

Chemical, Physical and Thermal Characterization of *Ensete ventricosum* Plant Fibre

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Abstract - World scenarios trending sustainable development are driving the researchers to find out materials from sustainable sources, largely from the nature itself. Tremendous efforts have been exerted to discover natural plant fibres and methods to modify them for various applications. *Ensete ventricosum* (EV) fibre is a plant fibre extracted from the pseudostem (leaf) part of *Ensete ventricosum*; a plant widely growing in the sub-Saharan, Central and Eastern African countries. In this work, attempts were made to characterize and study the properties of EV fibre – a fibre that was little studied before, if not at all. The chemical composition of this fibre was determined according to the TAPPI methods. The physical, tensile, morphological, structural, and thermal properties of the fibre were investigated by using advanced techniques such as Tensile Tester, SEM, FTIR, XRD and TGA. The results revealed that this fibre consisted of cellulose (64.46±0.23%), hemicellulose (22.47±0.27%), lignin (6.88±0.55%), ash (5.66±0.02%) and solvent extractives (0.54±0.03%). The fibre also, inherently, acquired essential properties such as tensile strength of 352 MPa, elongation at break of 3.2%, crystallinity index of 64.9%, moisture content of 12.2% along with high thermal stability. Findings of this study revealed that the technical EV fibre has comparable properties like that of many of the world class natural fibres such as abaca, flax, sisal, hemp, jute, kenaf and ramie fibres. As a result, apart from the existing traditional utilization, this fibre has unexploited potential to be used as a textile material for broad spectrum of conventional as well as technical applications.

Key Words: *Ensete ventricosum*, lignocellulosic fibre, characterization, FT-IR, XRD, TGA

1. INTRODUCTION

1.1. Advantages of Natural Fibres – Driving Factors Towards Sustainability

In this very first century of the third millennium, in an expanding world population and increasing affluence, there is an increased need of raw materials. At the same time, there is enormous awareness on filling up of landfills, depletion of resources, pollution of the planet, limited nature of non-renewable resources and the need for environmentally friendly materials [1]. Consequently, concerns are ever growing towards sustainability; and sustainable development becomes a trending issue. The well accepted definition of

sustainable development, a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, was coined by the World Commission on Environment and Development, Brundtland Commission, 1987 [2]. Its overall goal is the long-term stability of the economy and environment, which is only achievable through acknowledgement and integration of the three bottom lines: economic, environmental, and social concerns, throughout the decision-making process [2]. This concept drives business entities, including textile and engineering sectors, to consider various socioenvironmental issues vis-a-vis the economic aspects of their business.

Agro-based natural fibres have played a leading role throughout human history for production of conventional and technical textile materials [3,4]. Recently, there is an increased interest for natural fibres, particularly of plant origin, due to the facts that they are renewable, carbon neutral, widely distributed, moldable, anisotropic, hygroscopic, recyclable, versatile, non-abrasive, porous, viscoelastic, easily available in many forms, biodegradable, combustible, compostable, reactive and low cost [1,5,6]. These fibres also have a high aspect ratio, high strength to weight ratio, relatively low in energy consumption, and have good insulation properties for sound, electrical and thermal stimuli [1,5,7-9]. Some people may consider part of these properties, such as biodegradability and combustibility, as limitations but, in fact, these features provide a means of predictable and programmable disposal not easily achieved with other resources [1] such as synthetic fibres.

Based on their origin, natural fibres are classified in to plant fibres, animal fibres and mineral fibres and they are mainly composed of cellulose, proteins and mineral substances, respectively. Plant fibres are further subdivided in to several types according to the part of the plant used for their generation; the major ones being bast fibres, leaf fibres, seed fibres and fruit fibres [3, 10]. Except few fibres such as cotton (about 90% cellulose), all plant fibres occur as a natural composite consisting mainly of cellulose (α -cellulose), hemicellulose, lignin, pectins, and waxes.

1.2. Enset Plant (*Ensete ventricosum*) And Its Fibre In Brief

Ensete ventricosum plant (Fig-1), commonly known as Enset, belongs to the order Scitamineae, the family Musaceae,

and the genus *Ensete* [11, 12]. Morphologically it resembles a banana plant, but bananas belong to the related genus *Musa*. Genetically, enset is diploid (with chromosome number $n=9$), while the species of *Musa* have different ploidy levels (with $n = 10, 11$ or 14) [12]. As a common feature, both *Ensete* and *Musa* have a large underground corm, a bundle of leaf sheaths (pseudostem), and large paddle-shaped leaves. Although enset is thicker and larger than banana (often reaching up to 12 m in height and more than 1 m in diameter) both enset and banana are herbaceous perennial monocarpic crops. They produce flowers only once at the end of their life cycle [13]. At the end of the life cycle of enset (9-14 years), the true stem emerges through the leaf sheaths, and forms multiple flowers, fruits and seeds. In fact, the enset plant is usually harvested before it reaches maturity (from 3 years depending on altitude and genotype), before or just at flowering, for the carbohydrate-rich false stem (pseudostem) and underground corm. The fruits of enset, unlike that of banana, are seldom edible and therefore enset is often called false-banana [11].

Enset plant grows in domestic as well as in wild forms. The domesticated enset is mainly propagated vegetatively from suckers whereas most wild plants are produced from seeds, and the species appears to have an outcrossing reproductive system [11]. This plant occurs in sub-Saharan Africa and grows wild in many countries in Central and Eastern Africa including Ethiopia, Congo, Mozambique, Uganda, Tanzania and Zambia. In Ethiopia, wild enset occurs in the highlands in the southwestern part whereas the cultivated enset grows in a wider area comprising the central, southern and southwestern parts of Ethiopia, but mainly at higher altitudes ranging from 1500 to 3100m. Enset is presently the main crop of a sustainable indigenous African system, which ensures food security [11, 14] and it is well known for its drought resistance. In Ethiopia alone, more than 20 percent of the total population, concentrated in the highlands of southern Ethiopia, depend upon enset [11]. Besides its use as a source of copious quantities of carbohydrate-rich food, enset is also utilized for fibre production, animal forage, construction materials, as an ornamental, and for its medicinal values, with a demonstrated antimicrobial activity against viral, bacterial, fungal and nematodal diseases of humans.

Ensete ventricosum fibre is a plant fibre extracted from the pseudostem and leaf parts of the enset plant. Decortication of the pseudostem (leaf sheaths) of *Ensete ventricosum* provides starchy pulp - which along with the corm is processed and used as a food product, and a fibre as a byproduct. The extracted fibres are then sun dried and used, in rural areas, to make sacks, bags, ropes, cordage, mats, sieves and tying materials for construction (in place of nails). These fibres are very long, often cut to 1-2m during extraction but can be extended to 6m or more depending upon the height of pseudostem, the method of extraction and the intended end use. It is also strong and flexible enough to

be used for many applications. Additionally, there is enormous potential to extract and utilize fibres from the leafstalk (midrib) and fallen-sheath parts of this plant which are commonly used for animal feed, compost, fuel (firewood) and landfills. However, for the best of our knowledge, if not at all, little attempts were made to systematically investigate the properties of these fibres and their potential for textile and technical applications. In this work, efforts have been exerted to study various properties of EV fibre and to explore its potential for making conventional as well as technical textile products.



Fig-1: *Ensete ventricosum* plant

2. MATERIALS

Ensete Ventricosum (EV) fibre was obtained from local farm in Gumer, Gurage Zone, Southern Region, Ethiopia. Manually decorticated and sun dried EV fibre was used for this experiment without any prior treatments. Chemical reagents such as sulfuric acid, caustic soda, ethanol, acetone, sodium chlorite, hydrogen peroxide, sodium silicate, potassium dichromate, acetic acid, Mohr's salt and ferroin of all analytical grade were procured from SD Fine Chemicals Ltd., India.

3. METHODS

3.1. Fibre Extraction

The fibre was extracted from the pseudostem (stalk) part of EV plant by using hand decortication (scrapping) method. Naturally, the stalk was built with several layers of sheaths

which were tightly overlapped. After dismantling, every sheath was slitted in to 2-4 stripes of width 10-15cm each. The pulpy tissues were scraped out, traditionally, by using a sharp-edged blade (of bamboo) against bed plate (of flat wood) along the fibre length. The fibres were then sun dried in the open air.

3.2. Chemical Composition

The technical fibres were cut into fine chips and then used for determination of chemical composition according to the respective standard methods. The contents of ash, solvent extractives and lignin in the fibre were determined according to the standard TAPPI methods T211 om-02 (2002), T204 cm-97 (1997) and T222 om-02 (2002), respectively. A holocellulose mass which was prepared as per the standard method used by Chattopadhyay & Sarkar [15] was then separated in to alpha cellulose and hemicellulose (beta cellulose & gamma cellulose combined) contents of the fibre as per the TAPPI method T203 om-99 (1999). Two samples were studied to determine each component and the average readings were calculated and reported.

3.3. Physical and Tensile Properties of Individual Fibres

Diameters of individual fibres were recorded by using Optical Microscope (Leica DM EP, Switzerland) which was interfaced with suitable software (LAS V4.6). Objective lens of 10x (magnification) was used to record at least three diameter readings along the length of 30 individual fibres and the average diameter was calculated by using (Eq. 1):

$$d = \frac{(d_1+d_2+d_3+\dots+d_n)}{n} \quad (\text{Eq. 1})$$

where d is the average diameter of the fibre sample; d₁, d₂,..., d_n is average diameter of individual fibres in the sample; and n is the number of fibres measured in the sample.

Linear density of fibres was determined according to the gravimetric method based on the ASTM test method D 1577. The standard length (L) in meters of a specimen with N number of individual fibres was cut and weighed to get the weight (W) in grams of fibres. The average linear density (D) in denier of individual fibres was calculated by using (Eq. 2). Whenever relevant, the linear density was converted and used in 'tex'.

$$D = \frac{9000 W}{L.N} \quad (\text{Eq. 2})$$

Tensile properties were determined according to the standard method (ISO 5079; 1996) by using tensile testing machine (Tinius Olsen Tensile Tester - H5KS, Tinius Olsen Ltd, UK) interfaced with suitable software system (QMAT Professional). Nearly 60 individual fibres were randomly

tested by using a gauge length of 20 mm, with a speed of 10 mm/min and then average values of the readings were calculated. The ultimate strength (tensile strength), T in MPa, was calculated according to equation (Eq. 3).

$$T = \frac{F}{A} \quad (\text{Eq. 3})$$

where F: Tensile force exerted in newton (N) and A: Cross-sectional area of the fibre in square meter (m²). Here, the fibre cross-section was assumed to be circular.

Furthermore, ASTM 2495, 2001 standard method was used to determine ambient moisture content (MC, %) and moisture regain (MR, %) of the EV fibres; and the corresponding results were calculated according to equation (Eq. 4) and (Eq. 5), respectively.

$$MC, \% = \frac{(M_{os} - M_{od})}{M_{os}} \times 100 \quad (\text{Eq. 4})$$

$$MR, \% = \frac{(M_{os} - M_{od})}{M_{od}} \times 100 \quad (\text{Eq. 5})$$

where M_{os}: mass of original (moist) sample, and M_{od}: mass of oven dry sample.

3.4. Morphology of Fibres

The surface morphology of EV fibres was studied by using scanning electron microscope (Philips XL-30 SEM, The Netherlands). Prior to the test, fibre specimens were sputter coated with thin layer of gold-palladium (Au-Pd) to avoid polymer charging in the electron beams, which otherwise causes astigmatism (focusing problems and blurred images). The specimens were then mounted on the SEM tube (12mm×12mm diameter) by using carbon tabs. Scanning of fibre surfaces were carried out under suitable magnification settings with accelerating voltage of 10.0kV and the electron micrographs were recorded. The morphological characteristics of the fibres were then determined by analyzing the recorded scans.

3.5. Fourier Transform Infrared (FTIR) Spectroscopy Analysis

FTIR spectroscopic analysis was conducted to examine the chemical constitution of the fibres. FTIR machine from Shimadzu, Japan (Shimadzu 8400s) was used to record the IR spectra of the fibres. Attenuated total reflectance (ATR) mode was used to collect the spectra in the range of 640-4000 cm⁻¹ and %T values were recorded for 36 scans.

3.6. Crystallinity Analysis Using XRD

Crystallinity of EV fibres was studied according to XRD curves obtained from Shimadzu, Japan (XRD 6100 Shimadzu), equipped with Cu radiation (λ = 1.54 Å). The experiment was

performed in the reflection mode, scattering angle range of 2θ (5° - 35°), scan speed of $2^\circ/\text{min}$ and data interval (steps) of 0.02° . (Eq. 6) was used to determine the relative degree of crystallinity (CrI) of the fibres [16].

$$\text{CrI}(\%) = \frac{I_{002} - I_{\text{am}}}{I_{002}} \times 100 \quad (\text{Eq. 6})$$

where CrI represents the crystallinity index, I_{002} is the maximum intensity (in arbitrary units) of the 002-lattice diffraction and I_{am} is the intensity of diffraction in the same units at $2\theta \sim 19^\circ$ (in the valley between the two visible peaks). In other words, I_{002} and I_{am} represent the peak intensity values of crystalline and amorphous components, respectively.

3.7. Thermogravimetric Analysis

Thermal analysis provides a detailed thermal characterization that can be used to evaluate thermal stability of a fibrous material before using it for desired application such as in polymer composites. Thermogravimetric analysis (TGA) of EV fibres was conducted by using the DTG machine from Shimadzu, Japan (Shimadzu 60H DTG). Prior to this test, the fibres were dried at 65°C for 24h and kept in a desiccator. These fibres were cut in to fine parts and then tested by using aluminum pan (i.e. sample chamber) in a range of room temperature to 500°C under the inert atmosphere of nitrogen with a flow rate of $100\text{ml}/\text{min}$ and heating rate of $10^\circ\text{C}/\text{min}$.

4. RESULTS AND DISCUSSION

4.1. Chemical Composition

Investigations made on the chemical composition of enset fibre revealed that the fibre consisted of 64.46% cellulose, 22.47% hemicellulose, 6.88% acid insoluble lignin, 5.66% ash and 0.54% solvent extractives (Table-1). The combined weight of the two major components that make up holocellulose (i.e. cellulose plus hemicellulose) was 87%, which can also be used for various applications.

These results (of fibre composition) were compared with that of some important natural fibres (Table-3) from the literature [17-19]. It is evident that enset fibre showed a higher cellulose content than bamboo, banana and coir fibres. The cellulose content of EV fibres lies within the value ranges for abaca, jute, kenaf and sisal fibres. In the other hand, cotton, flax, hemp, pineapple and rami fibres have somehow higher cellulose content than EV fibres. Moreover, the hemicellulose content of EV fibres is nearly equal to that of abaca, bamboo, banana, hemp and kenaf fibres. The lignin content of EV fibres is lower than that of all the fibres except for cotton, flax and ramie fibres; which have a lower lignin content than EV fibres.

In conclusion, as compared to many of the well reported plant fibres, the EV fibre showed a relatively higher content of cellulose and lower content of lignin. As a result, this fibre could be considered as a potential source for making textiles and other technical products such as composites, cellulose-derivatives, pulps and papers.

Table-1: Chemical composition of EV fibre

EV Fibre	Cellulose	Hemicellulose	Lignin	Extractives	Ash
Composition (%)	64.46	22.47	6.88	0.54	5.66
Std. Dev. (%)	[0.23]	[0.27]	[0.55]	[0.03]	[0.02]

4.2. Physical and Tensile Properties

The physical and tensile properties of EV fibres were studied in terms of diameter, linear density, moisture content, tensile strength and elongation at break (Table-2). The results revealed that the individual fibres showed average diameter of $128\mu\text{m}$, linear density of 8.8tex, tensile strength of 352 MPa and elongation at break of 3.2%. Moreover, the fibres had a moisture content of 12.2% and moisture regain of 13.8%.

The tensile strength and elongation at break of enset fibre was compared with that of commercially important fibres obtained from literature (Table-3). The enset fibre showed tensile properties comparable with most of the commercially available fibres and its tensile strength (MPa) was nearly like that of abaca, banana, cotton and flax fibres. Moreover, enset fibre was stronger than sisal, bamboo and coir fibres. Elongation at break of enset fibre was like that of abaca, flax and sisal; and better than that of hemp, jute, kenaf and ramie fibres. These significantly good tensile properties of enset fibres are attributed to its high cellulose content and good crystallite orientation [20]. The hemicellulose component in the fibre creates a barrier between the cellulose polymer chains and this leads them to dissociate from each other. As a result, a strain develops and remains intact in the cellulose polymer chains. This, in effects, causes the fibres to have high tensile strength and elongation at break [21].

The moisture adsorption measurements depend on the chemical composition of the fibres and their molecular structure [22]. Therefore, the high moisture content and regain of EV fibres is attributed to the presence of abundant hydroxyl and other oxygen containing groups in the amorphous regions of hemicelluloses and cellulose.

Table-2: Physical and tensile properties of EV fibres

Fibre property	Average	Std. Dev.
Diameter (µm)	127.87	36.32
Linear density (tex)	8.75	1.31
Tensile strength (MPa)	351.67	130.30
Elongation at break (%)	3.16	0.66
Moisture content (MC)	12.15	0.016
Moisture regain (MR)	13.84	0.021

Table-3: Comparison of chemical composition and tensile properties of EV fibre with other natural plant fibres [3, 17-19]

Fibre	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Tensile strength (MPa)	Elongation (%)
Abaca	56-70.2	17.5-25	7-15.1	12-980	3-10
Bamboo	26-43	20.5-30	21-31	140-230	-
Banana	57.6-62.5	19-29.1	5-13.3	180-914	5.9
Coir	32-46	0.15-0.3	40-45	106-175	30
Cotton	82-96	2-6.3	0.5-1	300-700	7
Flax	71-75.2	8.6-20.6	2.2-4.8	345-1500	2.7-3.2
Hemp	68-81	2.0-22.4	3.5-10	690	1.6
Jute	61-71	14-20	12-13	393-773	1.5-1.8
Kenaf	53.5-72	21-20.3	9-17	930	1.6
Pineapple	80.5	17.5	8.3	1020	14.5
Ramie	68.6-76.2	13-16	< 0.7	560	2.5
Sisal	47.6-78	10-17	10-14	317.5	3-7
Enset	64.46	22.47	6.88	351.7	3.2

4.3. SEM Analysis

The scanning electron micrographs of EV fibres, shown in Figure -2, exhibited that this fibre maintained a light surface layer along its length and this layer may consist of non-cellulosic components (wax, pectin, lignin, hemicellulose etc.) that protect the core fibre cells. Like other reported leaf fibres such as abaca, sisal and banana [23, 24], the EV fibre exists in a multicellular bundle form comprising of several fibre cells (elementary fibres) and the adjoining fibre cells are cemented together by hemicellulose, lignin and pectin.

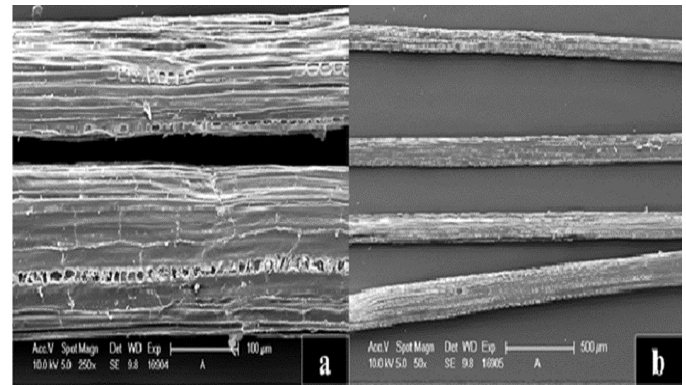


Fig-2: Scanning electron micrographs of EV fibres (a) 250× and (b) 50×

4.4. FTIR Analysis

FTIR spectra, a powerful tool to detect the specific intermolecular interactions in a polymer (such as fibrous materials) [25], was used to identify the functional groups associated with characteristic peaks and the results are presented in Figure-3 & Table-4. These results, within the frequency range of 4,000 cm⁻¹ to 640 cm⁻¹, showed that the EV fibre had distinct peaks at 3348, 2924, 1738, 1643, 1539, 1421, 1369 and 1327cm⁻¹.

The peaks in the band of 3348cm⁻¹ revealed that this fibre exhibited hydrogen bonded hydroxyl groups in its cellulose structure; somehow like other lignocellulosic fibres [26-28]. The sharp peak at 2924cm⁻¹, assigned to C-H and CH₂ stretching vibrations in the methyl and methylene groups [27,29] exhibited the presence of cellulose, hemicellulose and lignin [30]. The sharp peak at 1738 cm⁻¹ of the EV fibre is due to C=O stretching vibrations of aliphatic ester group in hemicellulose [31, 32]. The peak appeared at the wave frequency of 1643cm⁻¹ was assigned to the O-H bending vibration of adsorbed water in the fibres [26,32]. The weak absorbance peak at the frequency of 1595cm⁻¹ is attributed to the aromatic skeletal vibration of benzene ring in the lignin [32-34].

Absorption bands in the frequency range of 1500 - 640cm⁻¹ represent the fingerprint region of the IR spectra where various complicated vibrations occur. The peaks with frequencies of 1421cm⁻¹ bared a characteristic scissoring of CH₂ groups [26,35] in cellulose, hemicellulose & lignin [21,34]. Peaks at wave frequency of 1369 are attributed to the C-O stretching [33] in the cellulose molecules and that at 1327cm⁻¹ is attributed to vibrations in the phenolic O-H, S-ring and G-ring groups [26,35] of lignin. Absorption peaks at 1256 and 1099 cm⁻¹ in the spectra of the fibre are assigned to C-O stretching in acetylated hemicellulose and C-O deformation in the secondary alcohol plus aliphatic ethers, respectively. The peak indicating C-O stretching or O-H bending of C-OH group in cellulose was observed at the band 1157cm⁻¹ [36]. The absorbance peak at 1030 cm⁻¹ indicated

the presence of C-O, C=C and C-C-O stretching [30,37] which is due to the presence of cellulose, hemicellulose, and lignin in the fibre [34,38]. The peak at 899 cm⁻¹ is attributed to β-glycosidic linkages in the cellulose molecule [32].

Table-4: Characteristic IR peaks and their assignment for EV fibres

Wavenumber (cm ⁻¹)	Associated functional groups and compounds
3348	O-H stretching of hydrogen bonded OH group in cellulose and other origins
2924	C-H and CH ₂ stretching in methyl and methylene groups of cellulose, hemicellulose and lignin
1738	C=O stretching of ketone, carboxylic acid and ester groups in the hemicellulose
1643	OH-bending of adsorbed water
1595	C=C aromatic skeletal vibrations of benzene ring in lignin
1421	CH ₂ scissoring of cellulose, hemicellulose & lignin
1369	C-O stretching of cellulose
1327	Phenolic OH (deformation); C-O of syringyl ring (Lignin), plus G ring condensed stretching (Lignin)
1312	CH ₂ rocking vibration (Cellulose, Hemicellulose)
1256	C-O stretching of acetylated hemicellulose
1157	C-O stretching or O-H bending of C-OH group (Cellulose)
1099	C-O deformation in secondary alcohols and aliphatic ethers
1030	C-O, C=C and C-C-O stretch (Cellulose, hemicellulose, lignin)
899	β-Glycosidic linkages

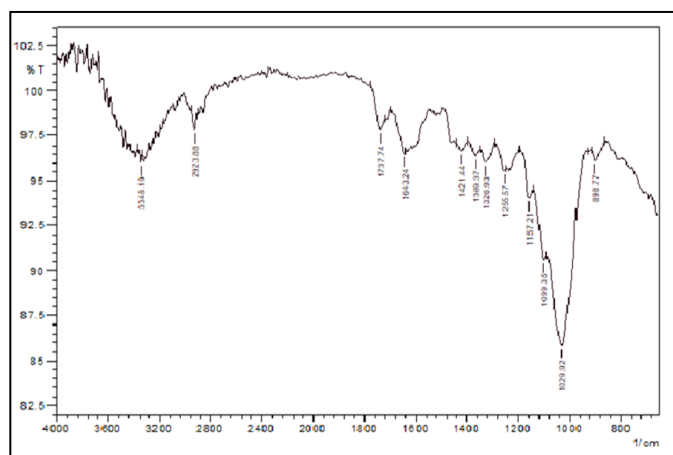


Fig-3: FTIR spectra of EV fibre

4.5. Crystallinity Analysis (XRD)

The x-ray diffractogram of EV fibres (Figure-4) showed two pronounced Bragg's peaks near 2θ = 22° and 2θ = 16°. The maximum intensity of diffraction was found at 2θ= 22.20° (I₀₀₂) and this intensity corresponds to the crystalline phase in the fibre cellulose. The intensity of diffraction found at 2θ=18.94°, which is the minimum intensity (I_{am}) found in the valley between the two peaks, corresponds to the amorphous phase in the fibre cellulose [16]. Crystallinity index of the fibre was calculated according to equation (Eq.6) and the results revealed that EV fibre acquired significantly high degree of crystallinity with CrI = 64.85% (Table-5). Moreover, the degree of crystallinity of EV fibres is compared with that of commercially known cellulosic and lignocellulosic natural fibres (Table-6) and the results of comparison revealed that crystallinity index of EV fibres is higher than that of banana, coir, jute and kapok fibres. This fibre, with crystallinity index like that of rami, cotton and abaca, is expected to owe high tensile strength and other mechanical properties that may lead to broaden the spectrum of its application for textiles and composites.

Table-5: Crystallinity of EV fibres

I _{am} (cps), at 2θ=18.94°	I ₀₀₂ (cps), at 2θ= 22.20°	CrI (%)
1226	3488	64.85

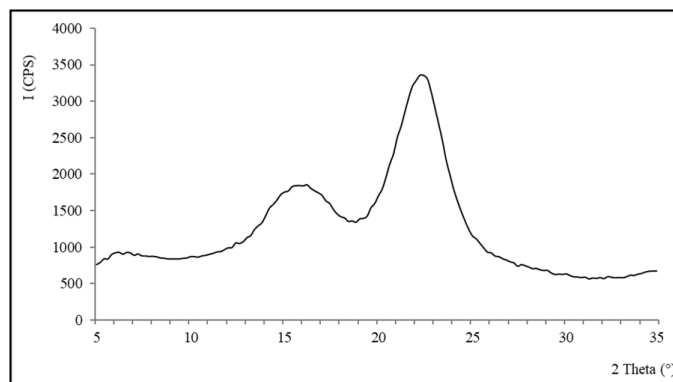


Fig-4: X-Ray Diffraction (XRD) Patterns of EV fibres

Table-6: Comparison of the crystallinity index of natural cellulosic/lignocellulosic fibres

Fibre	CrI (%)	Reference
Abaca	68	[21]
Banana	39	[39]
Coir	44	[21]
Cotton	65	[21]
Flax	86	[21]
Hemp	88	[28]

Fibre	CrI (%)	Reference
Jute	58	[21]
Kapok	35	[21]
Rami	62	[21]
Sisal	71	[28]
EV	65	This work

4.6. Thermal Characterization (TGA)

The changes in the mass of the EV fibre against the decomposition temperature was measured by TGA and the resulting graph and data are shown in Fig-5 and Table-7, respectively. The graph showed that EV fibres possessed significant thermal stability until the temperature was raised to 200°C and the major components of the fibre were degraded in the temperature range between 200°C - 400°C. The initial low temperature (30°C to 120°C) weight loss with peak at 54°C was associated with the evaporation of moisture absorbed due to the hydrophilic nature of the fibre. This weight reduction is highly dependent on the initial moisture content of the studied fibre. It was mentioned in the methodology part of this article that, before the thermal analysis, the EV fibres were dried at 65°C for 24h and then they were kept in a desiccator. As a result, in the initial low temperature range the fibre showed a lower weight percent loss (~7%) than its predetermined moisture content (~12.2%). Similar features of thermal analysis were also reported for other lignocellulosic fibres [40,41].

The three major components of EV fibre (hemicellulose, cellulose and lignin) undertaken pyrolysis reactions in three stages and Yang et al. attributed this decomposition pattern to the structural differences in the chemical components of wood fibres [27]. Being a natural lignocellulosic fibre, the hemicellulose, cellulose and lignin components of EV fibre were degraded at the peak temperatures of 258°C, 341°C and 400°C, respectively. The first stage decomposition temperature range (200°C to 300°C) was mainly associated with the decomposition of hemicellulose component with a weight loss of 20%. The degradation of cellulose was observed in the second stage temperature range (300°C - 400°C) with a weight loss of 44% and that of lignin was in the third stage range (400-500°C) with weight loss of 5%. Yang et al. reported that, unlike hemicellulose and cellulose, the pyrolysis of lignin persists in the broader temperature range of 160°C - 900°C [27]. At the temperature of 500°C, the residual char content of the overall decomposition reactions was found to be ~ 23%.

In conclusion, this fibre had significantly high thermal stability up to the temperature of about 260°C and therefore it has a good potential for applications in suitable technical textiles as well as composite materials.

Table-7: Thermal behavior of EV fibres

Stages of decomposition	Peak Temperature (°C)	Weight loss (%)	Residue at 500°C (%)
30°C - 120°C	53.53	6.97	22.88
200°C - 300°C	257.67	19.99	
300°C-400°C	340.72	43.76	
400°C-500°C	399.95	4.94	

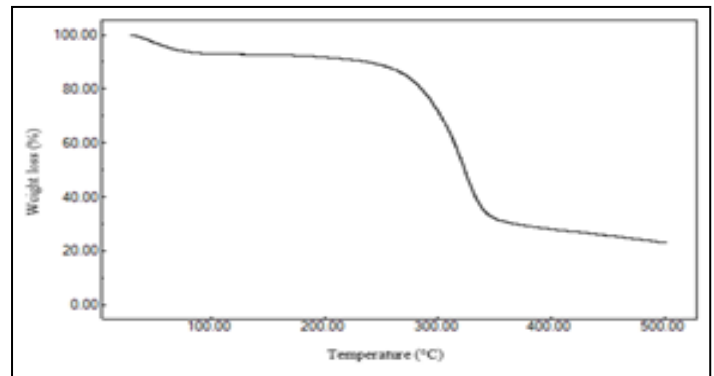


Fig-5: Thermograph (TGA) of EV fibres

5. CONCLUSION

In this work, attempts were made to investigate the properties of Ensete ventricosum (EV) fibre, extracted from the pseudostem part of Ensete ventricosum plant. Various methods and techniques were used to find out the inherent characteristics of this fibre that, in most circumstances, determine the ultimate application of the fibre. It was found that, EV fibre has a cellulose composition of 64.5%, tensile strength of 352MPa, elongation at break of 3.2% and moisture content of 12.2%. Furthermore, good crystallinity index (65%) and high thermal stability behaviors of this fibre could make it a competitive candidate to make natural fibre-based technical textiles as well as reinforcement materials in manufacturing tough and thermostable biocomposites.

The properties analyzed (e. g. cellulose composition, tensile strength and elongation at break, crystallinity index, and thermal behavior) of EV fibre are comparable with that of the well-known world class natural fibres (s. a. abaca, flax, sisal, hemp, jute, kenaf and ramie fibres). The discovered inherent characteristics implied that EV fibre has untapped potential for broad spectrum of applications in the fields of conventional as well as technical textiles.

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