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Cellulosic Enset fiber from agricultural waste as sustainable material for industrial application

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Abstract

Composite materials, sacks, and geotextiles used in agricultural and landscaping applications are predominantly fabricated from petroleum-based synthetic fibers, contributing significantly to microplastic pollution throughout their lifecycle. Substituting synthetic fibers with agricultural waste-derived alternatives, such as Enset (*Ensete ventricosum*) fiber, offers a promising pathway to reduce petrochemical dependence while enhancing environmental sustainability. This study comprehensively investigated the physico-mechanical properties and industrial potential of Enset pseudo-stem fibers as sustainable alternatives for textile and composite manufacturing. Characterization employed gas pycnometry, Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), thermogravimetric analysis (TGA), and tensile testing. FTIR analysis confirmed characteristic cellulose, hemicellulose, and lignin absorption peaks. Morphological examination revealed quasi-cylindrical fibers with diameters ranging from 70 to 265 µm (average: 156.4 µm) and diverse cross-sectional profiles including circular, bean-shaped, and serrated geometries. Density measurements yielded 1.48 g/cm^3. Tensile testing demonstrated strength values of 415–900 MPa (0.28–0.61 N/tex), comparable to commercial natural fibers including flax (500–900 MPa), jute (350–700 MPa), banana (529–914 MPa), sisal (400–700 MPa), and abaca (300–1600 MPa). Tensile strength exhibited inverse relationships with gauge length and fiber diameter, consistent with weakest-link theory. Thermal analysis revealed three-stage degradation with maximum decomposition at 550 °C. The hollow tubular morphology provides superior acoustic absorption (3000–6000 Hz). Beyond technical merits, Enset fiber valorization creates sustainable income opportunities for rural farmers while mitigating environmental impacts of synthetic fiber production and agricultural waste, positioning it as a viable eco-friendly alternative for packaging, geotextiles, composites, and acoustic applications.

Keywords Agro-waste fibers, Physicochemical characterization, Sustainability, Agricultural waste valorization

1 Introduction

The global shift toward sustainable materials has intensified research interest in lignocellulosic fibers derived from agricultural residues as alternatives to petroleum-based synthetic fibers [1–6]. Natural plant fibers offer notable advantages, including low density,

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biodegradability, renewable origin, and favorable specific mechanical properties, rendering them competitive with glass and synthetic fibers for applications in composites, geotextiles, packaging, and acoustic insulation [7, 8]. Agricultural waste streams represent particularly attractive fiber sources because valorization simultaneously addresses waste management challenges and creates economic value without competing with food production [8]. Among underexplored fiber sources, the pseudo-stem of *Ensete ventricosum*, commonly referred to as Enset or the false banana, generates substantial fibrous agricultural waste during traditional food processing in the Ethiopian highlands, where the crop sustains more than 20 million people. Enset fiber is a valuable by-product obtained from the pseudo-stem (trunk) of the enset plant during the preparation of the fermented food product kocho. On average, about 0.7 ± 0.1 tons per hectare of fiber can be extracted, and the annual production in Ethiopia is estimated at around 150,000 tons of fiber bundles, depending on agro-ecological conditions and landrace variations [1–4, 9–19]. Haile et al. [17], characterized *Ensete ventricosum* as a single-stemmed monocarpic plant occurring in both wild and cultivated forms (as shown in Fig. 1), with markedly different life cycles distinguishing these two populations [17–20]. The genus *Ensete* encompasses seven recognized species distributed across Africa and Asia. The Asian species include *Ensete superbum*, *E. glaucum*, and the more recently described *E. lecongkietii*, while the African continent hosts *E. ventricosum*, *E. livingstonianum*, and *E. homblei* in sub-Saharan regions, as well as *E. perrieri* in Madagascar [19–22]. Notably, *E. ventricosum* is the only species with a domesticated form, which is exclusively cultivated in Ethiopia, especially in south and southwestern Ethiopia, as shown in Fig. 2a and b. However, wild populations of *E. ventricosum* occur naturally throughout Central and East Africa, including the Democratic Republic of Congo, Zambia, Mozambique, Tanzania, and Uganda, though interestingly, the distribution of wild *E. ventricosum* within



Fig. 1 Parts of the Enset plant and its parts provisions [23, 24]

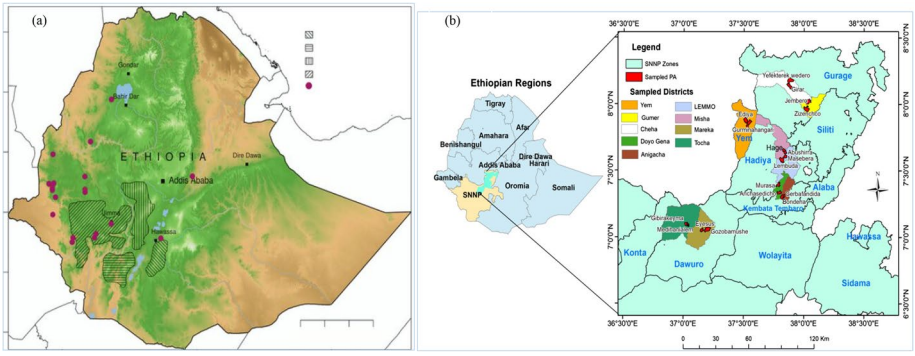

Fig. 2 Enset Plant Distribution: **a** Major domesticated and Enset-growing regions (shaded polygons) and wild Enset records (red points), Ethiopia [30], **b** Enset plant growing regions in south and southwestern Ethiopia [31]

Ethiopia itself remains quite limited. This distribution pattern suggests complex biogeographical and evolutionary dynamics underlying the relationship between wild and domesticated *Ensete* populations [19–37].

Despite this abundance, systematic characterization of Enset fiber's physicochemical, mechanical, and thermal properties remains limited, impeding its adoption in industrial material applications. Prior studies have reported only basic morphological dimensions without rigorous benchmarking against established noncommercial fibers [5, 8], and the socioeconomic dimension of fiber valorization has received minimal empirical attention. To address these gaps, the present study conducts a multi-technique characterization of Enset pseudo-stem fibers employing gas pycnometry, Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), thermogravimetric analysis (TGA), and single-fiber tensile testing, with results benchmarked against flax, jute, sisal, banana, and abaca fibers reported in the literature. The study additionally quantifies the ecological and economic potential of fiber waste valorization to provide a holistic assessment of this underutilized agro-industrial resource, thereby enhancing sustainable development objectives aligned with the global Sustainable Development Goals.

2 Materials and methods

2.1 Materials

Enset pseudo-stem was selected as the fiber source based on its documented agricultural importance in Ethiopia [9, 12, 26, 28] and the large volume of fibrous pseudo-stem waste generated as a byproduct of traditional kocho production, as shown in the Figs. 3 [30, 35–37].

2.2 Methods

2.2.1 Enset fiber extraction

Enset fibers are primarily extracted from the pseudo-stem and leaf sheaths using three principal methods manual, chemical, and mechanical, each with distinct advantages and limitations summarized in Table 1 [30–36]. Manual extraction involves scraping fibers from the pseudo-stem surface using wooden boards or iron ribbons, yielding high-quality fibers but remaining labor-intensive. Chemical extraction employs retting in water or sodium hydroxide solutions to remove non-cellulosic components and potentially enhance tensile strength. Mechanical extraction uses decorticating equipment such as raspadors for improved efficiency and scalability, though requiring capital investment, as



Fig. 3 Agro-waste Enset fiber

Table 1 The advantages and limitations of different methods of Enset fiber extraction methods [34, 35]

Fiber extraction methods	Advantages	Limitations	Reference
Manual extraction	• Higher quality of Fiber	• Limitations for large-scale production	[34–36]
Chemical extraction	• Effectively remove non-cellulosic components • Potentially increasing tensile strength		[34–36]
Mechanical Method	• Efficient for large-scale production	• Poor quality of Fiber	[34–36]

shown in Fig. 4. Regardless of method, extracted fibers undergo post-processing washing and drying to remove residual plant material [30–36].

To minimize operator-induced bias, all fiber extraction was performed by a single trained operator using identical stainless-steel blades maintained at a fixed 30° scraping angle, with a standardized pass sequence (3–4 passes per strip, inner to outer surface). Pre-defined acceptance criteria excluded fibers exhibiting visible kinks, contamination, localized cross-section narrowing, or mechanical surface damage. These fibers were discarded and replaced to maintain sample quality consistency. Extracted fibers were washed three times in distilled water (1:20 w/v, 15 min each), air-dried on mesh racks at 20–25 °C and 40–60% RH for 48 h, and stored in a desiccator. Future studies employing automated mechanical decortication under controlled process parameters are recommended to quantify and further mitigate this effect.

2.2.2 Enset fiber density analysis via pycnometer

Gas pycnometry with nitrogen displacement was selected for fiber density determination due to its high precision for porous materials, non-destructive operation, and ability to measure true skeletal density by penetrating surface irregularities and internal pores. Measurements were performed using an Anton Paar Ultrapyc 5000 with 99.99% nitrogen, five purge cycles, 10-minute equilibration per cycle, a chamber temperature of



Fig. 4 Manual Enset Fiber Extraction [36]

20 ± 0.1 °C, and a target pressure of 1.3 bar. Approximately 00.5 g of fibers were cut into 5–10 mm segments, oven-dried at 60°C for 24 h, and cooled in a desiccator prior to testing to ensure moisture removal and proper packing. Sample mass was measured with an analytical balance (±0.0001 g) and loaded into a 10 cm^3 chamber for analysis. Each specimen underwent ten consecutive measurement runs to improve statistical confidence. Reproducibility was ensured by testing five independent samples ($n = 5$), reporting densit y as standard deviation and maintaining a coefficient of variation below 2% [37, 38].

2.2.3 Chemical composition analysis of Enset fiber via FTIR

FTIR-ATR was selected for chemical characterization because it enables non-destructive identification of functional groups with minimal sample preparation and allows rapid screening of multiple fiber samples. The technique is well suited for detecting cellulose, hemicellulose, and lignin components, which are essential for understanding fiber be havior. Measurements were performed using FTIR spectrometer in ATR mode. Spectra were collected from 4000 to 400 cm^{-1} at a resolution of 4 cm^{-1} with 64 scans per sample and 64 background scans under ambient conditions [39].

2.2.4 Morphological characterization and diameter analysis of Enset fibers

Scanning electron microscopy (SEM) was used to characterize fiber surface morphology, defects, cross-sectional structure, and interfacial features relevant to composite applications because of its high magnification and large depth of field. Imaging was conducted

on an EVO-40 microscope at 15 kV with a working distance of 8–10 mm using a secondary electron detector, and micrographs were collected at 100×–5000× to capture multi-scale structural details. Fiber segments (5–10 mm) were mounted on aluminum stubs with carbon tape, oriented to expose longitudinal and cross-sectional surfaces, and sputter-coated with a 15 nm gold–palladium layer to prevent charging. Fiber diamete r was measured by optical microscopy combined with digital image analysis in accordance with ASTM D1577 to enable non-destructive statistical evaluation of dimensional variability. An Olympus microscope with a 10× objective and a calibrated 5-MP camera was used, and image analysis was performed with Image analysis software. Images were acquired at five equidistant positions along a 50 mm gauge length, and diameters were measured at three rotational orientations per position to account for non-circularity. The measuremnt were analyzed, and results were reported as mean ± standard deviation after excluding defective or non-uniform specimens to ensure data reliability [40–43].

2.2.5 Mechanical property analysis via universal testing machine

Single-fiber tensile testing was performed in accordance with ASTM D3379-75 to obtain reliable and comparable tensile strength while minimizing grip-induced failures and variability. Experiments were carried out at 23 ± 2 °C and 50 ± 5% relative humidity based on the test parameter illustrated in Table 2. Individual fibers were isolated, inspected, conditioned for 48 h, and mounted on cardboard tabs with cyanoacrylate adhesive to minimize stress concentration and grip damage. Fifty fibers (n = 50) were

Table 2 Summary of key experimental test parameters

Test method	Standard	Parameter	Details
Tensile testing	ASTM D3379-75	Equipment	Shimadzu UTM, 100 N load cell
		Gauge lengths	10, 25, 50 mm
		Crosshead speed	1 mm/min (strain rate ~ 0.01 s^{-1})
		Number of fibers	$n = 50$ per gauge length
		Temperature/humidity	23 ± 2 °C/50 ± 5% RH
		Data acquisition	10 Hz
		Statistical output	Mean, SD, CV%, Weibull modulus (m), scale parameter (σ_0)
Thermogravimetric analysis (TGA)	ISO 11358	Equipment (Germany)	TGA instrument
		Heating rate	10 °C/min
		Temperature range	23–600 °C
		Atmosphere	N_2 (99.999%), 50 mL/min total flow
		Sample mass	5–10 mg
		Replicates	$n = 3$
		Reported parameters	T_{10}, T_{50}, $T_t$max, mass loss per stage (%)
Density (gas pycnometry)	–	Equipment (Germany)	Anton Paar Ultrapyc 5000
		Gas	N_2 (99.99%)
		Pressure	1.3 bar
		Temperature	20 ± 0.1 °C
		Purge cycles	5
		Replicates	$n = 5$ (10 runs each)
		Precision	CV < 2%
Diameter measurement	ASTM D1577	Equipment (Germany)	Olympus optical microscope, 10× objective
		Measurement protocol	15 measurements per fiber (3 angles × 5 positions along 50 mm)
		Replicates	$n = 50$ fibers

tested to failure, and specimens breaking within 5 mm of the grips were excluded and replaced to ensure statistical validity .

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2.2.6 Thermogravimetric analysis (TGA) of Enset fiber

Thermogravimetric analysis (TGA) was employed to evaluate the thermal stability and degradation behavior of Enset fibers, which is critical for defining safe processing windows for composite manufacturing. The technique enables (i) Heating rate = 10 °C/min under N_2 atmosphere (99.999%). (ii) Quantitative stage mass losses: Stage I (23–147 °C): ~6% (moisture/volatiles); Stage II (147–370 °C): ~58% (hemicellulose + cellulose; DTG peak at 298 °C); Stage III (370–600 °C): ~18% (lignin char); Residual at 600 °C: ~18%. (iii) Clarification of 550 °C: This temperature does not represent a distinct cellulose or hemicellulose decomposition peak. It corresponds to the final char oxidation/residual lignin degradation plateau in the DTG profile, consistent with slow, broad lignin decomposition under inert atmosphere. Lignin's highly cross-linked aromatic structure results in a gradual mass loss extending well beyond 400 °C, with the DTG signal tail near 550 °C representing residual aromatic char degradation, not a discrete thermal event. This is consistent with published TGA data for flax (T_{tmax} ~340 °C), jute (320–350 °C), sisal (~ 330 °C), and banana (~ 310 °C). (iv) Processing window: safe composite processing is recommended below 200 °C to prevent hemicellulose decomposition onset (T_{10} = 237 °C) [44].

3 Results and discussion

3.1 FTIR spectroscopic analysis of Enset fiber

The Fourier Transform Infrared spectroscopic analysis of Enset fiber revealed characteristic absorption peaks corresponding to its principal chemical constituents: cellulose, he micellulose, and lignin, as illustrated in Fig. 5. The FTIR spectrum of untreated Enset fibers exhibited diagnostic absorption bands at 3346, 2956, 2876, 1730, 1641, 1463, 1161, and 1033 cm^{-1}, each providing specific information about the molecular structure and chemical composition of the fiber material.

The broad, intense absorption peak at 3346 cm^{-1} corresponds to O–H stretching vibrations of hydroxyl groups present in the cellulosic structure of Enset fibers. The breadth and intensity of this peak indicate extensive hydrogen bonding networks within the cellulose crystalline and amorphous regions, which directly correlate with the fiber's hygroscopic behavior and mechanical properties. Strong intermolecular hydrogen bonding in

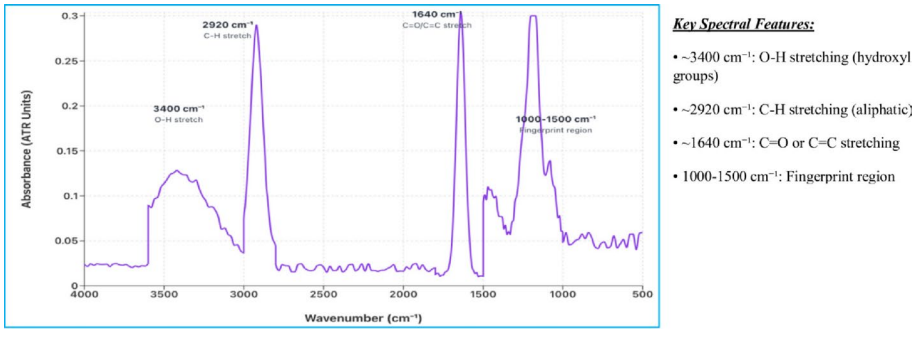

Fig. 5 FTIR analysis of Enset fiber

cellulose contributes to crystalline packing efficiency, which enhances tensile strength and modulus. However, the abundant hydroxyl groups also render the fiber hydrophili c, potentially compromising dimensional stability and interfacial adhesion in hydrophobic polymer matrices without appropriate surface modification. Similarly, the absorption bands at 2956 and 2876 cm^{-1} are attributed to asymmetric and symmetric C–H stretching vibrations in aliphatic methyl and methylene groups present in cellulose, hemicellulose, and lignin structures. These peaks confirm the presence of aliphatic hydrocarbon chains characteristic of the glycosidic rings in polysaccharides and propyl side chains in lignin [45–48]. A distinct carbonyl stretching peak observed at 1730 cm^{-1} indicates the presence of acetyl groups (–O–(C=O)–CH_3) associated with hemicellulose, specifically the acetylated xylan backbone common in monocotyledonous plants. The presence of this peak is mechanistically significant because acetyl groups reduce hydrogen bonding between hemicellulose chains and adjacent cellulose microfibrils, creating amorphous regions that decrease overall fiber crystallinity. The absorption at 1641 cm^{-1} is attributed to adsorbed water molecules and conjugated C=O stretching in lignin aromatic rings. This peak provides evidence of the fiber's moisture content and the presence of aromantic structure within the lignin component. The peak at 1463 cm^{-1} corresponds to C–H bending vibrations in methylene groups of cellulose and hemicellulose [45, 46, 48]. Moreover, the strong absorption bands at 1161 and 1033 cm^{-1} represent C–O stretching vibrations characteristic of the glycosidic linkages and C–O–C bridges in cellulose and hemicellulose polysaccharide structures. The intensity of the peak at 1033 cm^{-1} is particularly diagnostic of cellulose content, as it corresponds to the C–O stretching of the β-(1→4)-glycosidic bonds linking glucose units in cellulose chains. The relative intensity of this peak compared to other absorption bands can be used as a semi-quantitative indicator of cellulose content, with stronger absorption suggesting higher cellulose concentration, which correlates positively with mechanical strength and thermal stability. These findings demonstrate excellent agreement with previous investigations of Enset fiber composition, characterized raw Enset fibers and reported absorption peaks at 3331, 2917, 1730, 1665, 1422, 1156, and 1028 cm^{-1}, showing strong correspondence with the present results (peak position variations of less than 20 cm^{-1} are within typical experim ental uncertainty). Enset fiber typically contains 60–65% cellulose, 10–20% hemicellulose, and 5–10% lignin, indicating a composition comparable to other lignocellulosic fibers. For example, Flax contains about 65–75% cellulose, 10–20% hemicellulose, and 2–5% lignin [49], while Jute consists of approximately 60–65% cellulose, 20–24% hemicellulose, and 10–12% lignin [50]. Similarly, Sisal has 60–70% cellulose, 10–14% hemicellulose, and 8–12% lignin [51], Banana contains 55–65% cellulose, 15–20% hemicellulose, and 5–10% lignin [52], and Abaca exhibits 56–63% cellulose, 20–25% hemicellulose, and 7–9% lignin [53]. These values confirm that Enset fiber falls within the typical compositional range of natural lignocellulosic reinforcement fibers. This consistency confirms the reproducibility of Enset fiber's fundamental chemical structure across different samples, geographical sources, and processing conditions, supporting the reliability of FTIR as a characterization technique for this material [49–53]. Generally, the FTIR analysis provides critical insights into structure-property relationships that govern Enset fiber behavior in composite applications. The high concentration of hydroxyl groups indicated by the strong 3346 cm^{-1} peak suggests that surface modification treatments such as alkalinization, acetylation, or silane coupling will be necessary to reduce hydrophilicity and

improve compatibility with hydrophobic polymer matrices. The presence of the 1730 cm $^{-1}$ carbonyl peak associated with hemicellulose acetyl groups indicates that mild alkaline treatments will effectively remove these thermally unstable components, potentially improving thermal stability and reducing moisture absorption. The strong cellulosic C–O stretching peaks at 1161 and 1033 cm^{-1} suggest high cellulose content, which correlates with the favorable mechanical properties observed in tensile testing and positions Enset fiber competitively among other high-performance natural fibers such as flax, jute, and sisal [5, 44, 46].

3.2 Diameter analysis of single Enset fiber

Comprehensive measurements of individual Enset fibers revealed substantial diameter variability, ranging from 70 to 265 µm, with a mean of 156.4 ± 42.8 µm and a coefficient of variation of 27.4%, reflecting natural biological variation, as illustrated in Fig. 6a and b. The reported values of 70 µm and 265 µm in Fig. 6 represent the minimum and maximum diameters observed across the full 50-fiber population, not a single cross-section. Within-fiber diameter variability was also observed: measurements at five equidistant positions along each fiber showed a mean within-fiber CV of approximately 12 ± 5%, consistent with the anatomical taper and growth heterogeneity characteristic of natural plant fibers. Variability arises from anatomical factors (basal fibers being coarser than apical fibers), physiological influences (water, nutrients, and light), and extraction methods, with the present study isolating elementary fibers, yielding a broader range than previous reports. Fibers exhibit non-circular cross-sections, including circular, elliptical, and polygonal shapes, with a mean circularity index of 0.76 ± 00.12, necessitating multi -angle measurements. A systematic protocol involving 50 measurements per fiber (th ree angles at five positions) ensured accuracy and was validated using carbon reference fibers [54]. Diameter variability strongly affects mechanical properties: smaller-diameter fibers (70–120 µm) exhibited higher tensile strength (742 ± 98 MPa) compared to larger fibers (190–265 µm, 523 ± 87 MPa), demonstrating a significant negative correlation ($p < 0.001$). These findings highlight the importance of diameter characterization for optimizing fiber selection and composite perfromance [54]. This within-fiber variability is a known contributor to single-fiber tensile strength scatter and further justifies the application of Weibull statistical analysis for strength characterization (see Sect. 3.5).

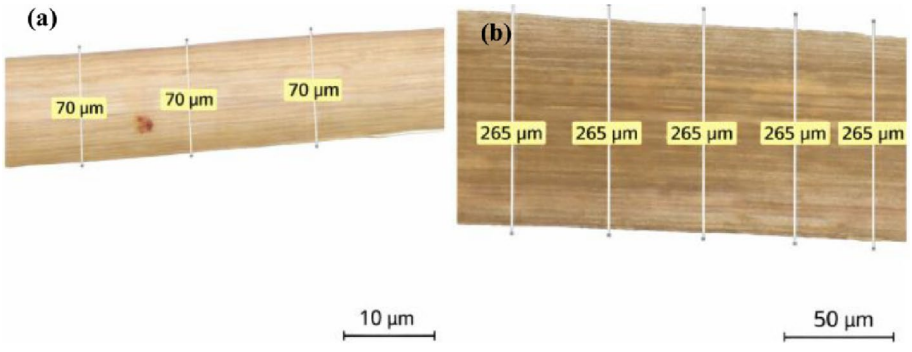

Fig. 6 Diameter analysis of single Enset fiber via polarized optical microscope: **a** Minimum diameter measurement value, **b**) maximum diameter measurement value

3.3 Morphological analysis of Enset fibers

Microscopic examination revealed that Enset fibers have a hierarchical structure, with elementary fibers exhibiting cylindrical morphology and diameters ranging from 70 to 265 μm, as shown in Fig. 7a and b. These elementary fibers naturally aggregate into technical fiber bundles via a middle lamella composed of pectin and hemicellulose. Each bundle contains a lot of elementary fibers, with a coefficient of variation of 42%, reflecting vascular organization within the pseudo-stem. The fiber cross-sections display diverse geometries, including circular, elliptical, and polygonal profiles, influenced by spatial constraints during tissue development, as shown in Fig. 7a. Cell lumens occupy 15–25% of the cross-sectional area, contributing to the relatively low fiber density of 1.4 8 g/cm³ and acoustic damping properties. Surface analysis revealed rough topography with protrusions, depressions, and adhered non-cellulosic components such as lignin, hemicellulose, pectin, waxes, and mineral inclusions. The cuticle layer on bundle exteriors and the middle lamella facilitate load transfer among elementary fibers during m echanical loading. Strong interfacial adhesion allows load sharing across fibers, while weak adhesion permits fiber sliding, reducing bundle strength. Tensile testing revealed two failure modes: brittle fracture in coarser fibers with defects and ductile deformat ion in finer fibers. Brittle fracture involves clean transverse breaks with minimal fibril pull-out, indicative of low fracture toughness. Ductile deformation shows longitudinal splitting, fibril separation, and progressive damage, accommodating higher strain. Finer fibers exhibit higher cellulose content and more ordered microfibrils, promoting longitudinal splitting while the coarser fibers have higher lignin and hemicellulose content, stiffening the structure and favoring brittle fracture. These microstructural features explain the relationship between fiber morphology, surface characteristics, and mechanical performance in Enset fibers.

3.4 Density analysis of single Enset fiber

Gas pycnometry measurements gave an average skeletal density of 10.476 ± 0.003 g/cm³ for Enset fibers, with very low variability, indicating excellent measurement precision and uniform material composition as presented in Table 3. Statistical analysis confirmed a normal distribution of density values, validating the reliability of the results. The measured density is slightly lower than that of pure crystalline cellulose (1.14–10.548 g/cm³) due to the presence of 15–25% lumen void space and the contribution of lower-density constituents such as hemicellulose and lignin. The value represents a volume-weighted average of these components, consistent with the fiber's lignocellulosic structure. Enset

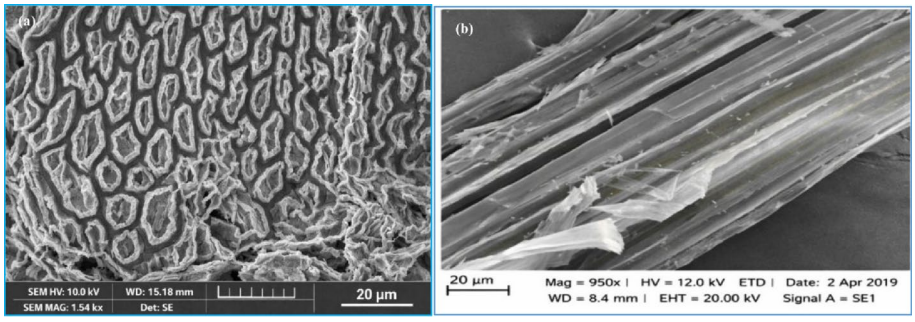

Fig. 7 SEM morphological analysis of Enset fibers: **a** cross-sectional View of Enset Fiber, **b** longitudinal View of Enset Fiber

Table 3 Density analysis of Enset fiber via pycnometer

Sample	Cell size	Weight (gm)	Volume (ml)	Density (g/ml)	RSD (%)	Avg. density (g/ml)	Uncertainty (%)	Density (g/cm^3)
Enset Fiber	Micro	0.4	0.2711	1.476	0.178	1.48	0.63	1.476

Table 4 The mechanical properties of a single Enset fiber

Fiber	Force (*N*)				Tensile strength (MPa)				Percentage elongation (%)			
	Min.	Max.	Ava.	STDV	Min.	Max.	Ava.	STDV	Min.	Max.	Ava.	STDV
Enset fiber	13.29	6.13	9.16	1.7	415	900	621	115	1.93	5.53	3.24	0.86

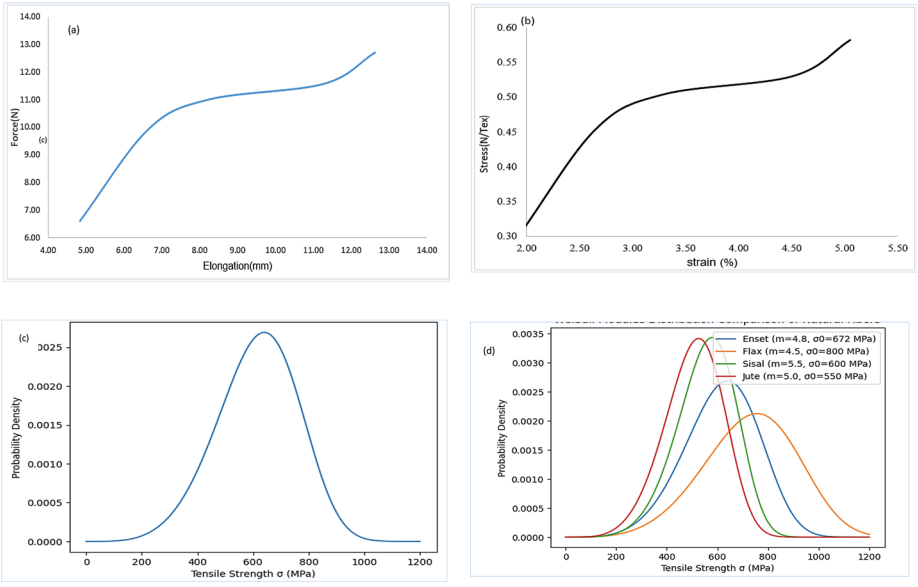

Fig. 8 Mechanical property analysis of single Enset fiber: **a** force-elongation curve, **b** stress–strain curve, **c** Weibull modulus distribution diagram of single Enset fiber tensile strength (m = 4.8, σ_0 = 672 MPa) and **d** single Weibull modulus distribution comparison diagram showing Enset fiber vs common natural fibers

fiber density closely matches other natural fibers such as jute, flax, hemp, and sisal, confirming its classification within the same material family. The relatively low density provides advantages for lightweight composite applications compared with glass and carbon fibers. When normalized by weight, Enset fibers exhibit favorable specific strength and stiffness for weight-sensitive structures. Moreover, its accurate density values allow calculation of fiber volume fraction and composite density using rule-of-mixtures relatio nships. Density data also enable estimation of void content in manufactured composites, supporting quality control and processing optimization.

3.5 Mechanical property analysis of single Enset fiber

Tensile testing of individual Enset fibers produced mean values of 9.16 ± 1.7 N breaking f orce, 3.24 ± 0.86% elongation at break, and 621 ± 115 MPa tensile strength, as described in Table 4; Fig. 8a and b. The tensile strength ranged from 415 to 900 MPa, reflecting the inherent biological and microstructural variability of natural fibers. The coefficient of variation of 18.5% falls within the typical range for lignocellulosic fibers, indicating reliable experimental results. Statistical analysis showed that strength follows a Weibull distribution with avarage tensile strength of 657 MPa, consistent with weakest-link

failure behavior. This strength indicates moderate scatter and compares favorably with fibers such as flax, banana, and jute [55–64]. Th e relatively high strength of Ense t fibers is attributed mainly to high cellulose content and favorable microfibril orientation, as shown in Fig. 7b. Enset fibers (70–120 µm) achieved a mean strength of 742 ± 98 MPa, whereas coarser fibers (190–261 µm) reached only 523 ± 87 MPa. This represents nearly a 30% reduction in strength for the largest fibers. Relativelly due to bark contenet in coarser enset fibers, these coarser enset fibers contain a higher probability of critical defects, greater lignification, stronger stress concentrations, and higher residual internal stresses. Consequently, selecting finer fibers improves tensile performance, alth ough processing becomes more difficult. The mechanical test result revealed that tensile strength decreased from 698 MPa at 10 mm to 621 MPa at 25 mm and 547 MPa at 50 mm. This reduction follows Weibull weakest-link theory, where longer specimens have higher failure probability [48–52]. This dependence must be considered when comparing literature values and predicting in-composite fiber strength. The estimated tensile strength is about 621 ± 4 MPa, comparable to jute and lower than high-performance flax and sisal [55–64]. Two-parameter Weibull distribution fitted to single-fiber tensile strength data ($n = 50$, gauge length 25 mm) yields: Weibull modulus m = 4.8 (shape parameter), scale parameter σ_0 = 672 MPa (characteristic strength). The modulus distribution confirms that Enset fibers exhibit variability comparable to established natural fibers such as flax (m = 3–6), sisal (m = 4–7), and jute (m = 4–6), as described in Fig. 8a. The Weibull modulus of 4.8 is consistent with reported values for flax (m = 3–6), sisal (m = 4–7), and jute (m = 4–6), indicating moderate but acceptable scatter for lignocellulosic natural fibers, as shown in Fig. 8b. The gauge-length dependence (698 MPa at 10 mm → 547 MPa at 50 mm) conforms to Weibull weakest-link scaling. Furthermore, gauge-length scaling (10–50 mm) follows Weibull weakest-link behavior, where longer fibers show reduced strength due to increased defect probability. Correspondingly, the statistical comparison with reference fibers (Table 5) confirms that Enset fiber tensile strength is competitive within the natural fiber family [64–66]. The moderate stiffness arises from semicrystalline cellulose and the presence of compliant hemicellulose and lignin. Similarly, the relatively high elongation at break provides ductility through microfibrillar slip and matrix deformation. This behavior enhances energy absorption a nd damage tolerance in composites. Generally, Enset fiber strength compares well with established natural fibers such as flax, jute, sisal, banana, and abaca, as described in Table 5. Its performance lies in the mid-to-upper range of lignocellulosic fibers. These results demonstrate that Enset fiber is a mechanically competitive reinforcement. It is

Table 5 Comparative physicochemical and mechanical properties of Enset fiber vs. selected natural fibers

Fiber type	Density (g/cm^3)	Diameter (µm)	Tensile Strength (MPa)	Elongation at Break (%)	T_{tmax} (°C)	Cellulose Content (%)
Enset (this study)	1.48	70–265 (mean 156.4)	415–900 (mean 621)	1.93–5.53 (mean 3.24)	298	~60–65
Flax	1.50–1.53	10–40	500–900	1.2–3.2	~340	~71–75 [67]
Jute	1.44–1.46	20–200	350–700	1.5–2.0	~320–350	~61–72 [68]
Sisal	1.33–1.50	100–300	400–700	2–7	~330	~67–78 [69]
Banana	1.30–1.35	80–250	529–914	1–3.5	~310	~60–65 [70]
Abaca	1.50	10–30	300–1600	3–5	—	~56–63 [71]

therefore suitable for use in natural fiber composites, technical textiles, and lightweight structural applications.

3.6 Thermal degradation stability performance analysis (TGA) of Enset fiber

Thermogravimetric analysis of Enset fiber under a nitrogen atmosphere revealed a characteristic different-stage degradation behavior, similar to that of most lignocellulosic fibers, as shown in Fig. 9. The Enset fiber TGA has been interpreted as substantially enhanced with the following clarification: (i) Heating rate: all TGA measurements were conducted under a constant heating rate of 10 °C/min under nitrogen atmosphere, which is consistent with standard protocols for lignocellulosic fibers. (ii) Quantitative mass loss per degradation stage: Stage I (23–147 °C): ~6% mass loss due to moisture and volatile extractive evaporation. Stage II (147–370 °C): ~64% mass loss corresponding predominantly to hemicellulose and cellulose decomposition (DTG peak at T_{tmax} = 298 °C). Stage III (370–600 °C): ~18% mass loss attributed to lignin degradation and char formation; residual char content ~ 18%. (iii) Clarification of the 550 °C maximum: The mass loss event reported near 550 °C does not represent a discrete hemicellulose or cellulose degradation peak. Rather, it corresponds to the final char oxidation/residual lignin degradation plateau in the DTG curve, consistent with the broad degradation profile of highly aromatic, cross-linked lignin structures under an inert atmosphere. This interpretation aligns with published data for sisal, flax, jute, and banana fibers, which also exhibit residual lignin decomposition tailing above 400 °C [53–55]. The T_{50} = 326 °C and T_{10} = 237 °C values define the practical processing window: safe composite processing temperatures should remain below ~ 200 °C to prevent the onset of hemicellulose decomposition and associated porosity, strength loss, and discoloration. (iv) Comparison with literature: The three-stage degradation behavior and characteristic temperatures of Enset fiber compare favorably with reported values for flax (T_{tmax} ~340 °C), jute (T_{tmax} ~320–350 °C), sisal (T_{tmax} ~330 °C), and banana (T_{tmax} ~310 °C), confirming comparable thermal behavior within the lignocellulosic fiber family [63, 64]. Generally, the thermal behavior of Enset fibers is comparable to jute, sisal, and flax, confirming their suitability for similar composite processing and applications.

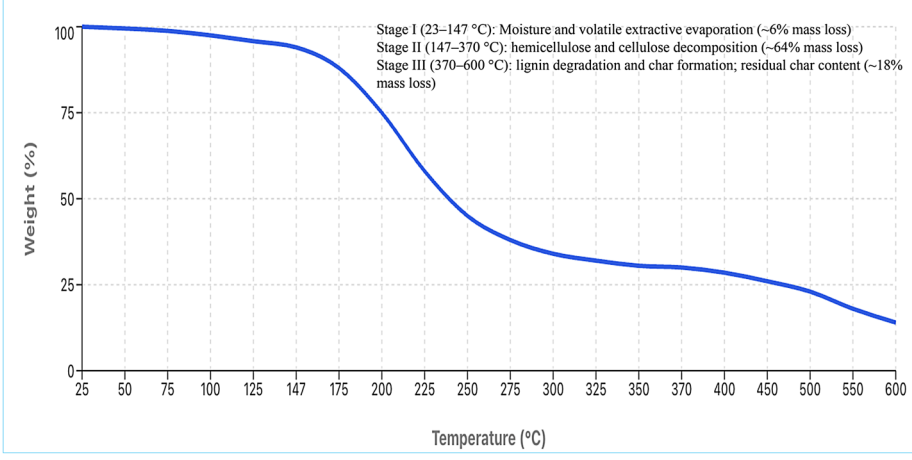

Fig. 9 TGA of Enset fibers

3.7 Ecological and economic benefits of agricultural waste Enset fiber

The Comprehensive global production statistics for Enset fiber remain largely unavailable, as research emphasis has traditionally focused on the plant's nutritional value rather than its fiber production potential [72, 73]. Nevertheless, regional yield estimates provide valuable insights into the substantial volume of fiber generated as agricultural waste.

3.7.1 Production volume analysis and economic quantification

While comprehensive global production statistics for Enset fiber remain limited due to historical research emphasis on nutritional rather than industrial applications, regional yield estimates provide valuable insights into the substantial volume of fiber generated as agricultural waste with significant economic and environmental implications. Rober t and Chernet developed yield estimates based on regional cultivated areas and avera ge yields, employing conservative assumptions: average yield of 27 kg harvested plant material per plant, planting density of 400 plants per hectare (corresponding to 2.5 m × 2.5 m spacing typical in traditional cultivation systems), and annual harvest of approximately one-quarter of the standing population (reflecting the multi-year growth cycle of Enset, with plants harvested at 3-5 years maturity). These parameters yield an estimated production of 108 quintals (10.8 metric tons) of total plant material per hectare annually. For the Southern Nations, Nationalities, and Peoples' Region, which encompasses 287,334 hectares under Enset cultivation, this translates to annual production of approx imately 2,482,574 metric tons of harvested plant material. Including an additional 26,821 hectares from Oromia Region (15,487 hectares from documented zones plus an estim ated 11,334 hectares from Borena zone), total national production reaches approximately 2,772,241 metric tons annually. However, these figures represent total harvested plant biomass including the starchy corm and pseudo-stem used for food production. The fiber fraction, derived primarily from the leaf sheaths and outer pseudo-stem layers separated during kocho processing, comprises approximately 15 – 20% of total plant dry weight based on traditional processing observations. Applying a conservative estimate of 15% fiber yield, the annual production of Enset fiber waste amounts to approximately 415,836 metric tons nationally. At the current average market price of 200 Ethiopian Birr per kilogram for processed fiber, complete utilization of this fiber resource would represent a gross value of approximately 83.2 billion Ethiopian Birr annually [73, 74].

3.7.2 Market context and economic development potential

It is critical to emphasize that these economic projections are highly context-dependent and represent theoretical maximum values rather than realized market potential. The actual market price exhibits substantial spatial and temporal variability influenced by fiber quality parameters (cleanliness, uniformity, strength, color), processing sophistication (hand-stripped versus mechanically processed), transaction volume (wholesale versus retail), seasonality, and geographical proximity to processing facilities or transportation infrastructure. Furthermore, the current market absorption capaci ty for Enset fiber products remains limited, and large-scale commercialization would likely require market development, product innovation, and value chain infrastructure investment. Nevertheless, even partial valorization of Enset fiber waste represents substantial economic development potential for rural farming communities in Enset-cultivating

regions. Conservative scenarios assuming utilization of 10% of available fiber waste (41,584 metric tons) at 50% of the quoted market price (100 Birr/kg) would still generate approximately 4.16 billion Birr annually, representing significant income enhancement for smallholder farmers who currently derive minimal or no revenue from this waste stream. Establishment of decentralized fiber processing cooperatives, development of value-added products (technical textiles, geotextiles, composites), and integration into national and international supply chains could progressively realize this economic pote ntial while simultaneously addressing environmental challenges associated with agricultural waste accumulation [72–76].

3.7.3 Environmental benefits: waste reduction and circular economy

The conversion of Enset fiber agricultural waste into value-added products addresses multiple environmental challenges while promoting circular economy principles. Currently, the vast majority of Enset fiber separated during kocho processing is discarded as waste, either left to decompose in field piles or burned to reduce volume. While biological decomposition returns some nutrients to soil, the slow degradation rate of lignified fibers results in unsightly waste accumulation in villages and processing areas, creating sanitation concerns and potential pest habitats. Open burning, practiced in some reg ions during dry seasons to manage accumulated waste, generates air pollution including particulate matter and carbon monoxide while representing a loss of potentially valuable biomass resources. Systematic collection and utilization of Enset fiber waste would eliminate these negative environmental impacts while creating economic value. The fiber's renewable, annually regenerating nature contrasts sharply with petroleum-based synthetic fibers derived from finite fossil resources, offering a sustainable alternative that reduces dependence on non-renewable materials [72–76].

Beyond direct fiber applications, the integration of fiber valorization into Enset agricultural systems can provide additional environmental benefits. Systematic collection of fiber waste for industrial applications encourages more complete biomass utilization and may incentivize improved Enset cultivation practices. The residual char or ash from thermal processing of fiber waste (for example, in biomass energy systems) can be r eturned to agricultural soils as a soil amendment, providing mineral nutrients (potassium, phosphorus, calcium, magnesium) and potentially improving soil carbon sequestration through biochar formation. The cultivation of Enset itself provides important environmental services in Ethiopian highland agroecosystems including year-round s oil cover that reduces erosion, deep root systems that stabilize slopes and improve soil structure, and large leaf canopies that moderate microclimate and provide shade for i ntercropped species. By creating economic value from both the food and fiber fractions of Enset, integrated utilization strategies may help preserve traditional Enset-based agricultural systems that provide these environmental benefits, countering trends toward r eplacement with annual grain monocultures that offer inferior environmental perfor mance.

3.7.4 Biodegradability and end-of-life advantages

A critical environmental advantage of Enset fibers is their inherent biodegradability through microbial action. Unlike synthetic polymers such as polyethylene, polypropylene, and polyester, which persist in the environment for decades or centuries,

lignocellulosic fibers undergo biological decomposition through enzymatic hydrolysis by bacteria and fungi, typically degrading completely within months to a few years depending on environmental conditions. This biodegradability significantly reduces long-term environmental impact and mitigates waste accumulation in landfills, oceans, and terrestrial ecosystems. The application of biodegradable Enset fibers in packaging materials offers particularly compelling environmental benefits. Coffee sacks, grain bags, and con sumer goods packaging manufactured from Enset fiber provide functional performance comparable to synthetic woven sacks while offering complete biodegradability at end-of-life. In agricultural applications, packaging materials contaminated with organic residues can be composted along with their contents rather than requiring separation and disposal, simplifying waste management and returning organic matter to agricultural systems. In regions lacking comprehensive waste collection infrastructure, the use of b iodegradable packaging materials reduces environmental contamination from escaped packaging waste [74–76].

3.7.5 Implementation requirements and strategic priorities

Realizing the full economic and environmental potential of Enset fiber requires coordinated investments and strategic interventions across multiple domains. Technical priorities include development of efficient, scalable fiber extraction and processing technologies suitable for smallholder contexts, establishment of fiber quality standards and testing protocols to ensure consistent product quality, and research on optimal fiber modification treatments and composite formulations for specific applications. Economic priorities include creation of market linkages between fiber producers and industrial consumers, development of value-added products with favorable market positioning, and establishment of fair and transparent pricing mechanisms that provide adequate returns to fiber producers. Institutional priorities include farmer training and capacity building in fiber processing and quality control, development of cooperative organizational structures for collective processing and marketing, and supportive policy frameworks that incentivize sustainable material development and provide preferential marke t access for bio-based products.

3.8 Industrial applications of Enset fibers

The favorable combination of mechanical strength, durability, and biodegradability exhibited by Enset fibers renders them suitable for diverse industrial applications spanning both traditional and emerging technological sectors.

Traditional applications: Conventionally, Enset fibers have been employed in textile and packaging industries, particularly for manufacturing sacks, wrappings, and containers used in transporting and storing agricultural and industrial commodities such as grains, coffee beans, and other bulk products. These applications capitalize on the fiber's inherent tensile strength, abrasion resistance, and cost-effectiveness as a natural packaging material.

Composite materials and structural applications: Consistent with trends observed in other widely utilized plant fibers, Enset fibers are increasingly being incorporated as reinforcing elements in polymer matrix composites. These fiber-reinforced composites find application in non-load-bearing and semi-structural components across multiple sectors, including roofing materials, building construction elements, and automotive

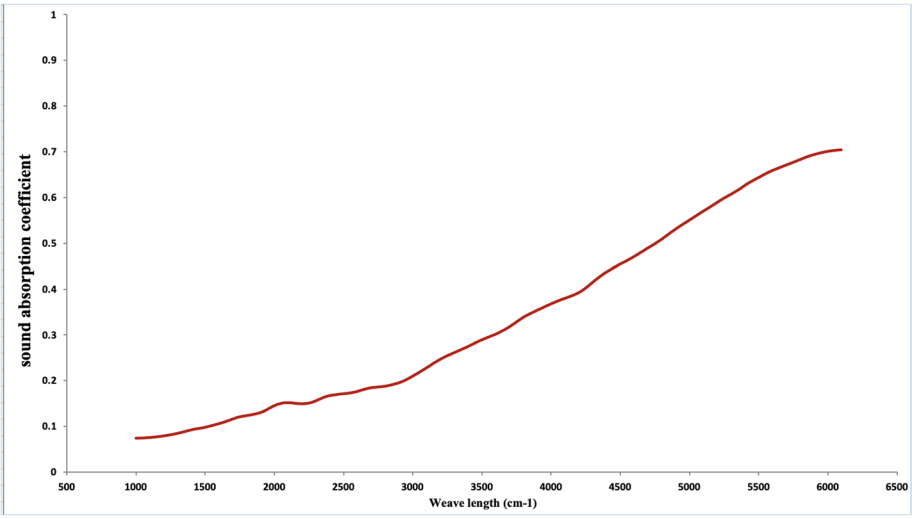

Fig. 10 Acoustic properties of Enset Fiber

interior components. The natural origin, renewable nature, and favorable specific mechanical properties of Enset fibers position them as attractive alternatives to synthetic reinforcements in applications where moderate mechanical performance is adequate.

Advanced and emerging applications: Recent research has explored higher-value applications leveraging the unique characteristics of Enset fibers.

Geotextiles and erosion control: Enset fibers are being utilized in the production of geotextile materials deployed in agricultural and landscaping applications for soil erosion prevention, weed suppression, and as seed-bed substrates [3, 10, 72, 76]. These biodegradable geotextiles offer environmental advantages over synthetic alternatives by naturally degrading after fulfilling their functional purpose.

Nanocellulose production: Advanced processing techniques have enabled the extraction of cellulose nanofibers from Enset, opening possibilities for high-performance applications in nanocomposites, functional coatings, and biomedical materials [3, 5, 24].

Home furnishings and textiles: Enset fibers are incorporated into floor coverings, carpets, rugs, and other interior furnishing materials, frequently blended with complementary natural or synthetic fibers to optimize mechanical properties and aesthetic characteristics [10, 72].

Acoustic applications: The distinctive morphological characteristics of Enset fibers, particularly their hollow tubular structure and internal voids, confer advantageous acoustic damping properties, as described in Fig. 7 [24, 76]. Temesgen et al. [3] demonstrated that Enset fabric exhibits superior sound absorption capabilities compared to conventional glass fiber materials across a broad frequency spectrum ranging from 3000 Hz to 6000 Hz, as shown in Fig. 10 [59, 61]. This exceptional acoustic performance positions Enset fiber as a promising sustainable alternative to flax and other natural fibers in environmentally conscious automotive and construction sectors where noise attenuation is critical. Furthermore, Temesgen and Eren [2] investigated the enhancement of acoustic properties through nanostructuring of Enset fibers [23, 54, 76]. Their research demonstrated that conversion of raw Enset fiber into green nanofiber forms through enzymatic treatment followed by mechanical disintegration resulted in a 47% improvement in acoustic absorption performance [23, 54, 76]. This significant

enhancement underscores the potential for advanced processing techniques to unlock superior functional properties and expand the application scope of Enset fibers into high-performance acoustic insulation materials for automotive, aerospace, and architectural applications [76]. These diverse and expanding applications demonstrate the versatility of Enset fiber as an industrial raw material, highlighting its potential to contribute to sustainable material development across multiple industrial sectors.

4 Conclusion

This study systematically characterized *Ensete ventricosum* pseudo-stem fibers from the Gurage and Hadiya highland zones of Ethiopia using a multi-technique analytical framework. FTIR-ATR spectroscopy confirmed the presence of the principal lignocellulosic constituents (cellulose, hemicellulose, lignin) via characteristic absorption bands at 3346, 1730, and 1033 cm^{-1}, indicating that surface modification treatments will be required to enhance fiber–matrix interfacial compatibility in hydrophobic polymer composites. SEM and optical microscopy revealed hierarchical fiber architecture with elementary fiber diameters of 70–265 μm (mean 156.4 ± 42.8 μm), diverse non-circular cross-sectional morphologies, and cell lumen fractions of 15–25%. Gas pycnometry yielded a skeletal density of 1.476 ± 0.003 g/cm^3, comparable to jute, flax, and sisal. Single-fiber tensile testing ($n = 50$; 25 mm gauge) demonstrated a mean tensile strength of 621 ± 115 MPa (range: 415–900 MPa), elongation at break of 3.24 ± 0.86%, and Weibull modulus m = 4.8, consistent with moderate variability characteristic of lignocellulosic fibers. Tensile strength showed a significant inverse correlation with fiber diameter ($p < 0.001$) and gauge length (698 → 547 MPa over 10–50 mm), in agreement with Weibull weakest-link theory. TGA under nitrogen (10 °C/min) revealed three-stage degradation: moisture loss (~ 6%, < 147 °C), hemicellulose/cellulose decomposition (~ 64%, DTG peak 298 °C), and lignin char degradation (~ 18%, 370–600 °C), establishing a safe composite processing limit below 200 °C. These property profiles are competitive with those of commercially established natural fibers and support the technical feasibility of Enset fiber for composite reinforcement, geotextile, packaging, and acoustic insulation applications. The substantial annual volume of Enset fiber agricultural waste (~ 150,000 tons in Ethiopia) represents both an environmental challenge and an economic opportunity for rural smallholder communities. Priority recommendations for future research include: (i) quantitative chemical composition analysis (TAPPI methods); (ii) composite fabrication and interfacial adhesion testing; (iii) standardized acoustic absorption characterization (ISO 10534-2); and (iv) life cycle and techno-economic analysis to support commercial-scale valorization. Correspondingly, the future studies include controlled benchmarking experiments with established fibers under identical processing and testing conditions to further validate the comparative performance of Enset fiber for engineering and composite applications.

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Author contributions

all the authors Alhayat G. Temesgen, J. Kaufmann, H. Cebulla in the conception of the study, presented results, and manuscript preparation.

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Data availability
All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate
This study did not involve human participants or animals. Therefore, ethical approval was not required for this research. All procedures performed in this study were conducted in accordance with relevant institutional and international guidelines. Not applicable. This study did not involve human participants.

Consent for publication
The manuscript does not contain any person's data in any form.

Competing interests
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