weaving.

Non-woven fabrics differ significantly from woven materials in that their strength does not originate from interwoven yarns but rather from matrix adhesion and frictional interaction between randomly arranged or aligned fibres. As emphasized by researchers, the structural integrity of non-woven composites relies heavily on the effectiveness of the bonding agent, since the absence of yarn interlocking limits load distribution and fibre entrapment.

While mechanical testing data for these non-woven composites is limited in this study, qualitative assessments during fabrication and post-curing stages offer insight into their structural characteristics and handling performance. Three primary attributes were observed:

4.7.1. Tensile behaviour

The tensile behaviour of the non-woven banana fibre-reinforced PVA composites was largely influenced by fibre orientation and interfacial bonding. The random distribution of fibres within the mat contributed to moderate tensile strength, as the absence of interlaced yarns limited stress transfer between the fibres and the surrounding matrix. Although cutting the fibres to uniform lengths and layering them evenly improved surface compactness and reduced void formation, the lack of fibre entanglement and mechanical interlocking restricted load-bearing efficiency. As a result, failure under tension is typically initiated through fibre pull-out and matrix cracking, highlighting the dependence of tensile performance on the quality of fibre-matrix adhesion.

4.7.2. Flexural behaviour

Under flexural loading, the non-woven composites exhibited lower stiffness and strength compared to their woven counterparts. The uniform but non-interwoven fibre arrangement offered minimal reinforcement against bending-induced deformation, resulting in early delamination and limited crack-bridging capability. While the parallel fibre alignment facilitated good resin penetration and reduced defects during fabrication, it did not enhance bending resistance. The flexural response was therefore dominated by the PVA matrix rather than fibre reinforcement, indicating that additional treatments such as surface modification or partial fibre alignment would be necessary to improve flexural rigidity and durability.

4.7.3. Impact resistance

Impact testing revealed that the non-woven composites absorbed moderate amounts of energy before failure, primarily due to the ductile characteristics of the PVA matrix. However, the discontinuous fibre network limited the transfer and dissipation of impact energy across the composite. The absence of inter-yarn friction and mechanical interlocking reduced the material's capacity to resist crack initiation and propagation under sudden loading. Consequently, the non-woven composites are more suitable for lightweight or semi-structural applications where flexibility and ease of processing are valued over high impact strength. Similar observations were reported by (Sekar et al. 2021), who found that non-woven natural fibre composites, though easier to

fabricate, often require supplementary mechanical or chemical modifications such as needle punching, cross-lamination, or surface treatment to enhance strength and toughness.

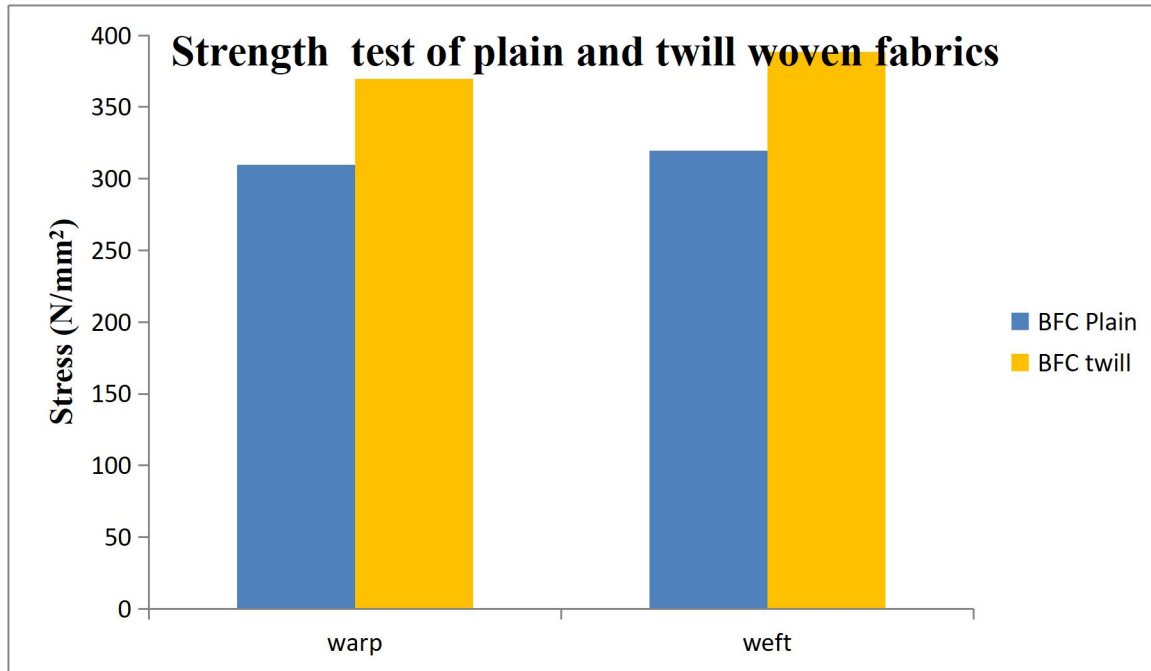
Given these, the non-woven banana fibre composites developed in this study demonstrated good structural uniformity and ease of fabrication but exhibited relatively lower tensile, flexural, and impact performance due to limited interfacial reinforcement. Their mechanical properties suggest potential for non-load-bearing applications; however, for enhanced performance in structural or impact-prone uses, future work should focus on improving fibre-matrix adhesion, optimizing fibre orientation, and exploring hybrid or chemically treated reinforcements to improve load transfer efficiency and mechanical reliability.

4.8. Woven fabric strength test

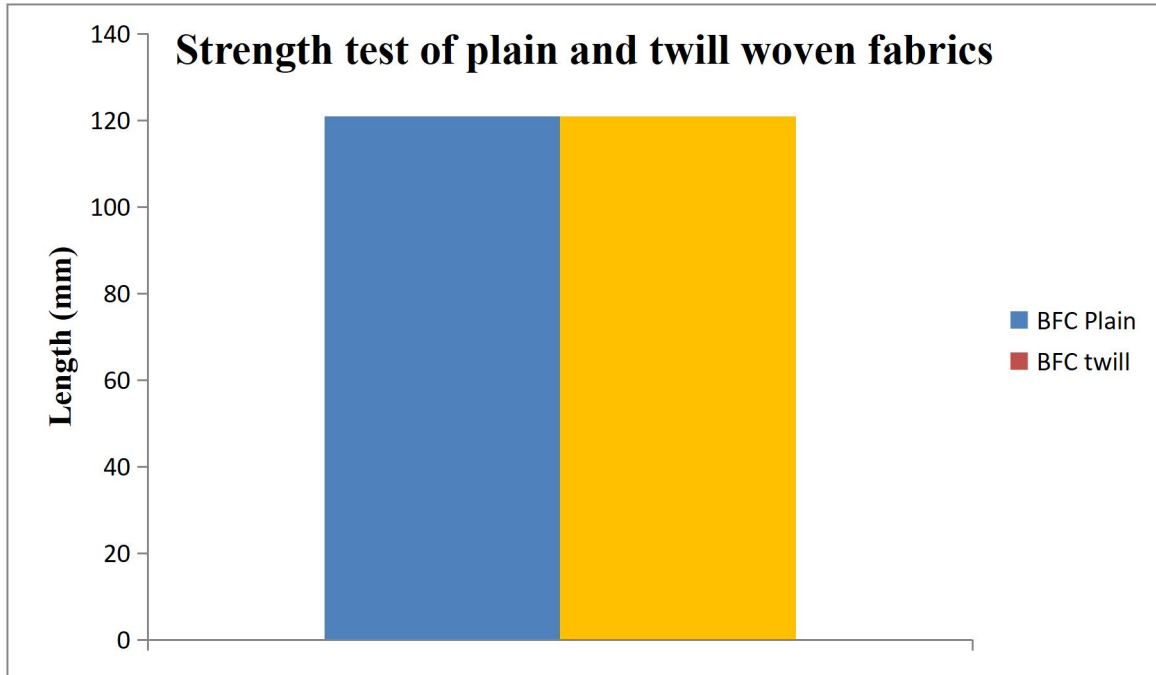
The mechanical performance of the woven banana fibre-reinforced PVA composites was assessed to determine the influence of fabric architecture specifically plain and twill weaves on tensile behaviour in both warp and weft directions. Prior to fabric construction, fibre bundles of varying sizes were tested to establish their tensile capacities. Based on these results, 50-bundle yarns were selected as they provided an optimal balance between strength and flexibility, enabling uniform weaving and improved structural integrity during composite fabrication.

As illustrated in Fig. 9 (a – c), the tensile strength in the weft direction was consistently higher than in the warp direction for both weave types. Twill-woven composites demonstrated superior elongation capacity compared to plain weaves, particularly in the weft direction (10.47 mm vs. 6.21 mm). This is attributed to the reduced number of interlacing points in the twill structure, which allows for greater fibre mobility and stretch under tensile load.

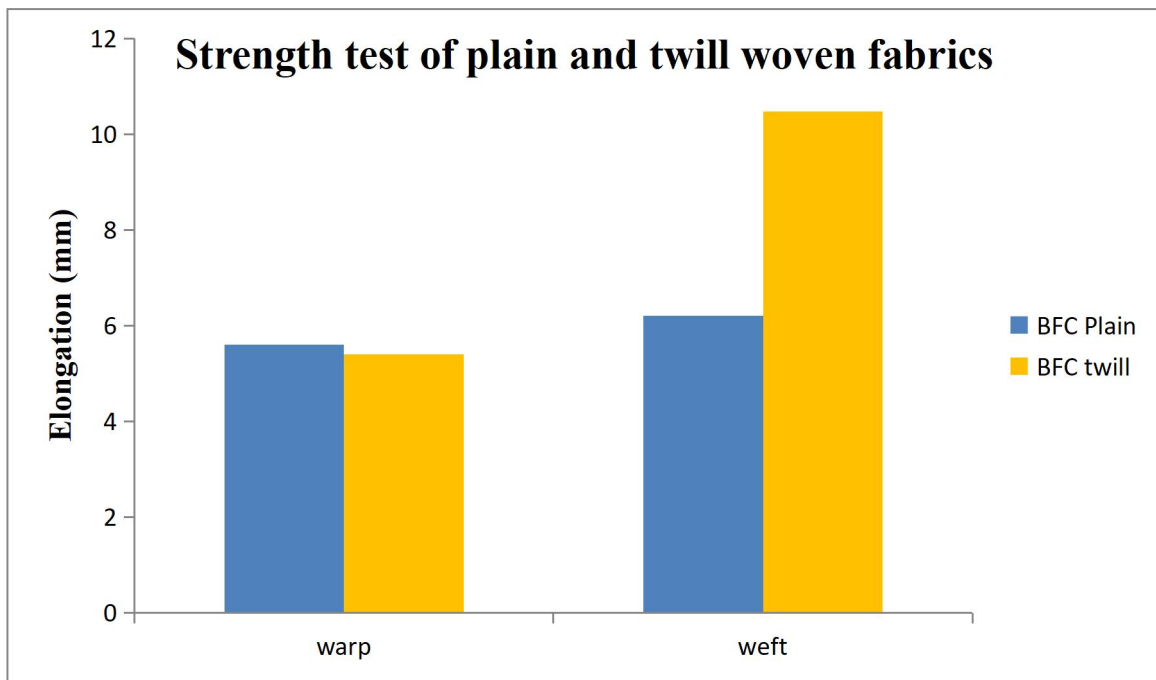
The average tensile strength of the twill weave in the weft direction was 388.5 N/mm^2 , compared to 319.5 N/mm^2 in the warp direction. For plain weaves, the strength difference between directions was less pronounced, reflecting their higher degree of interlacing and more uniform load distribution. The tighter geometry of the plain weave contributes to dimensional stability but limits elongation, while the diagonal configuration of the twill weave allows for better load transfer and improved deformation resistance.



(a)



(b)



(c)

Figure 9 (a – c) : Strength of Woven Composite Fabric Warpway and Weftway Fabric.

These differences highlight the importance of weave architecture in determining composite behavior. As also supported by earlier studies, the mechanical properties of woven fibre composites are influenced not only by yarn material and count but also by how the yarns are arranged, spaced, and interlaced within the fabric matrix.

While general fabric parameters such as yarn diameter, thread count, weave pattern, and inter-yarn spacing contribute to composite thickness, porosity, and permeability, their mechanical relevance lies in how they collectively influence stress distribution. For instance:

Yarn density and thread count affect the packing efficiency and the number of load paths available during stress application. Weave tightness and void size influence resin infiltration, which impacts fibre-matrix adhesion. The fabric geometry affects not just tensile strength but also flexural rigidity, impact resistance, and dimensional stability.

Given these, the twill-woven banana fibre composites show better elongation and tensile strength in the weft direction, suggesting their suitability for applications requiring moderate flexibility and strength. In contrast, plain weave structures offer higher dimensional stability, making them better suited for rigid panel or board-like applications.

4.9. Comparative analysis of woven and nonwoven banana fabric reinforced PVA composites

This section presents a comparative analysis of the mechanical performance of woven and non-woven banana fibre-reinforced PVA composites, focusing on tensile, flexural, impact, and compressive strength.

4.9.1. Tensile strength test

Tensile strength testing was conducted to assess the composites' resistance to axial loading and to determine the influence of weave structure on mechanical performance. As shown in Figure 10, the plain weave composite recorded the highest tensile strength of 20.03 N/mm^2 , followed by the multi-directional non-woven composite (19.42 N/mm^2) and the mat-oriented non-woven composite (18.83 N/mm^2). The twill weave composite

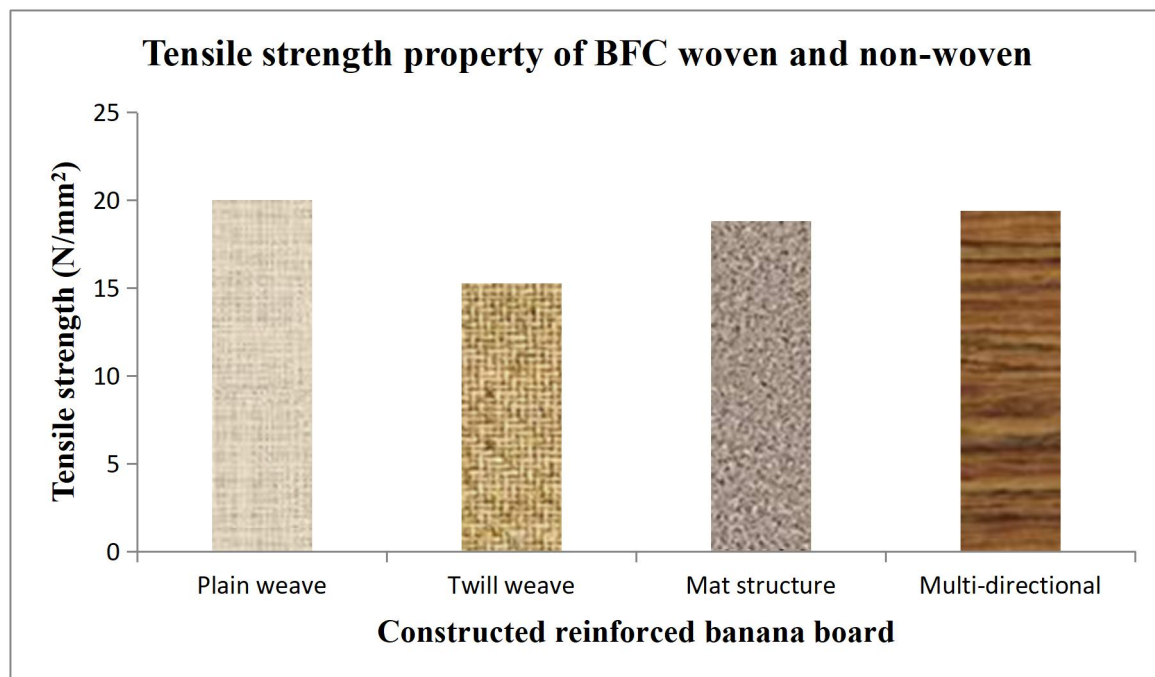


Figure 10: Tensile strength test results of BFC reinforced PVA board.

exhibited the lowest tensile strength at 15.28 N/mm^2 , representing approximately a 25 % reduction compared to the plain weave configuration.

The superior tensile behaviour of the plain weave composite is attributed to its tight interlacing pattern and high fibre alignment, which promote efficient stress transfer and restrict fibre pull-out during loading. Conversely, the diagonal structure of the twill weave, while advantageous for flexibility and elongation, introduces more inter-yarn spacing, thereby reducing its effective load-bearing capacity. The non-woven composites, particularly the multi-directional configuration, exhibited tensile strength values comparable to the woven counterparts, with only 0.61 N/mm^2 difference between the plain weave and multi-directional samples. This similarity suggests that when fibre bonding is sufficient, non-woven structures can emulate the tensile characteristics of woven fabrics.

These findings corroborate those of other researchers, who reported that woven fibre-reinforced composites generally outperform non-woven types due to enhanced fibre orientation and mechanical interlocking. Similarly, they emphasized the critical role of fibre alignment in improving tensile behavior, especially in structural composites. From a practical perspective, the performance of plain weave and multi-directional composites makes them promising candidates for moderate to high axial load applications, such as flat panels, lightweight structural boards, and loadbearing packaging materials.

Comparative research on the influence of weave architecture across different fibre reinforced systems further supports these observations. In hemp/epoxy composites, plain weave exhibited superior tensile strength relative to twill 2/2 weave due to reduced yarn crimp and enhanced structural balance. Similarly, basalt/epoxy composites displayed better mechanical performance in plain weave configurations compared to twill (Chairman et al. 2021). However, contrasting results were reported for bamboo/epoxy composites, where twill weave structures (5.4 mm thickness) demonstrated 12 % higher tensile strength and 22 % higher flexural strength than plain weave counterparts of equivalent thickness. Studies on plain weave carbon fibre-reinforced plastics (CFRP) have also revealed consistent tensile strength and fracture toughness across varied loading angles.

4.9.2. Bending resistance

Flexural strength testing was conducted to assess the composites' resistance to bending forces, a critical mechanical property for applications requiring stiffness and dimensional stability. The results, presented in Figure 11, reveal substantial variations in bending resistance across the four composite configurations. The plain weave composite exhibited the highest flexural strength at 42.52 N/mm^2 , followed closely by the multi-directional non-woven composite at 40.43 N/mm^2 . These results indicate that both tightly interlaced woven structures and well-oriented non-woven fibre arrangements can effectively resist bending loads. The twill weave composite showed moderate flexural strength at 32.16 N/mm^2 , while the mat-structured composite recorded the lowest value at 11.27 N/mm^2 , signifying limited stiffness and bending durability.

The superior performance of the plain weave composite is attributed to its regular interlacing pattern, which provides greater fibre-to-fibre contact and facilitates uniform stress transfer throughout the laminate (Gairola et al. 2020). The relatively strong performance of the multi-directional non-woven composite also underscores the importance of controlled fibre alignment in enhancing load transfer and flexural response, even in non-woven systems. In contrast, the random fibre orientation in the mat structure restricts efficient stress transmission under bending loads, resulting in premature failure and low flexural strength. These observations align with other researchers, who emphasized that fibre orientation and interfacial bonding are pivotal determinants of flexural rigidity and overall mechanical performance in natural fibre composites.

From a design perspective, the results indicate that plain weave and multi-directional composites are best suited for structural applications requiring high stiffness and shape retention, such as panels, boards, or support frames. The twill weave composite, while offering lower flexural strength, provides greater flexibility and drapability, making it suitable for applications where moderate bending resistance and formability are advantageous. Conversely, mat-based composites, due to their low flexural capacity, may be restricted to non-structural or aesthetic applications, unless their performance is enhanced through fibre surface treatments or hybrid reinforcement.

Research on textile-reinforced composites consistently highlights the profound influence of weave architecture on mechanical behaviour. (Sahbaz Karaduman et al. 2022) reported that quasi-unidirectional composites achieved the highest tensile and flexural strengths, followed by plain weave structures, while twill 2/2 weaves exhibited the weakest performance due to excessive yarn crimp and unbalanced geometry. Similarly, (Risteska et al. 2024) found that unidirectional prepreg reinforcements achieved superior longitudinal flexural strengths ($\sim 900 \text{ MPa}$), whereas woven prepreps (plain and basket) displayed balanced bidirectional properties ($\sim 450 \text{ MPa}$). Interestingly, twill prepreg composites

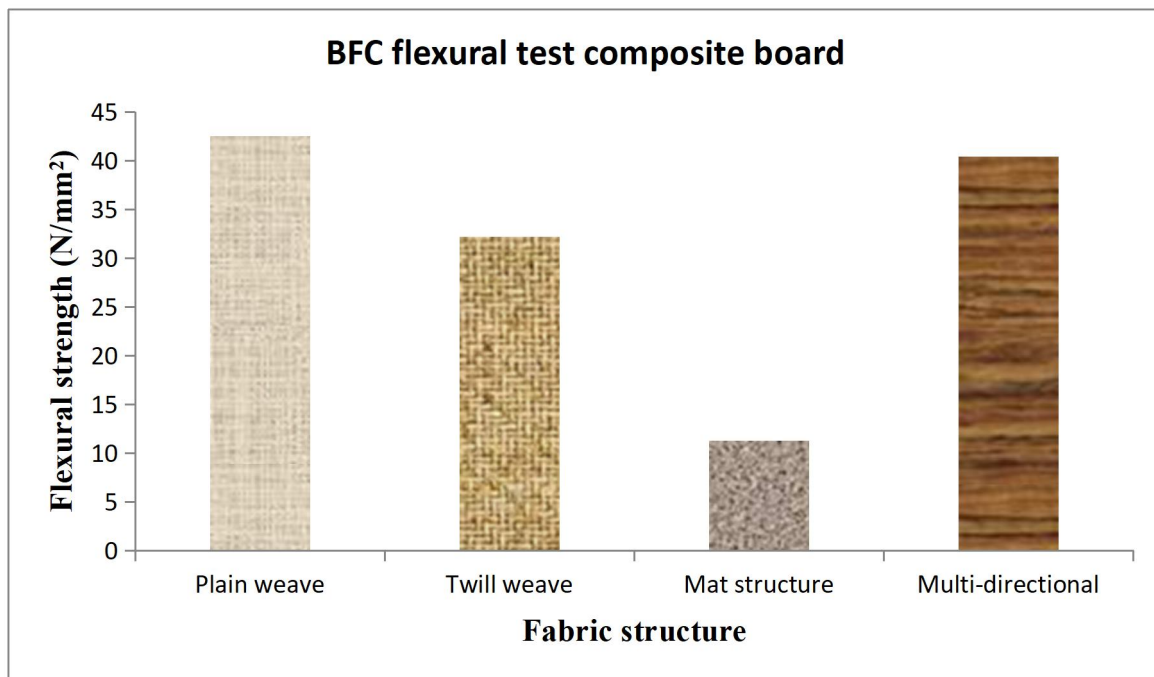


Figure 11: Flexural strength test results of the BFC reinforced PVA board.

showed over 20 % higher flexural strength than plain and basket weaves, suggesting that, under certain configurations, the diagonal interlacing of twill can enhance energy absorption and delay failure onset. In contrast, non-woven mat reinforcements exhibited the lowest bending resistance (~ 150 MPa), corroborating their inferior structural performance. Researchers further demonstrated that laminate stacking configuration and fabric waviness ratio play significant roles in determining composite failure mechanisms and stiffness distribution.

4.10. Impact strength

The impact strength of the banana fibre-reinforced PVA composites was evaluated to determine their capacity to absorb energy under sudden or dynamic loading conditions. This mechanical property is particularly vital for applications where materials are subjected to abrupt forces, such as in packaging materials, protective gear, and automotive interior components. The results, presented in Figure 12, show clear distinctions in energy absorption among the composite structures.

The nonwoven composites exhibited significantly higher impact resistance compared to their woven counterparts. Both the Mat Structure and Multi-Directional composites recorded impact strength of 1.3 J, whereas the Plain Weave and Twill Weave composites displayed lower energy absorption capacities of 1.13 J and 1.10 J, respectively. This indicates that the random fibre orientation and uniform fibre dispersion in nonwoven composites enhance their ability to dissipate impact energy more effectively. Such behaviour aligns with (Nguyen et al. 2022), who reported that nonwoven composites demonstrate superior shock absorption due to their disordered fibre arrangement, which hinders crack propagation and increases energy dissipation pathways.

In contrast, the rigid and structured alignment of fibres in woven composites, though beneficial for tensile and flexural performance, limits their capacity for plastic deformation under impact loading. The interlacing points in woven fabrics tend to act as stress concentrators, initiating micro-cracks and facilitating brittle failure under dynamic stresses. Consequently, the energy absorption potential of woven composites is inherently lower compared to that of nonwoven systems.

These findings suggest that nonwoven banana fibre composites are more suitable for impact-critical applications where energy dissipation and shock absorption are essential, such as helmet linings, cushioning layers, and automotive interior panels. In contrast, woven composites are better suited to structural or load-bearing applications, where rigidity, dimensional stability, and resistance to long-term deformation are prioritized.

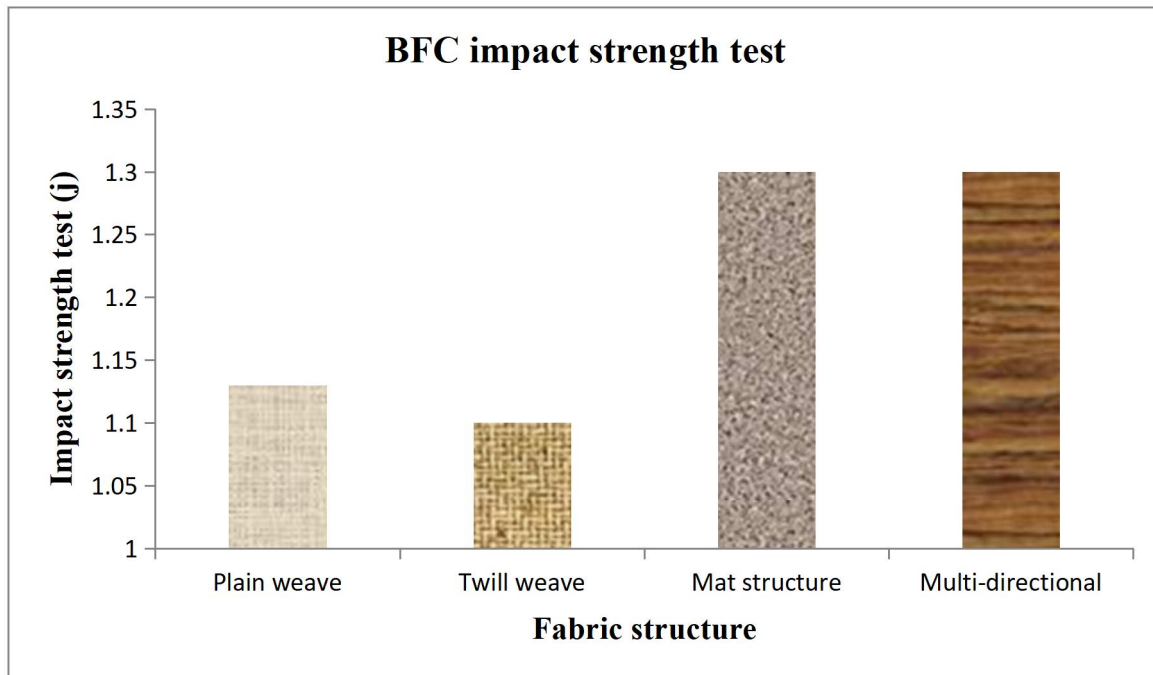


Figure 12: Impact test results of woven and non-woven BFC-reinforced PVA board.

Recent studies reinforce the superior impact performance of nonwoven-reinforced composites. (Kondrateva et al. 2025) demonstrated that epoxy composites incorporating nonwoven polyamide fabric maintained structural integrity under 6.67 J impact energy, exhibiting only delamination, whereas those without nonwoven reinforcement suffered complete failure with fibre breakage. The inclusion of nonwoven material increased compressive strength after impact from 260 to 320 MPa. Similarly, (Tiyek et al. 2024) found that interlayer nonwoven reinforcements in hybrid composites improved peak impact forces and reduced deformation, acting as crack-arresting barriers that enhanced overall damage tolerance. (Lin et al. 2020) reported superior puncture absorption in sandwich-structured nonwoven composites fabricated with high-strength polyester staple fibres, achieving 415 N stab resistance. Furthermore, (Karnoub et al. 2020) confirmed enhanced impact and mechanical performance in nonwoven glass fibre laminates compared to woven alternatives, supporting the consistent advantage of nonwoven architectures in absorbing and redistributing impact energy.

4.11. Compressive strength

The compressive performance of the banana fibre-reinforced PVA composites was evaluated to determine their ability to withstand compressive loads without undergoing failure or excessive deformation. This property is particularly important for applications where the material experiences compressive stresses, such as in load-bearing components, structural panels, or packaging systems. The results, presented in Figure 13, shows notable variations in compressive strength among the different composite structures.

The multi-directional nonwoven composite exhibited the highest compressive strength at 36.72 N/mm^2 , closely followed by the plain weave composite at 34.45 N/mm^2 . These results indicate that both well-oriented nonwoven fibres and tightly interlaced woven structures provide efficient resistance to compressive deformation due to enhanced fibre packing and improved matrix-fibre stress transfer. The twill weave composite showed moderate compressive strength of 29.11 N/mm^2 , while the mat structure composite recorded the lowest value at 18.36 N/mm^2 , suggesting poor load distribution and premature buckling under compression.

The superior compressive performance of the multi-directional and plain weave composites may be attributed to their balanced fibre orientation and uniform stress transfer throughout the matrix. The controlled fibre arrangement minimizes void formation and enhances interfacial adhesion, resulting in better load distribution and reduced micro-buckling during compression. Conversely, the random fibre distribution in the mat structure composite creates weak zones, which promote localized deformation and early structural collapse under compressive loads.

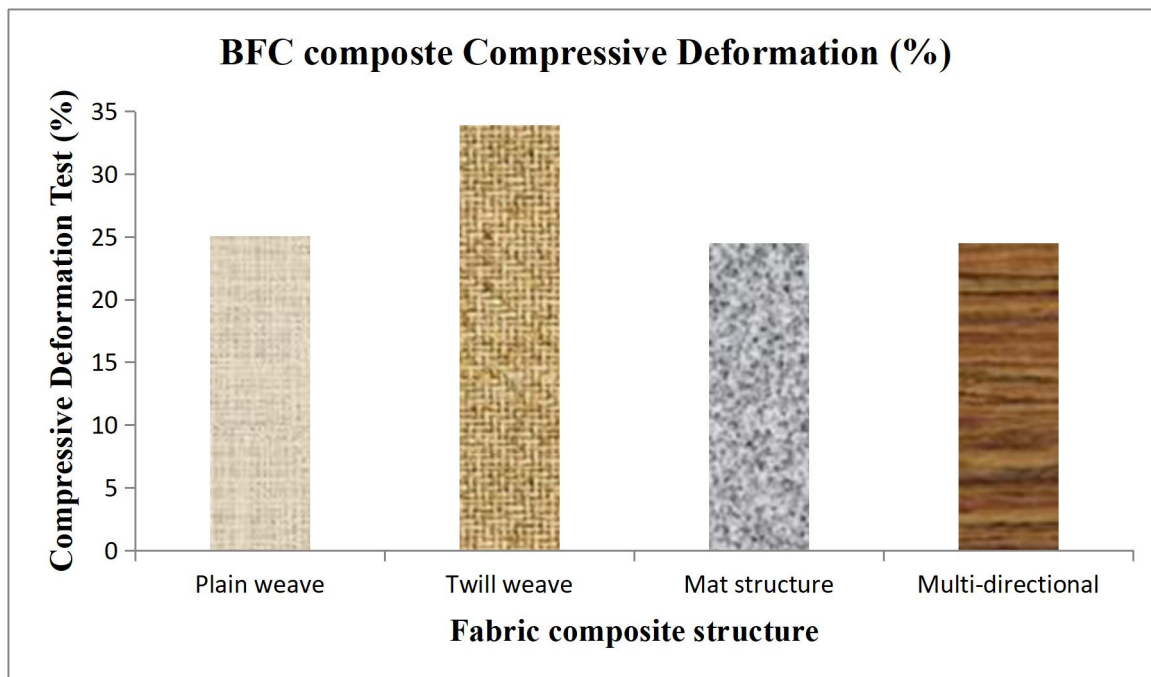


Figure 13. Compressive test result of woven and non-woven BFC-reinforced PVA board.

From an engineering standpoint, these findings suggest that multi-directional nonwoven and plain weave composites are best suited for applications requiring dimensional stability and compressive load-bearing capacity, such as wall panels, casing components, and reinforcement cores. In contrast, twill weave composites offer a compromise between flexibility and strength, while mat composites may require modification, such as resin impregnation enhancement or hybrid fibre blending, to improve their compressive stiffness and durability.

Previous studies corroborate these findings by demonstrating that fibre orientation and interfacial bonding play decisive roles in determining compressive performance. (Kandola et al. 2022) reported that aligned natural fibre composites exhibited up to 30 % higher compressive strength than randomly oriented systems due to improved fibre alignment and matrix load transfer efficiency. (Shah et al. 2023) observed that woven kenaf/epoxy composites showed superior compressive stability compared to nonwoven mats, attributing this to uniform fibre crimp and better consolidation during curing. (Mishra et al. 2021) similarly noted that unidirectional and plain weave jute composites achieved higher compressive strength due to their controlled architecture and reduced inter-laminar shear effects.

4.12. Possible application of BFC-reinforced PVA composite board

The banana fibre composite (BFC)-reinforced PVA boards developed in this study demonstrate promising mechanical properties, particularly in tensile, flexural, and impact strength, which suggest suitability for low-load interior construction applications, packaging, and furniture components. However, their application must be evaluated in relation to environmental performance and durability under real-world conditions.

While these composites exhibit acceptable performance in dry environments, their hydrophilic nature poses limitations. This is evidenced by the high-water absorption rates of the fibres, attributed to their amorphous cellulose regions as confirmed through FTIR and XRD analysis. Over prolonged exposure, water ingress may weaken the fibre–matrix interface and cause swelling, which compromises mechanical integrity. Furthermore, the PVA matrix, though biodegradable and adhesive, is water-soluble over time, potentially accelerating composite degradation in moist conditions (Okoronkwo et al. 2025). As such, these boards may require waterproof coatings or surface treatments for applications in humid or wet environments (Table 7).

The tensile strength of BFC composites, particularly the plain weave and multi-directional structures, falls near the lower boundary of the ASTM standard range. While lower than synthetic fibre-reinforced polymers, this performance is consistent with values reported for banana fiber-based composites. The relatively higher performance of the plain weave is attributed to better fibre alignment and interfacial load transfer. Flexural strength results further validate the suitability of BFC boards in structural applications.

Table 7: Provides a comparative performance summary of the fabricated BFC-PVA composites against typical ASTM standards and existing literature benchmarks

Property	Plain weave	Twill weave	Mat structure	Multi-directional (typical range)	ASTM standard	Relevant ASTM standard
Tensile (N/mm ²)	20.03	15.28	18.83	19.42	20–100	ASTM D3039 /D3039M
Flexural (N/mm ²)	42.52	32.16	11.27	40.43	30–150	ASTM D7264 /D7264M
Impact (J)	1.13	1.1	1.3	1.3	0.5–10	ASTM D256 (Izod)/ ASTM D6110 (Charpy)
Compressive Deformation (%)	25.08	33.9	24.52	24.52	1–5 (for fibre composites)	ASTM D695/ ASTM D6641 /D6641M

The plain weave and multi-directional composites fall within typical ranges for natural fiber composites (30–100 N/mm²), as reported by (Tiyek et al. 2024). The significantly lower flexural strength of the mat composite (10.27 N/mm²) may result from random fibre orientation and weak fiber-matrix adhesion.

However, impact strength remains below standard expectations for structural applications. With values ranging between 0.1 and 0.3, the composites exhibit limited energy absorption capacity. (Okoronkwo et al. 2025) note that natural fibres typically suffer from lower impact strength due to their brittle matrix interactions and lack of toughening mechanisms seen in synthetic alternatives. Compressive deformation values are notably high, ranging from 23.52 to 32.90 %, well above the typical 1 – 5 % range reported for natural fiber composites. This may be due to high porosity, insufficient cross-linking in the matrix, or fibre misalignment. These results suggest limited applicability in load-bearing compressive environments without further material reinforcement.

V. CONCLUSION AND FUTURE STUDIES

This study explored the fabrication and mechanical performance of woven and nonwoven banana fiber composites reinforced with polyvinyl alcohol (PVA) as a biodegradable matrix. The results demonstrated that the fibre orientation and fabric architecture significantly influence composite performance. Woven composites, particularly the plain weave configuration, showed superior tensile and flexural properties due to improved fibre alignment and effective stress transfer. In contrast, nonwoven composites, especially those with a multi-directional arrangement, exhibited better impact resistance, attributable to their random fibre orientation, which facilitates energy dissipation under sudden loading.

Despite these promising results, certain limitations were evident. Water absorption analysis confirmed the hydrophilic nature of untreated banana fibres and the susceptibility of PVA to moisture degradation. High compressive deformation values also suggest limited stiffness and structural integrity under compressive loads, making the composites more suited for low-load, indoor applications rather than high-stress structural uses.

The findings reaffirm the potential of banana fibre as a sustainable and locally available reinforcement material in biodegradable composites. However, to enhance the mechanical robustness and expand the functional scope of these materials, further research is warranted.

5.1. Policy implications, research, practical implications and recommendations

The findings of this study present several important policy implications. The use of banana fibre, an agricultural waste product, for composite development aligns with circular economy goals and sustainable development objectives. Policymakers should prioritize incentives for agro-waste valorization through support for small-scale enterprises and green manufacturing. In addition, policies that integrate natural fibre composites into public procurement standards and green building codes can drive demand for eco-friendly materials. Establishing clear technical and safety standards for bio-based composites will also foster market confidence and industrial applications.

From a research perspective, this study contributes valuable empirical data to the growing body of work on natural fibre-reinforced composites. It highlights the need for further investigation into the effects of fibre surface treatments, such as alkali or enzymatic modification, on mechanical strength and moisture resistance. Comparative studies involving treated versus untreated fibres, as well as advanced modelling of fiber-matrix interactions, could provide deeper insights into improving composite performance. Moreover, interdisciplinary research integrating material science, sustainability assessment, and rural development is essential for evaluating the socio-economic viability of scaling up such innovations.

The practical implications of this work are significant for industries in packaging, interior design, and low-load structural applications. The banana fibre composite boards developed, especially those using plain weave and multi-directional configurations, demonstrated adequate tensile and flexural properties suitable for applications such as interior partitions, ceiling panels, and biodegradable packaging. However, the relatively low impact resistance and compressive deformation of these composites suggest limitations in high-load or outdoor environments. Therefore, these materials are best suited for indoor applications or temporary-use products, particularly where environmental degradation and compost-ability are desired.

In light of the above, several recommendations are proposed. First, future work should focus on enhancing fibre properties through chemical or enzymatic treatments to improve adhesion and reduce water uptake. The use of alternative or modified polymer matrices with better hydrophobic properties should also be explored. Hybridizing banana fibre with other natural or synthetic reinforcements may yield composites with superior performance suitable for broader applications. Additionally, collaboration with standards organizations to develop testing protocols and certifications specific to natural fibre composites will support commercialization. Finally, community-level training for farmers and artisans on fibre extraction and initial processing can stimulate grassroots innovation and support local economic development.

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Competing interests

The authors declare no competing interests.

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