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Research Article

Influence of Layering Pattern, Fibre Architecture, and Alkalization on Physical, Mechanical, and Morphological Behaviour of Banana Fibre Epoxy Composites

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In the current investigation, the mechanical properties of epoxy composites reinforced with banana pseudostem fibres, specifically focusing on tensile and impact behaviour, are investigated. The manufacturing process employed the meticulous hand-lay-up technique to fabricate six distinct samples. These samples included various combinations of short and woven banana fibres, treated and untreated, as well as a hybrid configuration involving layers of woven and short fibres. A fixed weight ratio of 60% fibres to 40% epoxy matrix was maintained for consistency. To ensure optimal material integrity, a careful application of resin and hardener in a 10 : 1 weight ratio was layered, with each addition of fibre followed by thorough rolling to eliminate any potential bubbles. The density and void fraction of the resulting composites were meticulously assessed to gauge the influence of this layering approach. Additionally, an X-ray diffraction (XRD) analysis was conducted to ascertain the impact of the chemical treatment on the cellulose content of the fibres. Our findings revealed that the tensile and impact properties were notably superior in the woven fibre composites. In particular, the chemically treated woven banana fibre epoxy composite displayed impressive values of 64.95 MPa for tensile strength and 24.37 KJ/m^2 for impact strength. To gain deeper insights into the structure-property relationship, test specimens were analyzed using scanning electron micrographs. Lastly, comparative analysis by mapping the tensile properties from our present work with those from existing studies was carried out.

1. Introduction

In recent decades, composite materials have been extensively consumed for various applications due to their essential properties such as high strength, high stiffness, lightweight, good corrosion resistance, and high dimensional stability compared with conventional materials such as aluminium and steel. With the increased demand for newer and potential materials, research communities across the globe are looking for materials that satisfy customer needs at the minimum cost [1]. In addition, green economies, energy reduction, and biodegradability are the current issues that should be addressed to reduce environmental pollution. The literature infers that the yearly production of natural fibres from food crops is around 4 billion tons globally [2]. Subagyo and Chafidz revealed that 72.5 billion tons of banana fruit are harvested worldwide [3]. Further, it was also estimated that 4 tons of biomass waste are produced from every 1 ton of harvested banana fruits [4]. In Ethiopia, the banana farms cover 53,956.13 hectares, while 478,251.04 tons of banana fruits are collected annually [5]. The banana pseudostem can cause severe environmental pollution if not carefully managed. However, the appropriate use of this biomass can provide significant economic advantages too [3]. The fibres extracted from the banana pseudostem have good mechanical strength, are biodegradable, and are compatible with polymer resin in composite processing [6, 7].

The banana fibre is mainly composed of cellulose, hemicellulose, and lignin. Cellulose constitutes the primary content in natural fibre with a repeated linear chain of β-D-glucopyranose [8]. Hemicellulose is a branched chain compound formed from 5-ring and 6-ring carbon polysaccharides with a lower degree of polymerisation compared with that of cellulose, while lignin is a phenolic compound that provides rigidity to the natural fibre [9]. The crystalline cellulose regions are interconnected by a thread-like structure called the cellulose microfibrillar [10]. The microfibrillar angle concerning the fibre axis determines the mechanical strength of the natural fibre. The banana fibre has a strong affinity for moisture due to its hydrophilic nature [11]. The different properties of the bananas are presented in Table 1.

The chemical treatment of the natural fibre increases compatibility with polymer matrices by removing the unwanted waste from the fibre surface as a coupling agent, creating free radicals, or forming a new functional group and consequently reducing amorphous contents in the structure [13–15]. Chemical treatments are performed using chemicals that include acid, alkali, and silane that respond more effectively when their concentration and treatment interval are optimized [16, 17]. The alkalisation of banana fibre is the most common and cost-effective method that increases the crystallinity of fibre by removing amorphous constituents such as lignin and hemicellulose [18, 19]. Furthermore, during mercerising, the replacement of the -OH group by the $-ONa^+$ changes the hydrophilic nature of the fibre into hydrophobic; thus, compatibility with polymeric resin gets enhanced, and sensitivity to moisture reduces [20, 21]. Several investigations show that treating bananas with a 5% NaOH concentration increases the mechanical strength of composites [22]. Furthermore, the mechanical properties of the composites are also affected by the fibre architecture. The fibre for the processing of the composite may exist in long, short, or woven forms. The woven fabrics are produced by interlocking warp and weft yarns in a repeated weaving pattern. The weaving structure provides stability to the fibre through mechanical interlocking [23]. The woven natural fibres are used in the production of bio-based lamented composite. The woven fabrics are comfortable for handling and positioning during composite processing. The short fibre is an interesting fibre form in the polymer composite due to its high creep resistance, out-of-plane rigidity, and ease for automated production systems [24]. Alavudeen et al. investigated the effect of woven (plain and twill) and random-oriented banana/kenaf fibre on the mechanical behaviour of epoxy matrix composite [25]. The investigation reveals that plain-woven fibre composite has improved mechanical strength as compared to randomly oriented fibre composite. Haghighatnia et al. studied the effect of fibre length, fibre loading, and alkalisation on the mechanical behaviour of a hemp fibre-reinforced polyurethane composite. The study reveals that enhanced mechanical properties were obtained with a composite sample with 40 vol.% fibre loading and 15 mm fibre length [26]. The effects of *Parthenium hysterophorus* and *Impomea pes-caprae* fibres stacking sequences reinforced with epoxy were investigated by Raghunathan et al. [27]. The findings of the tests show that composites comprising upper layers of *Impomea pes-caprae* fibres and a core layer of *Parthenium hysterophorus* fibres had improved mechanical properties and lower water absorption. Santulli et al. investigated the effect of jute fabric and wool felt stacking sequences on the mechanical behaviour of epoxy matrix composite. The investigation revealed the incorporation of jute/wool fibre alternate layers to improve the load-bearing capacity of composite laminate compared with pure wool felt epoxy composite [28]. The effects of stacking sequence on the mechanical and water absorption properties of areca-pineapple fibre-based epoxy composites were investigated by Raghunathan et al. [29]. Due to the high amorphous content of the fibres, the three layers of areca fibre-based epoxy composites demonstrated improved impact (0.8 J) and water absorption (2.4%) capabilities.

The motivation of this study is to create awareness of the effective utilisation of the fibre extracted from the banana pseudostem, one of the abundant agricultural biomasses and less utilised in Ethiopia. In addition, most of the investigations have been done on the banana fibre polymer composite in either short or woven fibre independently but not combining both components. In this investigation, the effect of the fibre structure (woven and chopped) and their combined effect on the mechanical, physical, and morphological behaviours were carried out. Additionally, composites were prepared in sandwich form with a short banana fibre-reinforced epoxy core sandwiched between woven banana fibres to evaluate their properties. The scanning electron micrographs are used to understand the structure-property correlations, while the tensile properties of the present work are mapped to the existing literature for comparison.

Table 1: The physical, mechanical, and chemical properties of bananas [3, 12].

Width or diameter (μm)	Density (kg/m^3)	Microfibrillar angle (degree)	Initial modulus (GPa)	Tensile strength (MPa)	Cell L/D ratio	Elongation (%)
10–450	1350	10 ± 1	7.2–20.0	54-754	150	10.35
Constituents	Cellulose	Hemicellulose	Lignin	Pectin	Ash	Extractive
Contribution from 100%	60-65	6-19	5-10	3-5	1-3	3-6

2. Materials and Methods

2.1. Materials. The fresh banana fibre for this investigation is directly extracted from the pseudostem found abundantly around Arba Minch City, Ethiopia, as shown in Figure 1(a). The extraction was done manually by putting an individual layer of pseudostem on the inclined flat wood, and the pulp was removed using a bamboo stick (Figure 1(b)). The extracted fibre was dried in the sunlight for two days, as shown in Figure 1(c). LAPOX L-12 epoxy resin, K-6 hardener, and silicon-releasing agent were obtained from World Fibreglass and Water Proofing Engineering, Addis Ababa, Ethiopia. In addition, the distilled water and sodium hydroxide flack were obtained from the Atomic Educational Materials Supplier, Addis Ababa, Ethiopia.

2.2. Fabric Preparation. The dried fibre is soaked in distilled water, having a 5% NaOH solution for an hour (Figure 1(d)), then washed with water several times to remove excess solution until a pH of 7 is reached (Figure 1(e)) [30, 31]. The banana fibre is manually woven into the plain fabric using a handloom with a 0/90° fibre adjustment. The woven pattern consists of weft and warp yarns. The warp yarns are placed at 0° while weft-filling yarns are set at 90° with respect to the warp yarn. To make fabric, the following procedure was followed.

2.2.1. Carding/Combing. The treated and untreated banana fibres were combed by using a commercially available human hair comb. This was done to remove short fibre and get straight and parallel fibre (Figure 1).

2.2.2. Yarn Making. The textile yarn is a strand of fibre having a considerable length and a relatively small cross-section, with or without twisting. It is one of the critical factors that determine fabric properties. The influence of the extent of twist angle on the tensile strength of flax fibre composite was studied by Goutianos et al. [32]. The study reveals that the porousness of the strand declined by increasing the extent of twist, and the strength was reduced in response to fibre obliquity, hence upsetting the orientation competence. A high twist angle humbles the wettability of fibre and poor fibre-matrix interface. To sustain adequate wettability and to reduce fibre obliquity in this study, a minimum twist angle was used.

2.2.3. Weaving. The woven fabric was prepared by using a customised handloom having evenly spaced pin to tighten warp yarns, and a bifunctional heald and a read comb were used to open the shed and drive weft yarns to position, as depicted in Figure 1(f).

2.3. Composite Preparation. The composite for this investigation was prepared using the hand lay-up method with a fixed fibre-to-matrix weight ratio of 60 : 40 [33, 34]. The mould size of 170 × 400 mm was made from mild steel, and the surface was covered by polyethylene plaster to avoid direct contact. Both chemically treated and untreated fibre were chopped into 15 mm length [26]. Before chopping the fibre, it was combed to make it parallel and to avoid unnecessary disordered fibres. The silicon-releasing agent was applied uniformly to the mould to facilitate easy dismantling. The resin is mixed with a hardener with a 10 : 1 weight ratio. Stepwise, the resin and fibre layers were added until a prespecified amount of materials were held in the mould, and after placing a new fibre layer each time, it was rolled to remove entrapped air bubbles. Finally, the mould was covered by a plaster-sealed wooden board, and static pressure was applied during curing to avoid void formation. A total of six samples—untreated/treated short banana fibre composite (UTSB/TSB), untreated/treated woven banana fibre composite (UTWB/TWB)), and untreated/treated woven-short-woven banana fibre composite (UTWSWB/TWSWB)—were prepared. The flowchart depicting the preparation of composites is presented in Figure 2. The black arrow indicates the chemically treated short banana/woven fibre composite fabrication process. In contrast, the red arrow indicates the fabrication process for the treated short banana/woven fibre composite. For the fabrication of UTWSWB/TWSWB composite, the only difference is that 10 wt.% woven fibre is added to the bottom layer of the mould initially, then 20 wt.% of chopped fibre in the mid layer, and the rest 10 wt.% of woven fibre on the top layer, as shown in Figure 3.

2.4. Void Content Determination. The void in the composite was determined as per ASTM D2734-09, having specimen dimensions 25.4 × 25.4 mm [35]. It is expressed as a ratio of theoretical and actual density. The actual density of the composite was determined by using Archimedes's principle. It states that the object is partially or fully immersed in the fluid buoyed up by force equal to the weight of the displaced fluid. The volume of each sample was obtained from the displaced water level after immersion of the composite into the water and before immersion. Void in composite structure hinder mechanical properties and reduces product life span. The actual density and the void ratio were determined using the following equations:

$$\rho_a = \frac{\rho_w w_a}{w_a - w_w}, \quad (1)$$

Figure 1: (a) Banana plant. (b) Fibre extraction. (c) Drying under sunlight. (d) Fibre treatment. (e) Cleaning of fibres. (f) Weaving of fabric.

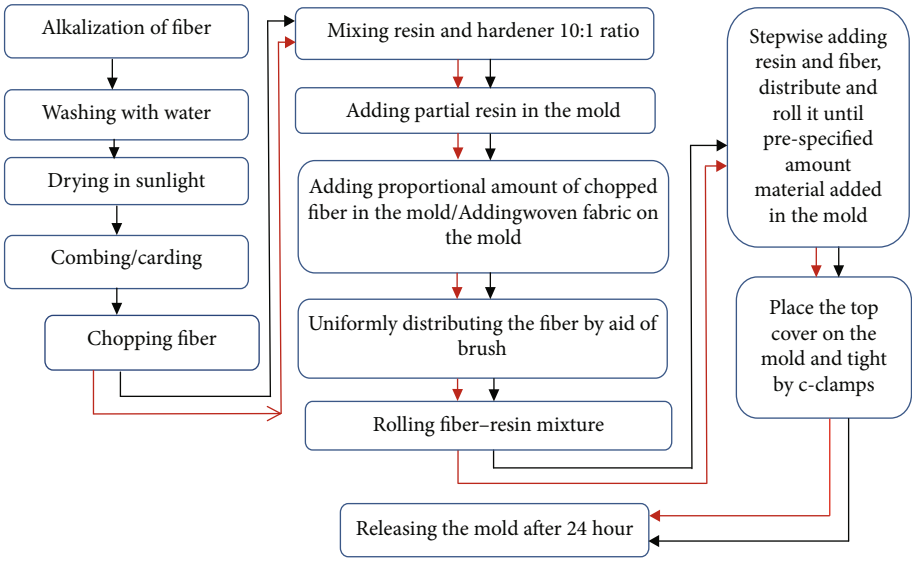

Figure 2: Flowchart representation of different composite preparations.

(a)

(b)

Figure 3: (a) Mould was clamped and left for curing. (b) Different types of composites prepared using the hand lay-up technique.

(a) (b)

Figure 4: Tensile test specimens (a) before and (b) after the test.

(a) (b)

Figure 5: Impact specimens (a) before and (b) after the test.

$$v_r = \frac{\rho_t - \rho_a}{\rho_t}, \quad (2)$$

where ρ_a is the actual density, ρ_w is the density of water, w_a is the weight in the air, w_w is the weight in the water, v_r is the void ratio, and ρ_t is the theoretical density.

2.5. Tensile Test. Tensile tests were performed using the Zwick universal test setup, which has a load cell of 30 kN capacity. The composite specimens were prepared as per ASTM D638-14 with a dimension of $165 \times 19 \times 3.5$ mm, as shown in Figure 4 [36]. During the test, the cross speed of the machine was adjusted to 2 mm/min. All 5 specimens were tested from each composition, and the average values were reported.

2.6. Impact Test. Impact tests were performed to know the amount of energy absorbed by the composite specimen at fracture. The notched samples were prepared with dimensions of $55 \times 10 \times 3.5$ mm having a notch depth of 2.54 mm conforming to ASTM D256-10, as shown in Figure 5 [37]. The test machine had a 30 kg weight-mounted pendulum with a hammer impact speed of 3.8 m/s.

2.7. X-Ray Diffraction Analysis (XRD), Scanning Electron Microscopy (SEM). The test was performed to study the crystallinity of the chemically treated and untreated banana fibre epoxy composites. The test was conducted with an X-ray tube with Cu-targeted α-radiation with a wavelength $\lambda = 1.5406$ Å at 40 KV and 30 mA. The scanning condition of the test was conscious scanning mode with an angular range of $2\theta = 5 - 55\circ$ and a scan speed of 2 deg./min. A scanning electron microscope (JEOL JSM 6380 LA) examines the test surfaces. The sputtering of specimens is performed with a JFC-1600 autofine coater JEOL.

3. Result and Discussions

3.1. Physical Characterization

3.1.1. Density and Void Fraction. The void is an inherited behaviour of the reinforced composite, so it is challenging to have a composite free of voids. However, it needs to be in a limited range because a slight increase in void fraction significantly affects the mechanical behaviour of the reinforced composite. Two specimens were taken from each sample, and their void fraction was calculated by comparing the theoretical and measured density composites. Then, the average values were presented in Table 2.

The UTSB composite reveals the maximum void fraction, implying it to be the most porous compared with the rest of the specimens. This may happen due to uneven fibre

Table 2: The density and void content analysis.

Composition	Theoretical density (kg/mm^3)	Experimental density (kg/mm^3)	Void fraction (%)
UTSB	1.25	1.224 ± 0.03	3.08 ± 0.08
TSB	1.25	1.226 ± 0.03	2.92 ± 0.07
UTWB	1.25	1.226 ± 0.03	2.84 ± 0.07
TWB	1.25	1.228 ± 0.03	2.68 ± 0.07
UTWSWB	1.25	1.226 ± 0.03	2.88 ± 0.07
TWSWB	1.25	1.227 ± 0.03	2.76 ± 0.07

distribution during composite processing, poor adhesion between fibre and resin, and lower crystallinity of fibres. The porosity may significantly contribute to lowering the mechanical strength of the UTSB composite. The void content of TSB was 2.92%, compared with UTSB, which has 3.08% porosity. This implies alkalisation of the fibre reduces the porosity level in the composite structure. The application of treatment to fibres enhances their compatibility and adhesion with the epoxy matrix. When the fibres establish a strong connection with the matrix, the tendency for air or voids to become entrapped between the fibres and the matrix during the composite fabrication process is notably diminished. Furthermore, TWB had a minimum void fraction compared with the UTWB specimens. The weave architecture allows easy handling and positioning of fibre during composite processing; thus, the void related to the agglomeration of fibre was minimised. The weave structure and surface modification of fibre enhanced fibre-matrix bonding; consequently, the TWB composite reveals the minimum porosity. The composites manufactured from the woven face and chopped fibres (UTWSWB and TWSWB) depict a lower void fraction than their chopped fibre counterparts (UTSB and TSB) and a higher void fraction than their woven fibre composite counterparts (UTWB and TWB). This implies that the incorporation of short fibre in sandwich form hinders the soundness of woven fibre composite.

Generally, the amount of void in the composite structure gets affected by the fibre architecture, the chemical treatment of fibre, and the layering pattern. The mechanical strength of the composite decreased with an increased void fraction. The voids act as crack initiation points and may cause catastrophic failure of the composite.

3.1.2. XRD Analysis. The XRD diffraction plot of NaOH-treated and untreated banana fibre epoxy composites is presented in Figure 6. The graph had two intense and broad peaks at two positions, $2\theta = 18\circ$ and $2\theta = 22\circ$, revealing evident crystallinity in banana fibre. The intense peak at ~22° is related to the crystalline portion of cellulose, while the peak at ~18° is related to amorphous cellulose [38, 39]. The chemically treated banana fibre composite had a higher peak in the range of $2\theta = 13 - 27\circ$ compared with the untreated fibre composite. This implies the removal of an amorphous constituent from the banana fibre, such as lignin and hemicellulose, as well as an amorphous portion of cellulose. However, no additional peak is seen in the reset part of 2θ, revealing that epoxy is amorphous. Furthermore, the amorphous peaks were observed at 12.02° with an intensity of 1088 for both treated and untreated banana fibres, and the crystalline peaks were observed at 21.66° for both with an intensity of 2706 for treated fibres and 2636 for untreated fibres. Based on the Segal equation, the crystallinity index calculated was CI (UTB) = 58.7 and CI (TB) = 59.8. Thus, the amount of cellulose available for bonding was more, and the aim of the work to enhance interface bonding was achieved by increasing the number of bonding sites.

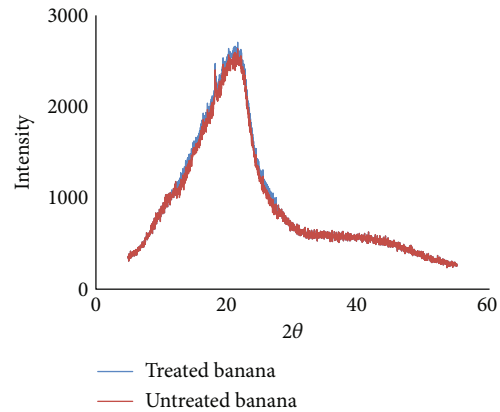

Figure 6: XRD plot of the treated and untreated banana fibre composites.

$$\mathrm{CI} = \frac{I_{Cr} - I_{am}}{I_{Cr}} \times 100. \quad (3)$$

3.2. Mechanical Characterization

3.2.1. Impact Test. Impact tests indicate the amount of energy absorbed by the material before failure. The impact behaviour of composite material is mainly affected by fibre-matrix adhesion, interlaminar bonding, and fibre architecture. The minimum average impact strength of 15 KJ/m^2 was obtained by the untreated short fibre epoxy composite, mainly due to the poor interfacial adhesion between the hydrophobic polymer resin and hydrophilic banana fibre (Figure 7(a)). The impact strength of the treated short banana fibre epoxy composite was noted to be 18.75 KJ/m^2, while 0.67 J energy was absorbed (Figure 7(b)). TSB absorbs 26.4% more energy than the untreated short fibre composite (UTSB). The improved capability of energy absorption by the TSB composite resulted from the enhanced interfacial bond between reinforcement and matrix. The impact strength of the UTWB composite was 20.62 KJ/m^2 and absorbed 0.73 J energy; this was 37.7% and 26.4% more energy than the UTSB and TSB composite, respectively. This implies that fibre structures affect the impact strength of the fibre-reinforced polymer composite. The TWB composite perceived a maximum impact strength of 24.37 KJ/m^2 and absorbed 0.87 J of energy. The TWB composite absorbed 19.2% more energy than the UTWB composite. This implies that fibre treatment

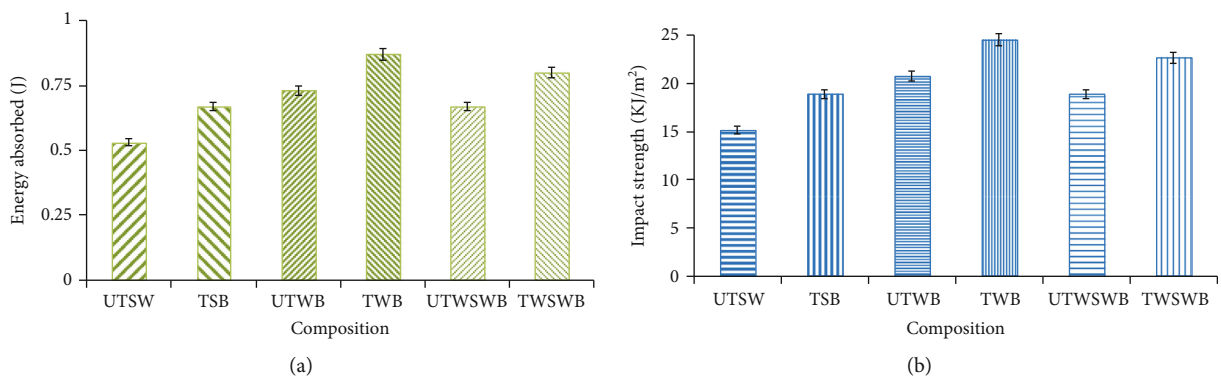

Figure 7: Impact response of composites in terms of (a) energy absorbed and (b) impact strength.

enhances the composite's impact strength by improving interfacial addition between fibre and matrix. The impact strength of the UTWSW composite was 21.56 KJ/m^2 and absorbed 0.67 J of energy. Compared with the UTSB and UTWB composites, it absorbed 26.4% more and 8.9% less energy, respectively.

When we analyzed the effect of fibre structure on the impact strength of banana fibre epoxy composite, short fibre composite had a lower impact strength than woven fibre composite, regardless of the effect of the chemical treatment. The impact strength of the short fibre composite mainly depended on the fibre-matrix interface adhesion. Due to the random orientation of fibres, there is a low probability of aligned fibres along the specimen in the longitudinal direction to resist the applied impact load in the transverse direction. Beg and Pickering revealed that the energy intake capacity of the discontinuous fibre polymer composite is impeded because many fibre ends act as stress concentration points [40].

Paul et al. pointed out that the fibre pullout and fibre-matrix debonding were the primary energy dissipation mechanisms that contributed to the impact strength of the short banana fibre polymer composite [41]. The case of the untreated short banana fibre epoxy composite (UTSW) had high fibre pullout and fibre-matrix debonding. Thereby, it absorbs less amount of energy compared with treated short fibre composite that has less fibre pullout (TSB). This is due to the fact that effective fibre-matrix adhesion prevents crack initiation and propagation prior to breakage. Therefore, interfacial bonding provides significantly more energy than energy obtained via fibre-matrix debonding and pullout [42].

The maximum impact strength was perceived by the chemically treated woven banana fibre composite (TWB). The weave structure enhances the impact strength of the banana fibre epoxy composite. The integrity and interlace of the warp and weft filament provide structural strength to the woven fabric. The structural stability of the fabric induces additional strength to the composite. In addition to this, the alignment of warp yarns along the specimen's longitudinal direction increases the number of individual fibres that bear impact load applied in a transverse direction [43]. Interfacial bonding strength, interlayer delamination, and fibre pullout may contribute to the impact strength of the woven fibre-laminated composite. The composite fabricated from woven face and short fibre mid layer had higher impact strength than short fibre composite, irrespective of the chemical treatment. This implies that the partial replacement of short fibre by woven fibre improves the impact strength of the short banana fibre polymer composite.

The TWB composite absorbed 0.87 J of energy; this had good agreement with the work reported by Dress et al. [44]. They reported that 0/90° woven sisal fibre treated with a 5% NaOH epoxy composite absorbed 0.91 J having an equal fibre load. Minor improvement for sisal fibre composite may happen due to the higher crystallinity of sisal fibre than banana fibre. Alavudeen et al. reported that the impact strength of plain woven banana fibre treated with 10% NaOH epoxy resin with 40 wt.% fibre loading was ~18 KJ/m^2. Still, the higher impact strength was perceived by the TWB epoxy composite [25]. Generally, fibre structure plays a significant role in the impact behaviour of banana fibre polymer composite followed by surface modification of fibre.

Both UTWSWB and TWSWB exhibit lower impact strength and energy absorption than the UTSW, TSW, UTWB, and TWB composites, which is mostly due to the random orientation of chopped banana fibres, which hinders the absorption of an abrupt applied load. Furthermore, woven fibres are subjected to sudden loads, as are the UTWB/TWB composites; however, unlike the plain core of the UTWB/TWB composites, the UTWSWB/TWSWB composites have a short banana fibre core, which absorbs less energy due to random orientation and may cause cracks within the fibres, resulting in fibre breakage and subsequent specimen failure. As a result, the mechanical properties of the UTWSWB and TWSWB composites decreased significantly.

3.2.2. Tensile Test. The representative stress-strain curves of different banana fibre-reinforced epoxy composites are presented in Figure 8. The stress-strain profiles of all the composites show typical brittle behaviour before failure. However, all the composites undergo a large amount of strain before failure. UTSB and TSB exhibited lower strengths to failure as compared with woven composites and a combination of woven and chopped composites.

The chopped banana fibres cannot transfer stress effectively after the failure of the matrix due to the random orientation of the fibres and improper bonding between

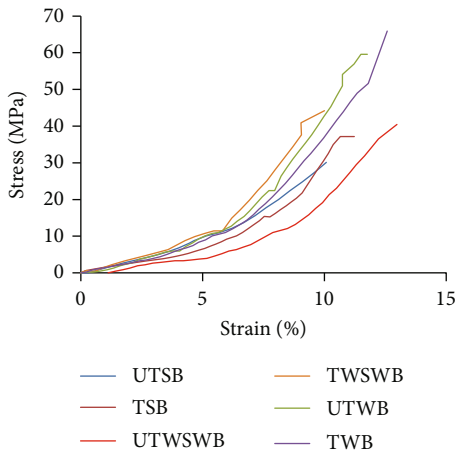

Figure 8: The representative stress-strain profiles of different banana fibre composites.

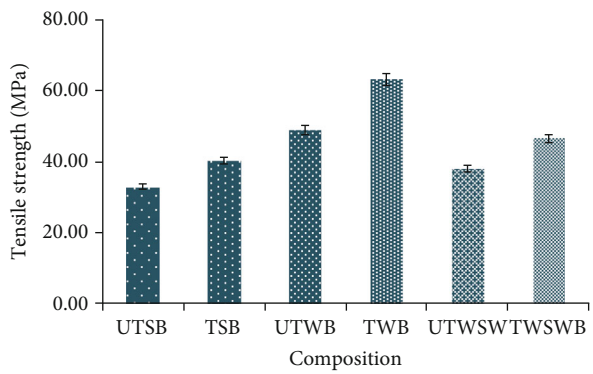

Figure 9: Tensile strength of different banana fibre epoxy composites.

constituents. Although treatment of the fibres assists in improving the strength slightly, considering the overall effect, the ability to withstand the stress is reduced.

On the other hand, the woven composites perform relatively better than the chopped composites due to better interfacial bonding between constituents. The woven fibres also assist in effectively transferring the stress due to their orientation in line with the tensile loading. The treated woven composites reveal good properties compared with those of the untreated ones due to the good bonding of constituents, mainly attributed to the treatment of fibres. The chopped and woven banana composites show intermediate properties compared to the woven and chopped composites. The combination of the chopped and woven fibres results in lowering the properties of the composites as compared to the woven ones due to ineffective stress transfer between constituents. The random orientation of the chopped fibres severely hinders the ability of the woven fibres to effectively transfer the stresses. Furthermore, the equal composition of the chopped and woven fibres (20 wt.%) decreases the effect of the woven fibre's ability to effectively resist the tensile loading and thereby reduces the properties of composites.

The tensile strength of different banana fibre epoxy composites is presented in Figure 9. The maximum tensile strength of 62.87 MPa was obtained with the chemically

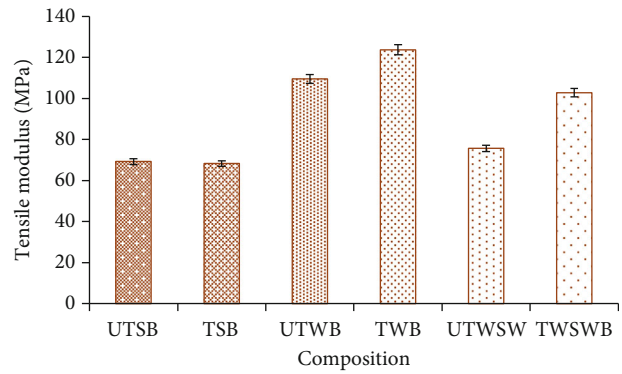

Figure 10: Tensile modulus of different banana fibre epoxy composites.

treated woven banana fibre epoxy composite (TWB). The untreated woven banana fibre epoxy composite (UTWB) had a maximum tensile strength of 48.68 MPa; when compared with the treated woven banana fibre epoxy composite, the untreated woven fibre composite showed a 29.14% decline in tensile strength.

The treated woven fibre composite improves tensile strength because NaOH treatment enhances the interfacial bond between the epoxy resin and banana fibre by degrading the waxy layer and amorphous content such as lignin and hemicellulose [45]. The alkalisation of banana fibre provides rougher fibre that offers many anchor points to aid the bond formation with polymer resin [46]. The minimum tensile strength of 32.63 MPa was obtained with untreated short banana fibre. This showed a 98.46% decline in the tensile strength compared with the treated woven composite and 49.18% compared with that of the untreated woven fibre composite. The average tensile strength for the TWB composite was 40.07 MPa, and when compared with the TWB composite, 56.90% decreases in tensile strength were observed. The composite prepared by putting short fibre in the middle and woven fibre skin showed insignificant variation from the tensile strength of its short fibre composite counterpart.

The fibre architecture is the significant factor that affects the tensile strength of the banana fibre epoxy composite. The minimum tensile strength exhibited with chopped fibre epoxy composite may happen due to ineffective stress transfer within the composite along the load direction. This investigation is in good agreement with the result revealed in the published work [25]. The study has shown that randomly oriented banana fibre epoxy composite had lower tensile strength than woven fibre with equal fibre loading (40 wt.%). The integrity and interlace of filament in weave architecture provide structural strength to fabric [47]. The fabric strength coupled with fibre-matrix adhesion allows uniform transfer stress within the composite structure; hence, woven fibre composite bears a high tensile load irrespective of the chemical treatment. In addition to this, the comfort ability of the fabric to handle and position in the production process permits even the distribution of resin and minimises void formation. Generally, the fibre structure is a significant factor that affects the tensile strength of the

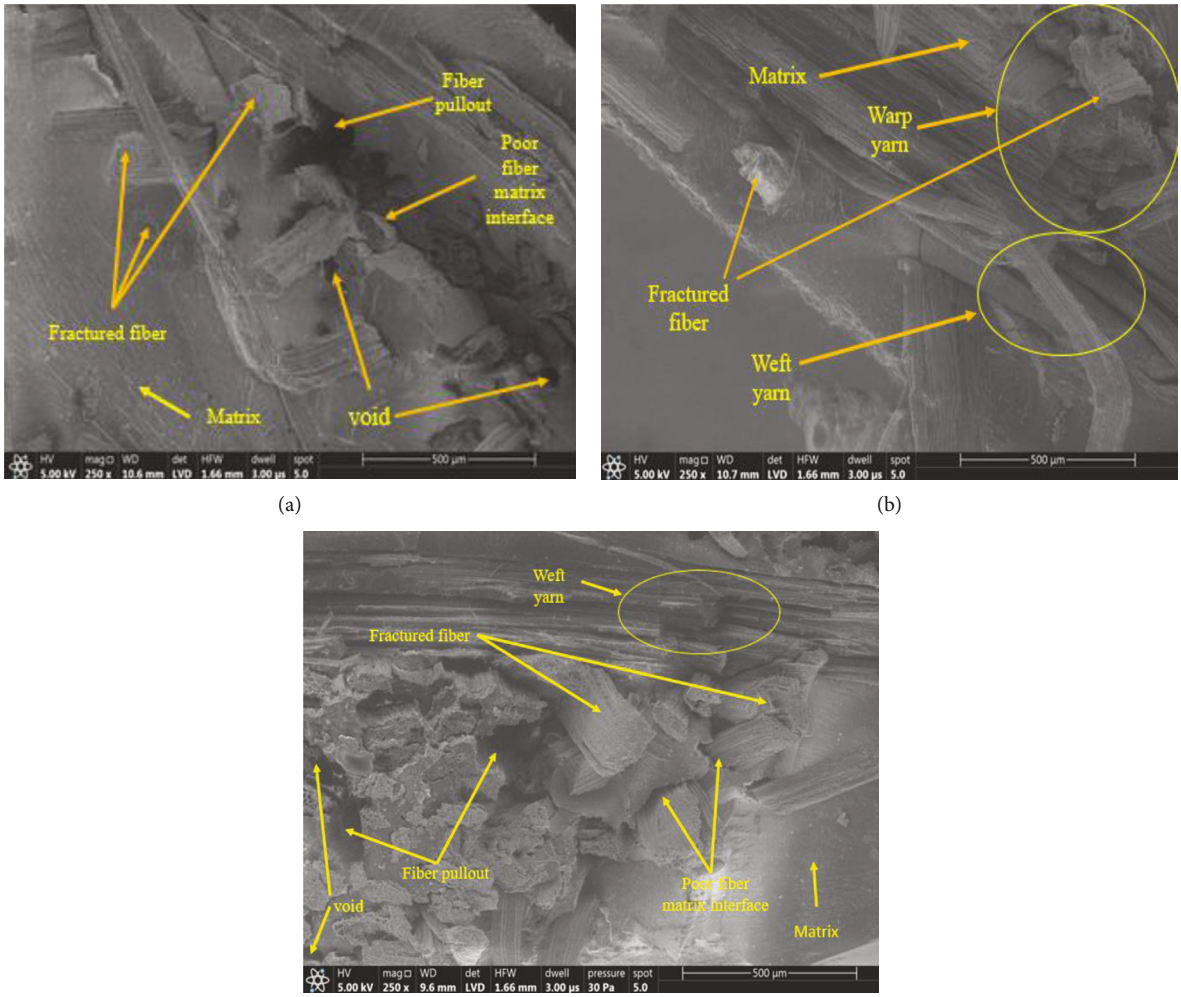

Figure 11: The scanning electron micrographs of (a) UTSB, (b) UTWSWB, and (c) UTWB.

banana fibre epoxy composite. TWB fibre epoxy composite withstands the maximum tensile load. This may happen due to the alignment of warp yarns in the direction of external load, the interlock of warp and weft yarns in a weave structure [48], and improved fibre-matrix bonding due to chemical treatment [49].

The tensile modulus of all the composites is presented in Figure 10. The slope of the initial linear section of the stress-strain response is used to calculate the tensile modulus. In line with tensile strength trends, the UTWB and TWB composites reveal a higher modulus than the UTSB, TSB, UTWSWB, and TWSWB composites, respectively. UTSB and TSB depict a tensile modulus of 69.18 and 68.3 MPa, respectively, while UTWB, TWB, UTWSWB, and TWSWB show a tensile modulus of 109.49, 123.65, 75.68, and 102.75 MPa, respectively. The UTSB and TSB composites have a lower tensile modulus than all other compositions, owing to the fact that chopped banana fibres are ineffective in assisting with load transfer and hence have a lower modulus. The UTWB and TWB composites, on the other hand, exhibit increased tensile modulus due to effective load transfer from the woven fibres to the matrix that is free of chopped banana fibres. In line with the strength trends, UTWSWB and TWSWB show tensile modulus intermediate to short banana fibre composites (UTSB and TSB) and woven banana fibre composites (UTWB and TWB), which is mostly ascribed to the combined effect of chopped banana fibres and woven fibres. The elongation at break measured from the stress-strain curves is noted to be 10.08, 11.22, 11.76, 12.58, 12.98, and 10% for UTSB, TSB, UTWB, TWB, UTWSWB, and TWSWB, respectively. The elongation at break for all the composites is nearly equal to that of the TWB and UTWSWB composites, revealing higher values than other compositions.

3.3. Scanning Electron Micrographic Analysis. The scanning electron micrographs of the tensile-tested specimens for different banana fibre-reinforced epoxy composites are presented in Figure 11. Figure 11(a) shows the chopped banana fibre composites, wherein the chopped banana fibres can be seen in the micrographs. These chopped fibres provide adequate strength to the matrix during loading due to their random orientation. Figure 11(b) depicts the woven banana fibre composites, wherein the woven fibre above

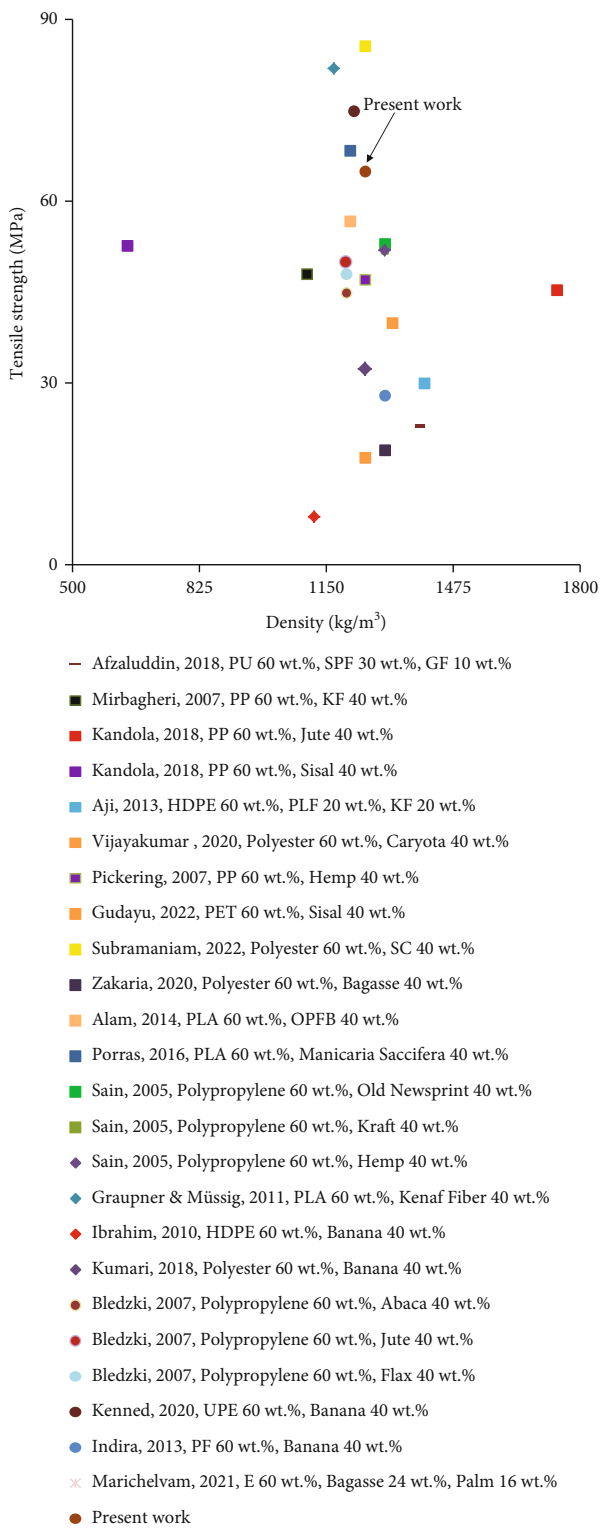

Figure 12: Property map depicting the density and tensile strength of various fibre-reinforced composites [33, 50–67]. (Note: PU: polyurethane; SPF: sugar palm fibre; GF: glass fibre; PP: polypropylene; KF: kenaf fibre: PLF: pineapple leaf fibre; PET: polyethylene terephthalate; SC: *Sansevieria cylindrica*; PLA: polylactic acid; OPFB: oil palm fruit bunch; HDPE: high-density polyethylene; UPE: unsaturated epoxy).

the matrix can be seen. The woven banana fibres, unlike chopped fibres, provide strength due to their weaving pattern that provides more resistance to loading mainly attributed to the excellent bonding between constituents and good interfibre strengths. Figure 11(c) shows the composites prepared by utilising chopped and woven fibres. It can be observed that the chopped fibres and woven fibres are appropriately mixed with the matrix. The combined effect of chopped and woven fibres is very advantageous in enhancing the overall properties of composites.

3.4. Property Map. The tensile strength of banana fibre-reinforced epoxy composite from the present work was compared with the available literature with a fixed fibre-to-matrix weight ratio of 40 : 60 as the optimum composition. Figure 12 depicts the comparison of tensile strength with their density to indicate the efficacy of composites studied in the present work. The mapping of the properties acts as a guide for the research community and industrial personnel to compare the properties of composites with different reinforcements. The composites made from sugar palm fibre, glass fibre, kenaf fibre, pineapple leaf fibre, *Sansevieria cylindrica*, and oil palm fruit bunch fibres reinforced in different thermoplastic and thermosetting matrices are compared. Compared with all the composites, the density of the banana fibre-reinforced epoxy composites is observed to be higher than that of several thermoplastics reinforced with kenaf and sisal, while it is more or less equal to or lower in comparison with several composites compared in this work. However, the tensile strength of the composites in the present work is higher than most of the composites owing to the excellent compatibility of the constituents and the highly resistant banana fibres. Thereby, signifying the use of banana fibres in the most widely utilised matrix resin. The property mapping of different composites thereby infers that banana fibre-reinforced epoxy composites from the present study aptly provide good tensile properties with low density and can be utilised in several envisaged applications. Furthermore, the abundantly available banana cultivation in Ethiopia can be effectively used to meet specific composite demands.

4. Conclusions

This study examines the properties of woven/short banana fibre epoxy composites, extracted from underutilized banana pseudostems, as a sustainable alternative to synthetic fibres. The hand lay-up method was employed, maintaining a 60 : 40 weight ratio of fibre to matrix. Parameters included fibre architecture, chemical treatment, and layering pattern. The key findings indicate that mercerized banana fibre composites displayed superior mechanical properties and a lower void fraction compared to their untreated counterparts. Chemically treated woven banana epoxy composites exhibited the highest tensile strength (64.95 MPa) and impact strength (24.37 KJ/m^2). Scanning electron micrographs further confirmed the excellent load resistance of woven composites due to strong bonding and effective stress transfer. Property mapping of composites also affirms the suitability of banana composites for envisaged applications.

Data Availability

All the data used for the study is available in the manuscript.

Conflicts of Interest

The authors declare no competing interests.

Authors' Contributions

Gezahgn Gebremaryam, Kiran Shahapurkar, and Venkatesh Chenrayan worked on the conceptualization. Gezahgn Gebremaryam, Fadi Althoey, and Haitham M. Hadidi were responsible for the methodology. Vineet Tirth, Ali Algahtani, Tawfiq Al-Mughanam, Abdulaziz H. Alghtani, and Manzoore Elahi M. Soudagar supervised the study. Gezahgn Gebremaryam and Kiran Shahapurkar contributed to writing the original draft. Kiran Shahapurkar, Venkatesh Chenrayan, Vineet Tirth, and Manzoore Elahi M. Soudagar carried out the investigation. Ali Algahtani, Tawfiq Al-Mughanam, Hassan Alqahtani, and H. C. Ananda Murthy provided substantial contributions to the review and editing.

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