

Alkali Treatment Effects on the Tensile Characteristics of Vacuum-Infused Banana and Flax Woven Fiber Composites

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ABSTRACT

This experimental research work investigates the alkali treatment of natural fiber-reinforced composites (NFRCs) prepared from banana and flax woven fibers for mechanical behavior. The fundamental purpose of this study is to explore the Banana and Flax woven fibers as reinforcement in polymer composites, regarding different concentrations of alkali solution (4%, 6%, and 8%) and their influence on the tensile properties of the two natural fibers. The density of each developed composite is also evaluated. The composites were made using a vacuum infusion process, providing good impregnation and uniform resin distribution. A tensile test was conducted using ASTM D3039 for tensile strength, modulus, and tensile strain behavior. For untreated samples of banana fiber composites, ductility was comparatively high at 34% strain, with a moderate tensile strength of 26.12 MPa. Application of a 6% alkali treatment elevated tensile strength to 42.83 MPa and tensile modulus to 772.82 MPa, albeit at a reduced ductility of 5.4%. These results suggest enhanced interfacial bonding but greater brittleness. Flax fiber composites had a different response, where untreated flax fiber-reinforced composites exhibited a tensile strength of 49.55 MPa, a tensile modulus of 391.33 MPa, and a ductility of 8.48%. In contrast, alkali treatment markedly enhanced ductility, peaking at 16.02% for the 4% treated composites. Each composite, regardless of being untreated or alkali-treated, exhibited distinct mechanical behavior when processed under varying concentrations, illustrating the optimization depth needed for each fiber type to achieve the desired strength, stiffness, and ductility. The study does illustrate the potential of tailored alkali treatments in the form of enhanced performance on composite materials made with banana and flax woven fibers, reinforcing the materials' prospects for sustainable lightweight structural solutions.

1. Introduction

The increasing demand for acceptable and environmentally suitable materials has propelled research into natural fiber-reinforced polymer composites [1]. These natural reinforcements, such as banana and flax fibers, offer the potential for high specific strength coupled with lower density, making

them attractive for various applications [2]. The growing awareness of the environmental impact of synthetic materials is a primary driving force behind the increasing demand and research interest in natural fiber-based composites [3,4]. This research investigates the influence of varying alkali concentrations on the tensile strength and density of composite materials reinforced with banana and flax

fibers in a weave structure, where the composites are manufactured using the vacuum infusion technique.

Natural fibers, derived from renewable resources, have garnered attention for their mechanical properties, lightweight nature, and biodegradability. The utilization of natural fibers as reinforcements in composites is driven by the quest for sustainable replacements to synthetic fibers such as glass and carbon, which are often associated with adverse environmental impacts. Previous studies have demonstrated that banana fibers, known for their strength and elasticity, can significantly enhance the tensile properties of polymer composites [5,6]. Woven banana fiber composites, in particular, benefit from the inherent structural integrity provided by the woven arrangement, which facilitates improved stress distribution under tensile loads. This has led to findings such as those of Sekaran et al. [7], who documented enhanced tensile and flexural characteristics in woven banana and glass fiber epoxy composites. Conversely, flax fibers represent another promising natural reinforcement option, particularly known for their exceptional tensile strength relative to their weight [8]. Investigations into flax fiber-reinforced polymer composites have consistently improved mechanical properties, rendering them suitable for various applications ranging from civil engineering structures to lightweight vehicle components [9]. Recent literature emphasizes the role of the orientation of fibers and treatment in optimizing the mechanical performance of flax composites, indicating that the orientation of fibers can substantially influence the resultant mechanical properties [10].

Additionally, the hybridization of different natural fibers presents an opportunity to leverage the unique properties of each fiber type to achieve a composite material that excels in mechanical performance. For example, by combining banana and flax fibers, researchers have observed enhancements in tensile strength and impact resistance attributed to the complementary nature of these fibers when integrated into a polymer matrix [10]. With the ecological benefits of using natural fibers, their incorporation into polyester or epoxy matrices serves as an avenue to decrease the environmental stress typically linked with synthetic composites [11]. A key feature influencing the tensile strength of these composites is their manufacturing process, specifically the treatment and arrangement of fibers. For instance, treating banana fibers with alkali solutions has significantly

improved tensile properties due to increased interphase adhesion between the fiber and matrix, facilitating more effective stress transfer [12]. As highlighted by Hosseini et al., incorporating nano-sized additives into these composites has further enhanced their performance by improving the fiber-matrix interaction [13]. Another study by Naveena et al. [14] explored the development of hybrid composites deploying natural fibers reinforced with polypropylene, highlighting their mechanical properties and possible applications within various industries, ranging from automotive to construction. Thus, NFRCs are sustainable and promising green materials for industries, particularly in the automobile sector. However, natural fibers are susceptible to absorb moisture as they are hydrophilic in nature, which lowers the interfacial adhesion between the fiber-reinforced and the matrix, negatively impacting their mechanical properties, giving dimensional instability, and developing internal stresses [15]. The alkali treatment is crucial in enhancing the physical and chemical bonding among these fibers and the polymer matrix, thus maximizing the composite's performance in various structural applications.

Given the promising prospects of alkali treatment for bolstering the mechanical properties of various natural fiber composites, this research aims to meticulously investigate the influence of alkali treatment on the tensile properties of banana and flax fiber-reinforced composites. This study endeavors to elucidate the intricate relationship between different treatment concentrations and their subsequent effects on fiber characteristics, ultimately providing a comprehensive understanding of how specific surface modifications can lead to enhanced material performance.

This investigation will systematically explore the alterations in fiber morphology, surface chemistry, and interfacial adhesion resulting from varying alkali treatment parameters. By analyzing the tensile strength, tensile modulus, and strain at break of the resultant composites, this research seeks to identify optimal treatment conditions that yield superior mechanical performance for both banana and flax fibers when incorporated into an epoxy matrix. The findings of this study are anticipated to contribute significantly to the growing body of knowledge on natural fiber composites, offering valuable insights for the development of sustainable and high-performance materials suitable for diverse engineering applications.

Table 1 summarizes relevant literature concerning the tensile properties of banana and flax fiber-reinforced

composites, drawing comparisons in mechanical performance.

Table 1

Previous investigation on banana/flax fiber-reinforced polymer composite

No	Reference	Composite Matrix	Fiber Reinforcements	Key Findings
1	Irawan and Sukania (2015) [5]	Epoxy	Banana Fiber	Alkali treatment enhances tensile strength; untreated fibers perform significantly lower.
2	Venkateshwaran et al. (2011) [16]	Epoxy	Banana Fiber	30-40 mm fiber length yields optimal mechanical performance; hybridization with sisal shows positive effects.
3	Sekaran et al. (2015) [7]	Epoxy	Woven-Banana and Glass Fiber	Woven composites have improved tensile strength, flexural strength, and impact energy compared to conventional composites.
4	Biresaw and Yigezu (2022) [8]	Polymer	Flax and False Banana Fiber	Superior tensile performance observed; optimal properties achieved with unidirectional fiber orientation.
5	Jubair et al. (2021) [17]	Epoxy	Banana and Glass Fiber	The material properties of various hybrid composites exceed those of individual fiber systems.
6	Kumar S et al. (2024) [10]	Epoxy	Banana and Corn Fiber	Enhanced tensile properties compared to singular fiber composites, indicating a potential for tailored combinations.
7	Sivaranjana and Arumugaprabu (2021) [6]	Polyester	Banana Fiber	Demonstrates a 30-50% increase in tensile and flexural strength through effective reinforcements.
8	Nguyen and Nguyen (2021) [9]	Epoxy	Banana Fiber	Swelling effects in fiber treatment yield preferable mechanical properties for bio-epoxy composites.
9	Naveena et al. (2021) [14]	Polypropylene	Sisal-Banana, flax-banana and sisal-flax fiber	Exploring the synergy between fibers yields over 30% improvement in tensile properties compared to single fiber composites.
10	Vivek et al. (2020) [18]	Epoxy	Sisal-Banana and Kenaf-Flax	A study revealed that adding 30% fibers by volume enhances the flexural toughness of composites. However, the strength lowers if the fiber loading is higher than the optimum amount. In addition, an increasing trend in the bagasse ash (BGA) factor causes a decrement in flexural strength of the composites.
11	Frącz et al. (2021) [19]	Poly (3-hydroxybutyric-co-3-hydroxyvaleric acid) (PHBV) biopolymer	Hemp fibers and flax fibers	The study concluded that each filler, whether plant-based or from a polymer matrix, requires an individually selected fiber alkalization method to improve the specific characteristics of bio-composites. Furthermore, treatment with 2%, 4%, and 6% NaOH influenced tensile strength, with optimal performance observed at lower NaOH concentrations.

12	A. Gunge et al. (2019) [20]	Polyvinyl alcohol	Plain woven banana fabric	The study revealed that 6% NaOH-treated Woven Banana Fabric and Polyvinyl alcohol composite exhibit the greatest tensile strength of 131.5 MN/m ² , flexural strength of 94.2 MN/m ² , and impact strength of 1.3 J/m ² when compared to untreated and certain treated composites.
13	Mostafa and Uddin (2015) [21]	soil-cement	Banana fibers	With 6% NaOH, the Alkali treatment intensified fiber-matrix adhesion by removing impurities, resulting in improved mechanical properties.
14	Lai et al. (2019) [22]	Cementitious	Flax fibers	Roughened surface from alkali treatment resulted in better bonding within the matrix, enhancing tensile properties.
15	Dunisho et al. (2020) [23]	Polyester	Enset fibers	With 5 wt. % NaOH enhanced bonding improved mechanical strength and reduced moisture absorption in composites.
16	Cai et al. (2015) [24]	-	Abaca fibers	The elastic modulus of abaca fibers subjected to a 5 wt. % sodium hydroxide solution improved by 41%. In contrast, treatment with 10 wt. % and 15 wt. % NaOH solutions lowered 24% and 29%.
17	Singh et al. (2021) [25]	Polylactic acid	Flax fibers	The enhanced mechanical properties observed in hybrid composites, as opposed to single-fiber composites, were primarily attributable to the implementation of alkali treatment.
18	Mejía Julio César et al. (2012) [26]	-	Banana fibers	The application of a 5% NaOH solution significantly enhances the mechanical characteristics of banana fibers (<i>Musa paradisiaca</i>) by virtue of the alkali treatment process. This process primarily aims to disrupt hydrogen bonds within the fiber's network structure and remove hemicellulose, lignin, wax, and oils. Consequently, this leads to increased surface roughness and reduced hydrophilicity, positively influencing the fibers' strength and stiffness.

The suitability of flax and banana fibers for reinforcing composite structures has been established in prior research. Additionally, these studies suggest that alkali treatment has a substantial impact on the material-related properties of the enhanced natural fiber composites [27]. Specifically, research by Irawan and Sukania [5] and A. Gunge [20] have shown that alkali treatment enhances the tensile strength of banana fiber composites, while Frącz et al. [28] observed that NaOH treatment at lower concentrations affects the tensile strength of flax fibers. Furthermore, concentrations around 6% NaOH are effective in improving fiber-matrix adherence and mechanical properties in both banana and woven banana fabric composites. Therefore, in this study, we investigated the effect of alkali treatment on flax and banana fiber-reinforced composites using NaOH concentrations of

4%, 6%, and 8% to explore a range around this reported effective concentration and to identify optimal treatment parameters for both fiber types. This methodical approach allowed for a direct comparison of the efficacy of varying alkali concentrations on the tensile performance of both flax and banana fiber composites. The insights gained will contribute to a more nuanced understanding of how surface modifications influence the mechanical behavior of these sustainable materials.

2. Materials and Methods

2.1 Materials

Banana fabric (plain woven) was procured from Suvetah Textile, India. Easy Composites, UK,

supplied Flax Fabric (Twill 2/2) and epoxy resin (Huntsman, CY 219 with hardener HY 5160). The properties taken from technical data sheets are given

Table 2

Physical and Mechanical Properties of Flax and Banana Fabric

Reinforcement	Weave Style	Fabric Thickness (mm)	Weight (GSM)	Count	Tensile Strength (MPa) in warp	Tensile Strength (MPa) in weft	Tearing strength (MPa) in warp	Tearing strength (MPa) in weft
Banana	Plain Weaving	0.055	60-70	65	0.296	0.201	>0.025	>0.017
Flax 200 Dry	Twill 2/2	0.068	200	5.5	0.678	0.837	>0.099	>0.099

Table 1

Properties of Epoxy [29] [30] [31]

Component / Property	Value	Unit
RenLam CY219 (Resin)	100	Parts by Weight
Rec HY5160 (Hardener)	60	Parts by Weight
Gel Time	1.3	Hours
Demoulding Time	16	Hours
Tensile Strength (CY219)	~70	MPa
Modulus of Elasticity (CY219)	3.5	GPa
Glass Transition Temperature (CY219)	~200	°C
Thermal Conductivity (CY219)	0.2	W/m·K
Tensile Strength (HY5160)	~80	MPa
Modulus of Elasticity (HY5160)	4	GPa
Flexural Strength (HY5160)	~120	MPa
Impact Strength (HY5160)	~60	kJ/m ²
Moisture Absorption (HY5160)	<0.5	%

3. Experiment Procedure

3.1 Alkali Treatment Procedure

The composite material's strength is fundamentally related to the quality and effectiveness of the bonding mechanism occurring at the interface of reinforcing fibers and matrix material [32]. The interface of

for fabrics in Table 2, and for the resin are given in Table 3.

composite materials can be effectively modified through the application of chemical treatments. These treatments facilitate interactions between the fiber and resin materials present on the composite layers. Amongst various treatment processes involving chemical reactions that have been extensively investigated, alkali treatment has emerged as the predominant coupling agent employed to enhance the bonding in the middle of fiber and matrix material [33]. The application of alkali treatment was observed to have a notable influence on the mechanical properties of materials under investigation. Furthermore, this specific utilization of hybrid composites exhibited relatively splendid properties in comparison to other composite materials. Nevertheless, as reported by [34], alkali-treated natural fibers had better mechanical properties because they increased the adhesion that exists within the reinforcement and matrix material. All natural fibers are composed of lignin and cellulose-pivoted fibers. The presence of semi-cellulose substance on the exterior surface hinders adequate bonding in between the matrix and fiber [35]. The treatment of fabric is given below:

- We cut the plain woven banana fabric and flax fabric into 1-meter pieces.
- Both fabrics were soaked in separate containers for an hour at room temperature in an alkali solution containing 4%, 6%, and 8% concentrations.

- C. The treated fabrics were rinsed with tap water and then with distilled water to ensure that any excess sodium hydroxide was removed from their surfaces.
- D. The washed fabrics were dried at room temperature until all moisture was completely removed.

The selection of 4%, 6%, and 8% NaOH concentrations for alkali treatment was investigated by prior studies, indicating that this range is optimal for enhancing fiber surface morphology while avoiding structural degradation. Concentrations below 4% are often insufficient to remove surface-bound hemicellulose and lignin, while concentrations above 8% can damage cellulose microfibrils, reduce crystallinity, and compromise tensile properties [35, 24, 28]. Thus, this controlled range enables improved fiber-matrix interfacial bonding by increasing surface roughness and exposing hydroxyl groups without undermining mechanical integrity.

3.2 Composite Processing

Flax / Epoxy and Banana / Epoxy composites were developed with the help of the vacuum infusion technique, in which woven flax and woven banana were deployed as reinforcement, and Epoxy was selected as a matrix material. The resin-to-hardener ratio of 100:60 by weight was selected based on the stoichiometric balance recommended by the manufacturer, ensuring optimal crosslinking between epoxide and amine groups to form the composite layers.

In the current study, two layers of woven reinforcing fabric (either banana or flax) were laid directly over each other in a 0°/0° orientation, i.e., without any angular offset. The warp and weft directions of both layers were perfectly aligned to ensure uniform load distribution along the fiber axes. This configuration was deliberately chosen to eliminate cross-ply effects, isolate unidirectional tensile behavior, and focus on the influence of alkali treatment and fiber type on mechanical performance. Plain woven Banana fabric was cut to 304.8 mm x 304.8 mm and treated with alkali solution with 4, 6, and 8% for one hour. The same procedure was used for flax fabric.

Composite sheets (304.8 mm x 304.8 mm) consisting of 2 layers of pure banana fabric for untreated banana were later subjected to the process of vacuum infusion with the resin. In order to maintain infused fibers under a uniform pressure of 100 mbar for a day (at ambient temperature), a vacuum pump was used. Subsequently, a post-curing step took place in an oven at 80 °C for 1 hour. The curing temperature of 80°C was selected based on its compatibility with epoxy systems such as RenLam CY219/HY5160, where moderate thermal energy accelerates crosslinking without exceeding the thermal stability limit of alkali-treated banana or flax fibers (~100–120°C) [16,31]. Curing at 80°C facilitates uniform polymerization, reduces residual stresses, and prevents fiber embrittlement or delamination, which are commonly observed at higher post-curing regimes.

The same method was carried out for all composites. The various Composite designation and their weights before and after fabrication are mentioned in Table 4. A flowchart of the methodology is given in Figure 1.

Figure 2 outlines the steps involved in creating a composite laminate, starting from raw material, followed by alkali treatment and cutting to mold dimensions. Simultaneously, resin and hardener are mixed. The treated fabric is then placed in a mold with the resin mixture and subjected to a curing process, resulting in the final composite laminate.

The careful control of parameters during each stage, from fiber treatment to the final curing, is crucial for achieving optimal mechanical properties in the resulting composites. The alkali treatment, for instance, enhances the interfacial adhesion between the natural fibers and the epoxy matrix by removing impurities and increasing surface roughness, thereby improving the load transfer capabilities and overall structural integrity of the composite materials.

Table 4 presents the composite sample codes along with their respective masses measured before and after fabrication. Each designation indicates the fiber type (BFRC: Banana Fiber-Reinforced Composite; FFRC: Flax Fiber-Reinforced Composite), the concentration of NaOH used for treatment, and a consistent two-layer configuration.

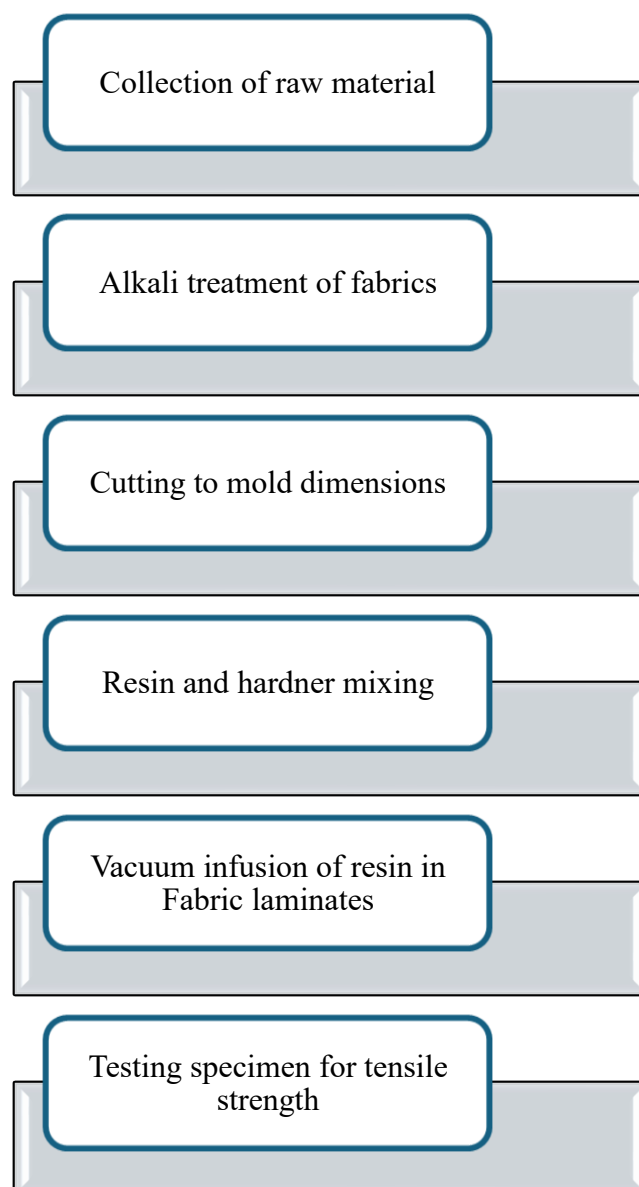
Table 4

Composite Codes

Category	Code	No. of Layers	Alkali Treatment (%)	Laminates Weights	
				Befor e in (g)	Af ter in (g)
Banana Fiber Reinforced composites (BFRC-2)	Untreated Banana	2	0	14.5	35.4
4-BFRC-2	4TB	2	4	17.3	45.3
6-BFRC-2	6TB	2	6	14.6	43.9
8-BFRC-2	8TB	2	8	16.9	49.5
Flax Fiber Reinforced Composite (FFRC-2)	Untreated Flax	2	0	41.4	139.4
4-FFRC-2	4TF	2	4	50.9	196.8

As shown in Table 4, all BFRC samples exhibited an increase in laminate weight after fabrication, regardless of NaOH concentration. While the weight gain was generally consistent, slight variations were observed. Notably, the samples treated with 4% and 8% NaOH showed a marginally higher weight increase compared to the 6% sample. However, the

differences are not substantial enough to suggest a clear trend, indicating that further investigation or statistical analysis may be necessary to assess the significance of alkali concentration on laminate weight gain. At 4%, partial removal of surface impurities (e.g., waxes and hemicellulose) may have exposed additional hydroxyl groups, enhancing wettability and allowing greater resin penetration. Similarly, at 8%, excessive etching may have increased surface roughness and porosity, facilitating deeper resin infiltration and contributing to higher composite weight. In contrast, the 6% concentration may represent a threshold where fiber surface activation and matrix saturation reach equilibrium, leading to no significant additional uptake. This trend aligns with prior studies noting that moderate alkali concentrations enhance surface chemistry without overexposing the fiber [20][28].

**Fig. 1** Flow Chart of the Methodology

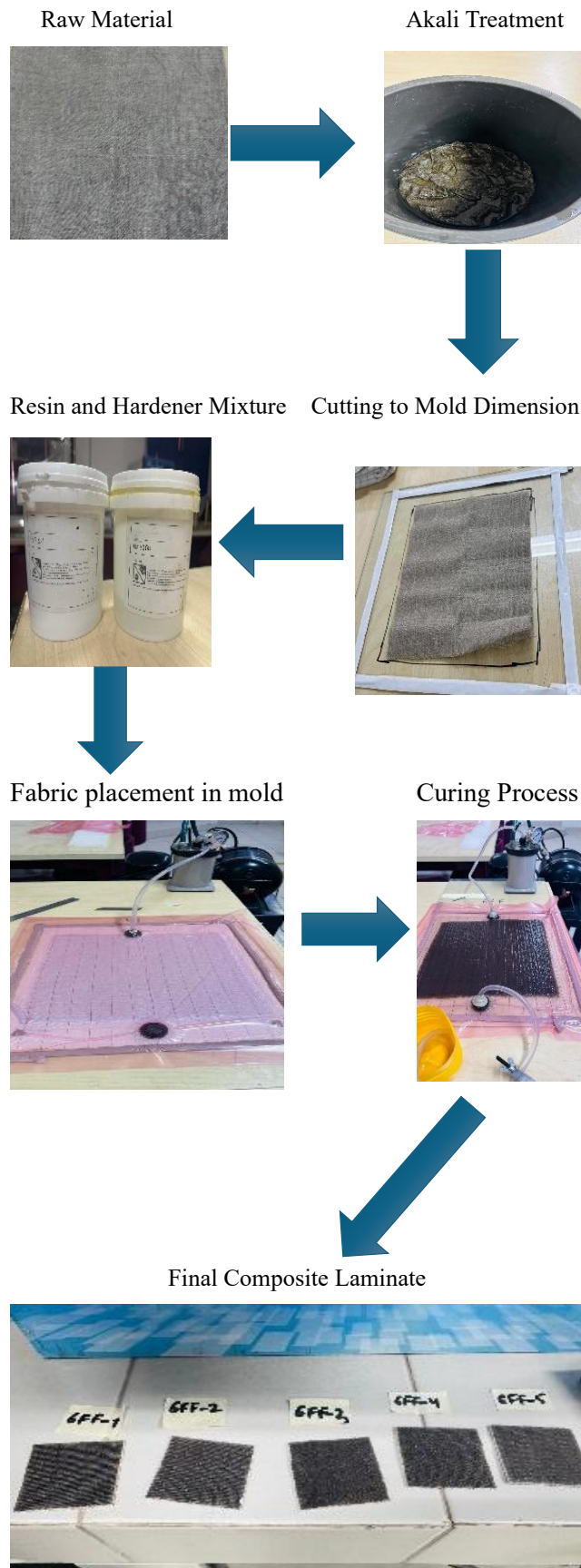


Fig. 2 Fabrication process of composite laminate

3.3 Density and Void Fraction

Density is fundamentally described as the ratio of mass and volume of a body. The density of composite materials can be determined using the following formula:

$$Density = \frac{1}{\frac{w_f}{\rho_f} + \frac{w_m}{\rho_m}}$$

Where,

w_f = weight fraction of fiber and is given by $w_f = \text{Wt. of fiber} / \text{Wt. of composite}$,

ρ_f = density of fiber,

w_m = is the weight fraction of the matrix,

ρ_m = is the density of the matrix

The void fraction is calculated to estimate the number of voids existing within the composite. It is given by

$$Void\ fraction = \frac{\rho_{theoretical} - \rho_{experimental}}{\rho_{theoretical}}$$

Experimental density is calculated using Archimedes' principle.

3.4 Tensile Test Procedure

Tensile testing was conducted in accordance with ASTM D3039 using a universal testing machine (Instron 3366, 10 kN capacity), as shown in Figure 3. Specimens were cut to a gauge length of 150 mm and tested at a crosshead speed of 10 mm/min. Flat rectangular specimens were used to suit the woven fiber architecture and ensure effective load transfer. Each specimen was aligned carefully in the grips to prevent slippage. A uniaxial load was applied until failure, with load–displacement data recorded to calculate stress–strain behavior, including ultimate tensile strength, break load, and strain at failure. As per ASTM D3039, five replicates were tested for each composite configuration to ensure statistical reliability. In addition to the gauge length, other specimen dimensions such as width and thickness are provided in Table 6. Table 7.

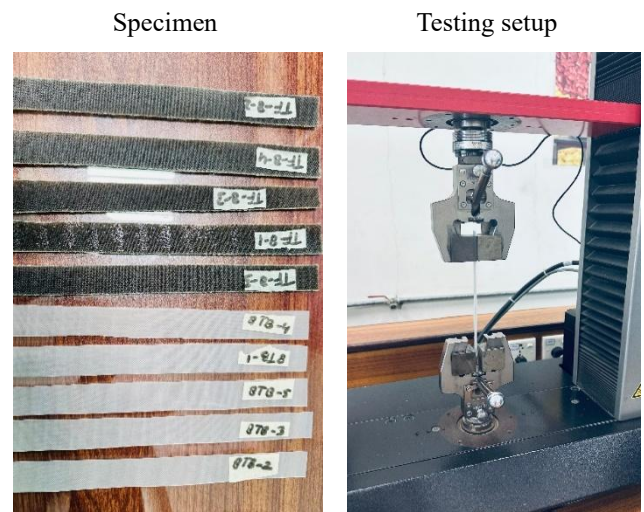


Fig. 3 Composite tensile specimens and Setup

4. Results and Discussion

4.1 Density and Void Fraction

Figure 4 and Table 5 illustrate a comparison between the theoretical and experimentally calculated densities of six composite samples. In all instances, the experimental density was marginally lower than the theoretical value. This slight reduction is attributed to the vacuum infusion curing method employed for the laminates, which effectively minimized the presence of void fractions within the material.

Experimental densities were generally lower than theoretical densities, indicating the presence of manufacturing voids. For BFRC, experimental density increased with alkali treatment up to 6% (peaking at 1.2432 g/cm³) before slightly decreasing at 8%. This suggests optimal densification around 6% treatment. FFRC experimental densities (around 1.2 g/cm³) showed less variation with alkali treatment compared to untreated samples, implying a less pronounced effect on Flax fiber packing within this range.

The void content analysis revealed that untreated BFRC had 8.49% voids, which significantly reduced to a minimum of 0.33% at 6% alkali treatment, suggesting this concentration is optimal for reducing porosity in BFRC. For FFRC, the untreated void content was 6.38%. Alkali treatment did not show a consistent reduction; the 6% treatment resulted in the highest void fraction (8.64%) among FFRC samples. This indicates a different or less predictable effect of alkali treatment on void formation in FFRC compared to BFRC.

Table 5

Theoretical and Experimental Density of Composites

Code	Theoretical density (g/cm ³)	Experimental Density (g/cm ³)	Void fraction
Untreated Banana	1.3028	1.1922	8.49
4TB	1.3338	1.2374	7.23

6TB	1.2473	1.2432	0.33
8TB	1.2474	1.2258	1.73
Untreated Flax	1.2909	1.2086	6.38
4TF	1.2740	1.199	5.89
6TF	1.3139	1.2004	8.64
8TF	1.2740	1.2014	5.7

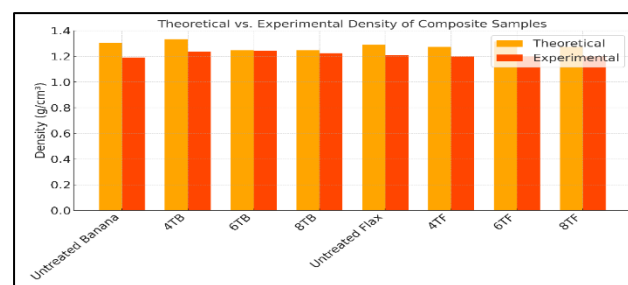


Fig. 4 Theoretical and Experimental Density of Composites

4.2 Tensile Test

The primary goal of this study was to evaluate the tensile properties of natural fiber-reinforced composites fabricated with two different natural fabrics. The various tensile properties are mentioned in Table 6 for Flax and Banana composites with varying concentrations of Alkali treatment.

Table 6

Tensile Properties determination and results

Code	Tensile Modulus (E_t)	Tensile Strength (σ_M)	Strain at Tensile Strength (ϵ_M)	Stress at break (σ_B)	Strain at break (ϵ_B)	Specimen Thickness (h)	Specimen Width (b)	Cross section (A_0)
	MPa	N/mm ²	%	N/mm ²	%	mm	mm	mm ²
Untreated Flax	391.33	49.55	8.46	49.15	8.48	1.35	25.23	34.07
4TF	194.84	24.03	15.44	20.74	16.02	1.94	24.36	47.31
6TF	244.70	28.20	15.40	26.07	15.91	1.62	24.56	39.80
8TF	223.97	17.43	14.77	14.12	14.99	1.9	25.66	48.81
Untreated Banana	561.21	26.12	33.97	25.70	34.00	0.40	24.08	9.63
4TB	577.92	31.36	37.30	30.92	37.38	0.48	24.12	11.58
6TB	772.82	42.83	5.38	41.91	5.45	0.45	24.42	10.99
8TB	370.54	23.48	31.97	22.99	32.04	0.45	9.99	11.82

The stress-strain behavior of both flax and banana fiber-reinforced composites, as indicated in Figure 5 and Figure 6, demonstrates clear trends in stiffness variation, governed by the slope of their respective curves. In flax composites, the untreated fibers exhibited the steepest slope, indicating the highest Young's modulus and suggesting minimal structural disruption and effective stress transfer. Conversely, in banana composites, maximum stiffness was observed at 6% alkali treatment, likely due to optimal removal of hemicellulose and improved fiber-matrix bonding. For both fiber types, 4% treatment yielded moderate modifications to stiffness, slightly reduced in flax and slightly enhanced in banana, highlighting the nuanced impact of surface modification. Notably, 8% alkali treatment consistently resulted in the lowest slope across both materials, indicating mechanical degradation due to excessive delignification and disruption of cellulose structure. These results underscore the importance of controlled alkali treatment in enhancing composite performance, with 6% treatment emerging as the most effective concentration for maximizing stiffness without compromising fiber integrity.

This trend is further corroborated by the Young's modulus values presented in Figure 7 and Figure 8, which illustrate the mechanical response of flax and banana fiber composites, respectively, across various alkali treatment concentrations. Notably, Figure 7 shows that untreated flax fibers exhibit the highest modulus, while Figure 8 highlights a substantial increase in stiffness at 6% treatment for banana fibers, confirming the contrasting optimal treatment levels for each fiber type.

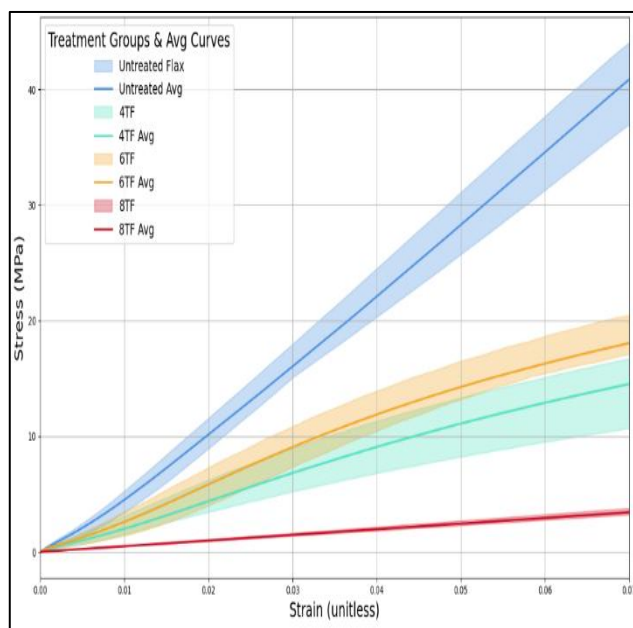


Fig. 5 Stress-Strain Curves for Flax Composites (Untreated and Treated)

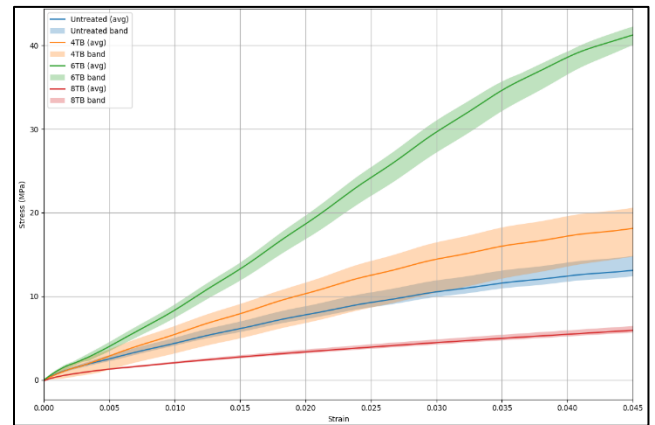


Fig. 6 Stress-Strain Curves for Banana Composites (Untreated and Treated)

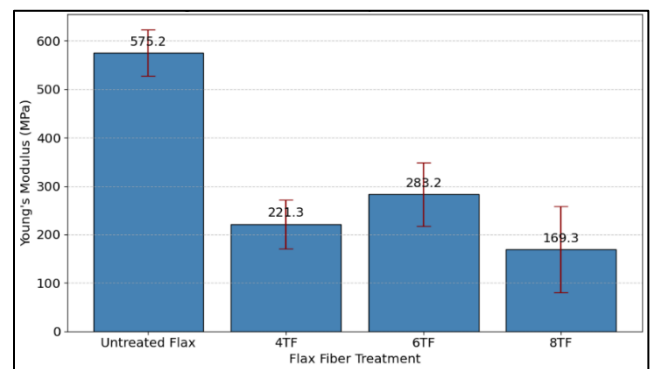


Fig. 7 Young's Modulus for Flax Composites (Untreated and Treated)

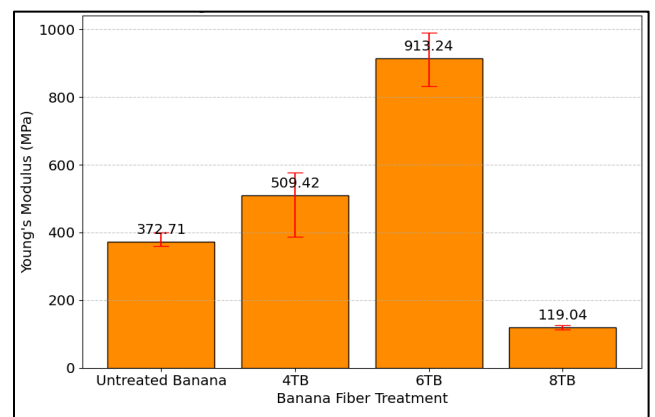


Fig. 8 Young's Modulus for Banana Composites (Untreated and Treated)

4.2.1 Flax Composite Behavior

The tensile strength and modulus of Flax are consolidated in Figure 9. The untreated flax composite (FFRC2) demonstrated the highest tensile strength of 49.55 MPa and a tensile modulus of 391.33 MPa, with moderate strain at a maximum load of around 8.46%. This performance sets the baseline against which alkali-treated samples are evaluated. When treated with 4% and 6% alkali concentrations (4TF and 6TF), tensile strength significantly decreased to 24.03 MPa and 28.20 MPa, respectively. Interestingly, these samples exhibited higher strain at tensile strength

(15.44% and 15.40%) and strain at break (16.02% and 15.91%), suggesting that while their strength dropped, they became more ductile. This may reflect early-stage disruptions to the fiber structure or incomplete removal of surface impurities, causing weaker fiber-matrix bonding. The tensile modulus, however, increased slightly with these treatments (194.84 MPa and 244.70 MPa), suggesting a modest gain in stiffness. This is typically associated with the partial removal of hemicellulose and lignin, which exposes more cellulose and improves initial load transfer characteristics. The 8% alkali-treated sample (8TF) demonstrated a further drop in tensile strength to 17.43 MPa, the lowest among all flax composites, yet with one of the highest strains at break (14.99%) and strain at tensile strength (14.77%). This indicates improved ductility but at the cost of strength, likely due to over-treatment that may degrade fiber integrity or result in excessive fiber-matrix debonding. Overall, while alkali treatment modifies the interfacial bonding by removing non-cellulosic components, the data reveal that higher concentrations may lead to diminishing returns in tensile strength. The balance between stiffness and ductility is treatment-specific, and for flax composites, lower to moderate treatments (around 6%) may offer a better compromise. However, the untreated variant remains the most tensile-robust.

These findings suggest that while alkali treatment can be beneficial for certain aspects of natural fiber composites, an optimal concentration must be carefully determined. Excessive treatment, as observed with the 8% alkali solution, can lead to detrimental effects on the fiber's intrinsic strength, ultimately compromising the composite's overall tensile performance. Therefore, further research could focus on tailoring alkali treatment parameters to specific fiber types and desired composite applications to achieve a more balanced enhancement of both strength and ductility.

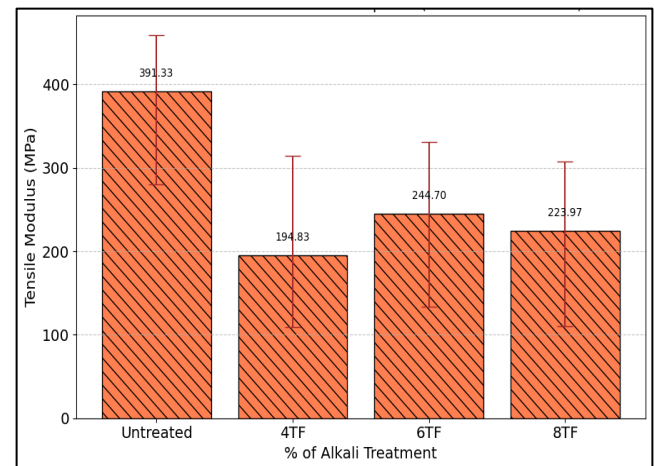
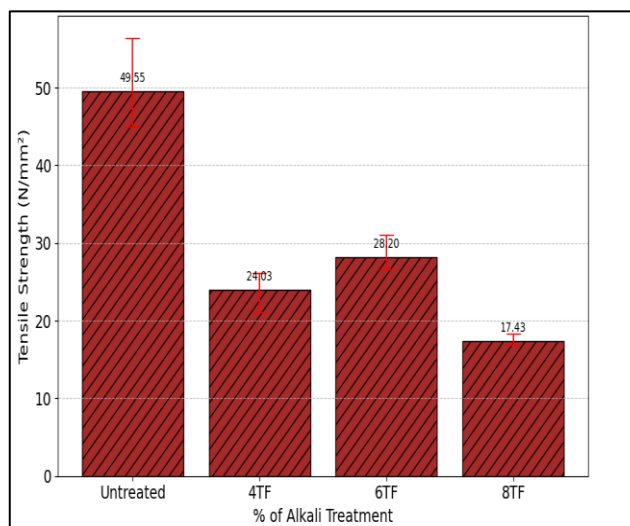


Fig. 9 Variation of tensile strength and tensile modulus with increasing chemical treatment (Flax)

4.2.2 Banana Composite Behavior

The tensile strength and modulus of the banana fiber-reinforced composites (untreated and treated) are consolidated in Figure 10. Untreated Banana Composite (untreated banana) recorded a tensile modulus of 561.21 MPa and a tensile strength of 26.12 MPa, with ductility indicated by strain values around 34%. 4% Treated (4BF) increased the tensile strength to 31.36 MPa and the elastic modulus marginally to 577.92 MPa, along with a moderate improvement in strain ($\approx 37.3\%$). Notably, the 6% alkali treatment significantly enhanced both the tensile modulus (772.82 MPa) and tensile strength (42.83 MPa); however, it reduced the ductility drastically (strain at tensile strength and break around 5.4%). This indicates that at 6%, the treatment optimizes the fiber-matrix adhesion to yield higher stiffness and strength, but over-treatment may also lead to embrittlement. With 8% Treated (8BF), the tensile properties declined slightly, with an observed tensile modulus of 370.54 MPa and tensile strength of 23.48 MPa, while ductility values ($\approx 32\%$) were closer to the untreated composite. This suggests that excessive alkali treatment beyond an optimal level may deteriorate the mechanical performance by degrading the fiber structure.

The untreated banana composite was found to have a tensile modulus of 561.21 MPa while its tensile strength was 26.12 MPa. The untreated flax composite (FFRC2) had a tensile modulus of 391.33 MPa and a tensile strength of approximately 49.55 MPa. This shows that the untreated flax composites possessed a relatively higher tensile strength as compared to the banana composites, which is completely aligned with the findings from Ku et al. [36], in which it was noted that natural fibers may vary significantly in various mechanical properties depending on their type and treatment. Furthermore, the alkali treatment of both

fibers aimed to enhance interfacial bonding, an essential factor in composite performance. Research by Ramadevi et al. [37] has also supported this, indicating that improved fiber-matrix adhesion through surface treatments can certainly lead to better mechanical properties.

The 8% alkali-treated flax composite (8TF) showed a reduced tensile modulus of 223.97 MPa and a lower tensile strength of 17.43 MPa compared to the untreated sample. However, its tensile strength strain (14.77%) and strain at break (14.99%) were notably higher, indicating increased ductility despite compromised stiffness and strength. This observation suggests that while the alkali treatment can enhance both stiffness and ductility characteristics, it may, however, cause a compromise to be made on tensile strength performance at particular concentration levels. This very observation remains consistent with findings reported by M. Kodal and Topuk [38], who, in their research, reported that alkali treatment has the potential to improve the tensile strength properties of flax fiber composites. Nevertheless, excessive treatment applications may result in the degradation of the fiber structure itself. Adding to this point, the scholarly work from Hao and Wu [39] highlights that alkali treatment enhances interfacial bond strength, which holds a crucial role in the mechanical performance exhibited by composites.

Regarding the banana composites, the application of a 6% alkali treatment, designated as (6TB), did result in a considerable increase in tensile modulus, achieving 772.82 MPa, and tensile strength as well, reaching 42.83 MPa. However, it must be noted that ductility experienced a significant reduction, as seen in strain at break figures, around 5.4%. These outcomes indicate that the most optimal treatment concentration for banana fibers may be situated on a lower level than what is appropriate for flax fibers, thereby stressing the fiber-specific characteristics of treatment influences. This observation is corroborated by the findings of Hao and Wu [39,18] who noted that mechanical properties observed in natural fiber-reinforced composites are becoming heavily influenced by the very nature of their interface. This facet is, in turn, being affected by the treatment which is applied.

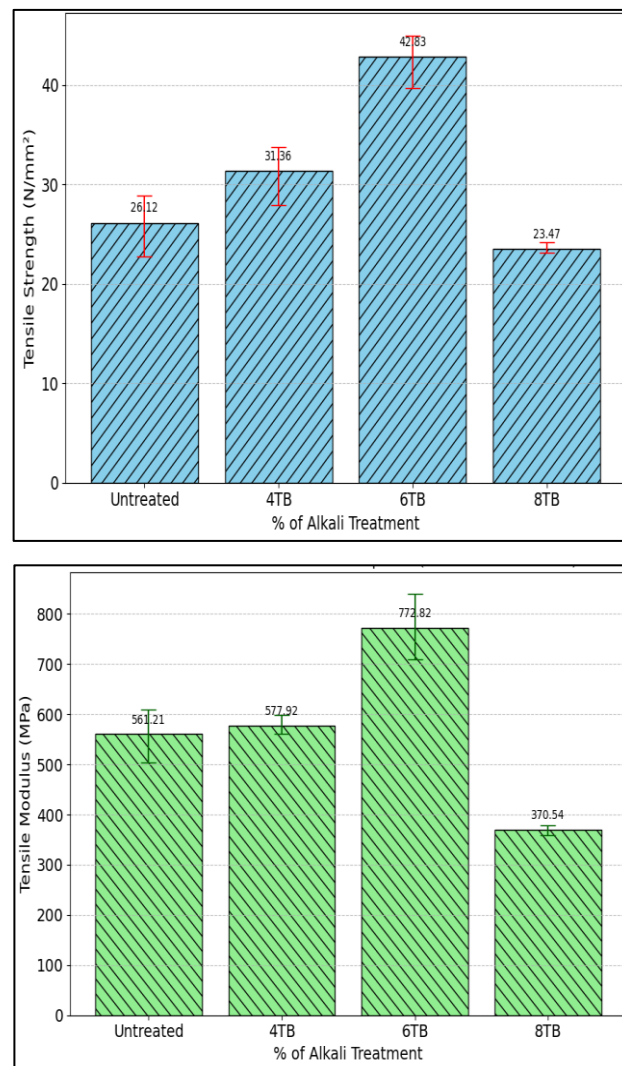


Fig. 10 Variation of tensile strength and tensile modulus with increasing chemical treatment (Banana)

4.3 Comparative Analysis with Existing Literature

The mechanical performance of the natural fiber composites developed in this study was assessed against the existing literature, with specific emphasis on the tensile strength outcomes of banana and flax fiber-reinforced polymer composites. The present work demonstrates a significant improvement in the tensile characteristics of banana woven fiber composites following alkaline treatment. The untreated banana fiber composites exhibited a tensile strength of 26.12 MPa, which increased to 42.83 MPa upon 6% NaOH treatment, representing an approximate enhancement of 64%. This improvement is attributed to enhanced fiber-matrix adhesion, resulting from the partial removal of surface impurities and hemicellulose, which leads to improved interfacial stress transfer under loading. However, this came at the cost of ductility, which dropped from 34% to 5.4%, suggesting a shift towards the brittle nature in the treated composite.

On the other hand, flax-woven fiber composites exhibited a reduction in tensile strength after treatment. The untreated flax composite achieved a tensile strength of 49.55 MPa, whereas all levels of alkali treatment resulted in a reduction in both tensile strength and modulus, although ductility improved significantly, peaking at 16.02% for the 4% NaOH treatment. This aligns with Frącz et al. [28], who reported that flax fibers treated with higher alkali concentrations (e.g., 10%) exhibited weaker mechanical properties due to excessive fibril damage and cell wall degradation.

Compared to earlier studies, the tensile strength achieved in this study for banana fiber composites falls within the reported range. For instance, Irawan and Sukania [5] obtained a higher tensile strength of 62.3 MPa using alcohol-treated banana fibers, while Cai et al. [24] reported an even higher strength of 131.5 MPa for 6% NaOH-treated banana fabric reinforced in a PVA matrix, highlighting the role of matrix selection. Nguyen and Nguyen [9] observed optimum performance for banana fiber/epoxy composites at 20 wt.% fiber loading, supporting the fiber content sensitivity seen in our vacuum-infused composites.

For flax composites, Singh et al. [25] achieved a tensile strength of 23 MPa with untreated flax fibers in a PLA matrix, indicating a better performance of our untreated flax/epoxy composite (49.55 MPa). However, unlike flax, banana fiber composites in this study responded more positively to alkali treatment, corroborating previous findings such as A. Gunge et al. [20], which suggested that banana fibers would tolerate moderate alkali treatment better than flax due to their higher cellulose content and fibers morphology.

This study further distinguishes itself by employing vacuum infusion, which ensures uniform resin penetration and reduces voids, unlike the manual methods of manufacturing composite materials widely used in previous works. Additionally, the simultaneous comparative assessment of two natural fibers under identical process and testing conditions, a factor rarely addressed in previous literature, provides a new insight into fiber-specific treatment optimization.

5. Conclusions

The vacuum infusion curing process for the laminates led to a significant reduction in void fractions.

The stress-strain analysis revealed that the slope of the curves, corresponding to the material stiffness,

varied significantly with the level of alkali treatment for both flax and banana fiber composites.

For flax composites, the untreated fibers exhibited the highest slope and Young's modulus, indicating superior stiffness. Any level of alkali treatment led to a reduction in stiffness, with the 8% treated group showing the most pronounced decline due to likely structural degradation of the fibers.

In contrast, banana fiber composites showed an optimum stiffness at 6% alkali treatment, as evidenced by the steepest slope in the stress-strain curve and the highest Young's modulus value. This indicates effective hemicellulose removal and enhanced fiber-matrix adhesion. However, over-treatment at 8% resulted in mechanical deterioration.

Alkali treatment significantly impacts the tensile properties of flax and banana fiber-reinforced composites, with the optimal treatment concentration being fiber-specific.

For flax composites, the 8% alkali treatment (8TF) decreased the tensile modulus to 223.97 MPa and the tensile strength to 17.43 MPa, compared to the untreated sample (FFRC2), which had a tensile modulus of 391.33 MPa, a tensile strength of 49.55 MPa, and a strain around 8.5%. However, the strain at tensile strength increased to 14.77%, indicating reduced stiffness but improved ductility, which may benefit applications requiring greater deformation and energy absorption capacity.

For banana composites, a 6% alkali treatment (6TB) yielded the highest tensile modulus at 772.82 MPa and tensile strength at 42.83 MPa, but at the cost of significantly reduced ductility (strain around 5.4%) compared to the untreated sample (tensile modulus 561.21 MPa, tensile strength 26.12 MPa, strain around 34%), indicating potential embrittlement.

Although the current study focused on 4%, 6%, and 8% NaOH concentrations, the noticeable decline in ductility at 6% suggests that intermediate concentrations (e.g., 5%) may yield a better balance of strength and flexibility. Future studies may investigate this range to refine the alkali treatment process for enhanced mechanical performance.

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