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Chemical Composition and Microstructural Characterization of Water-Retted Banana Stem Fibers

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Abstract

The aim of this study was to determine the chemical composition and carry out the microstructural analysis of fibers derived from plantain stems, with a view to their application in textiles as an alternative source of cellulose. Plantain stems (HB) from Cameroon of the false French variety were used. The fibers were extracted using a water retting process and then characterized. Quantitative analyses of the chemical constituents were carried out using Technical Analysis for Pulp and Paper Industry (TAPPI) methods on dry, powdered fibers with an average particle size of around 315 µm. Microscopic analyses were carried out using Scanning Electron Microscopy (SEM). The results of the chemical analyses showed that the fibers contained 60% - 64% cellulose, 19% - 20% hemicellulose, 8% - 10% lignin, and 3.5% - 4.5% pectins. The results of the structural analyses show an irregular surface with numerous filaments, impurities, cells, and pores that correspond to the typical surface of most natural plant fibers. The chemical and structural characteristics of the fibers highlight their potential as cellulose-rich natural fibers.

Keywords

Chemical Composition, Textile, Banana Stems, Microstructural Analysis, Cellulose

1. Introduction

Banana trees (*Musa* spp.) are monocotyledonous plants grown in intertropical regions [1]. They are non-woody herbaceous plants that can grow to several meters in height. Bananas are an important food crop in Central and West Africa in general, and in Cameroon in particular [2]. Banana trees are giant perennial grasses resulting from intra- and interspecific hybridization of two diploid forest species: *Musa acuminata* (banana) and *M. balbisiana* (plantain) [3]. Growing bananas (*Musa* spp.) is of major socio-economic importance to the people of Central and West Africa [4], and in Cameroon bananas are the third most important export product after fuel and timber [5]. Banana cultivation generates a large amount of biomass, which is little exploited. This waste, mainly made up of pseudostems, leaves, rachis, and fruit peels, is rich in organic matter and remains largely underexploited [6]. The use of plant biomass residues is particularly significant in tropical countries, where forestry, food, and cash crop production are important economic activities that generate a wide range of residues [7]. Fibers are extracted from banana stems and can be used to make rope, baskets, and cardboard packaging. Banana plant waste, including leaves and pseudostems, has been used to develop biodegradable materials as a sustainable alternative to single-use plastics for food packaging [8].

Fibrous materials surround us; they protect us from the elements, are linked to our well-being, and are central to our daily lives. Natural fibers account for a third of the world's fiber production [9]. Plant fibers are still booming in the textile, automotive, and civil engineering sectors [10]. Fiber is a material that can be transformed into yarn and then into fabric. It is also a material that can be used in industrial applications. Fiber quality encompasses a number of factors, including fiber length, diameter, strength, flexibility, and fineness, all of which are crucial factors in determining its transferability and end applications [11]. Plant fiber is a composite in itself. The reinforcement is made up of layers of partly crystalline cellulose microfibrils. The latter is coated with an amorphous polysaccharide matrix (hemicellulose and pectin), which is associated by hydrogen and covalent bonds with the lignin [12].

Textiles represent a fundamental material format that is widely integrated into our daily lives [13]. Non-woody plants offer several advantages, including short growth cycles, moderate irrigation and fertilization requirements, and low lignin content, resulting in reduced energy [12]. Synthetic fibers, notably polyester, polyamide, and acrylic, have become predominant in clothing manufacture, replacing natural materials such as cotton, linen, and wool, as well as synthetic fibers such as viscose and rayon [14]. The use of natural fibers in textile production has attracted considerable attention because of their renewable nature and their lower environmental impact compared with synthetic fibers [15].

Growing environmental concerns due to pollution from the textile industries have led to the treatment of textile fibers of plant origin as a renewable source for various industrial and textile applications in particular. The biodegradability of

banana fibers and their availability as agricultural waste can be considered a sustainable source of textiles [16]. The incorporation of new environmentally friendly materials is an unavoidable necessity [17]. Plant fibers are an interesting alternative to synthetic fibers, which are frequently used as textile fibers [18].

In this study, banana stem fibers of the false French variety are used to determine their chemical composition and analyze their microstructure.

The aim of this study is to determine the chemical composition and to carry out the microstructural analysis of fibers from the stem of the plantain banana, with a view to textile application as an alternative source of cellulose.

2. Materials and Methods

2.1. Sampling

Three characterized samples of banana stem fiber (H1, H2, and H3) from the False French variety were analyzed. The fibers were obtained by biological water retting of cut pseudostem strips in distilled water at approximately 23˚C. The retting durations were 20 days for H1, 25 days for H2, and 30 days for H3. Thus, the three samples correspond to increasing retting durations and were analyzed to assess the effect of retting time on the physicochemical and morphological characteristics of the extracted fibers. The banana tree stalks were collected from CARBAP (African Center for Research on Banana and Plantain), located in the Littoral region of Cameroon, Moungo Department, Djombé Penja district, with geographical coordinates: Latitude: 4.548437 and Longitude: 9.619688 (4˚32'54.4" North and 9˚37'10.9" East), Cameroon. A total of 10 per sample sourced from fibers of banana tree stalk (HB) plantain "*Musa sapientum*" of the species "faux French" variety cultivated in Cameroon to guide their use for textile applications. Samples H1, H2, and H3.

2.2. Methods

In order to determine the chemical composition of fibers extracted from plantain stems, a series of separation methods was used to obtain the various chemical compounds present in the extracted fibers (cellulose, hemicellulose, lignin, pectins, waxes). Quantitative analyses of the fiber constituents were carried out using the TAPPI method on dry powdered fibers with an average particle size of around 315 µm. Weighing was carried out on a 0.1 mg precision balance. Each chemical assay was performed on the 10 samples with analytical repetitions per sample: moisture content, ethanol-benzene extract, aqueous extract, pectin, lignin, holocellulose, cellulose, ash, and wax. The pooled mean and standard deviation given in Section 3.2 summarize the three samples obtained after different retting durations (20, 25 and 30 days); they do not estimate the uncertainty within any single retting duration.

All tests were carried out according to the procedures described in the literature [19], with a few minor modifications. The precise references for the standards and methods used for each chemical composition are shown in **Table 1**.

Table 1. Standards and methods used for chemical analysis [20] [21].

Properties	Standars/Methods
Solubility ethanol-Benzene	Standard ASTM 1107-56
Lignin	Klason method
Holocellulose	TAPPI T19m-54
Cellulose	Kurschner and Hoffer's method
Wax content	Conrad method

2.2.1. Moisture Content (%)

The moisture content of banana stem fibers was determined using Equation (1) [22]. Half-masses of ten samples were placed at room temperature 25˚C ± 2˚C with 63% relative humidity for 24 hours. The samples were then dried in an oven set at 105˚C for 24 hours to obtain a constant anhydrous mass, and the final mass mf of each sample was measured. The moisture content (%*Hu*) was determined using Equation (1).

$$\%Hu = \frac{m_i - m_f}{m_i} \times 100 \quad (1)$$

m_i : Initial mass (g);

m_f : Final mass (g);

(%*Hu*): Moisture content.

2.2.2. Ethanol-Benzene Extract (%Es)

Before acid hydrolysis, the extracts must be extracted with an ethanol-benzene mixture to remove resins, oils, fats, waxes, and tannins. These acid-insoluble compounds would distort the Klason lignin assay if they were not removed. ASTM Standard 1107-56 is used for the Ethanol-Benzene extract [23].

Extraction is carried out hot using a Soxhlet assembly consisting of a flask heater support, a flask heater, a flask, the Soxhlet itself containing an extraction cartridge, and a coolant. A sample cartridge containing 6 g of powdered fibers was introduced into a Soxhlet, which was mounted between a flask filled with 800 mL of ethanol (96%)-benzene (99%) (1:2 v/v) and a coolant; then the assembly was fixed to a flask heater support. The extractables were removed by controlled leaching with a siphon every 10 minutes. Once this time had elapsed, the cartridges were removed from the Soxhlet, evaporated at a temperature of 70˚C under reduced pressure for one hour, and then cooled in a desiccator. The dissolution time after several cycles was 7 h. The amount of ethanol-benzene extract (%*Es*) was determined using Equation (2) [20] [21].

$$\%Es = \frac{m_{Es}}{m_d} \times 100 \quad (2)$$

m_{Es} : Mass of ethanol-benzene extract (g);

m_d : Mass of previously dried fibers (g).

2.2.3. Aqueous Extract (%*Ws*)

This extraction is necessary to remove water-soluble compounds. The result of the ethanol-benzene extract (Residue 1) is used to determine the aqueous extract. The Residue 1 cartridges are introduced into a Soxhlet using the same set-up as that used for the previous extract, but the reagent used in the previous set-up has been replaced by 100 mL of distilled water. The mixture was heated for 7 hours. The result obtained (Residue 2) was filtered onto a sintered glass crucible, then washed with distilled water, incubated at 105˚C for 12 hours, then cooled in a desiccator for 12 hours and weighed. The hot water extract content (%*Ws*) was determined using Equation (3) [21] [24].

$$\%Ws = 100 \times \frac{m_W}{m_{res1}}\left(1 - \%Es\right) \tag{3}$$

m_W : Mass of the extract in water (g);

m_{res1} : Mass of residue 1 (g).

2.2.4. Pectin Content (%*PS*)

The mixture containing residue 2 with a mass of 1.5 g was introduced into an Erlenmeyer flask containing 50 mL of 2% hydrochloric acid solution and heated to reflux under magnetic stirring in a water bath at 80˚C for 4 hours. Residue 3 was then obtained by filtration on a sintered glass crucible, washed with distilled water, and dried for 12 hours in an oven at 105˚C. Residue 3 was then cooled in a desiccator for 12 hours and weighed. The pectin content (%*PS*) in the hydrochloric acid extract was determined by Equation (4) [23].

$$\%PS = 100 \times \frac{m_{Ps}}{m_{res2}}\left(1 - \%Es\right) \tag{4}$$

m_{Ps} : Mass of extracted pectin (g);

m_{res2} : Mass of residue 2 (g).

2.2.5. Lignin Content (%*L*)

The lignin content was determined using the Klason method. This procedure is a reference method for determining lignin in wood and other plant matter. The ground and sieved lignin was first extracted with a mixture of ethanol and benzene (residue 1) to remove lipophilic extractables such as waxes, fats, certain resins, and gums from the wood. 500 mg of the dried residue 2 was hydrolyzed in 15 mL of 72% sulphuric acid for 2 hours at room temperature. The mixture was then diluted by adding 500 mL of water to reduce the sulphuric acid content to 3%. Hydrolysis was continued by reflux heating in a dilute acid medium for 4 hours at a temperature of 80˚C. The mixture was then filtered, washed, dried in an oven at 100˚C for 12 hours, and weighed. However, lignin is the only component that is insoluble in water, so it separates from the fibers. The lignin content corresponding to Klason lignin was determined using Equation (5) [23] [25].

$$\%L = 100 \times \frac{m_L}{m_{res2}}\left(1 - \%Es\right) \tag{5}$$

m_L : Mass of lignin (g);
m_{res2} : Mass of residue 2 (g).

2.2.6. Holocellulose Content (%*HC*)

The chemical extraction of holocellulose consists of completely delignifying the lignocellulosic material and recovering the polysaccharide fraction (cellulose and hemicellulose), which can also be separated later. For this, the Soxhlet assembly is used again. A mass of 1.5 mg of residue 2 was introduced into a sample holder cartridge, then the cartridge was introduced into a Soxhlet, which was mounted between a flask filled with 60 mL of distilled water and a cooler. The assembly was then fixed on a flask heating support. The assembly was heated under reflux at 75˚C for one hour. Next, 0.2 mL acetic acid and 3 mL 15% v/v sodium chlorite were added every hour for 7 hours. The result obtained (residue 4) was filtered, washed with demineralised water, and then left to stand for 2 hours before being rewashed with ethanol. Finally, it was dried at a temperature of 105˚C for 12 hours. Holocellulose content was determined using Equation (6) [23] [25].

$$\%C = 100 \times \frac{m_C}{m_{HC}} \left(1 - \%HC\right) \tag{6}$$

m_C : Mass of cellulose (g);
m_{HC} : Mass of holocellulose.

2.2.7. Cellulose Content (%*C*)

The cellulose content was determined using the Kürschner and Hoffer method [20]. Briefly, 1 g of holocellulose was introduced into an Erlenmeyer flask containing 50 mL of a nitric acid-ethanol solvent mixture (1:4, v/v), prepared using ethanol (96%) and nitric acid (16 N). The flask was connected to a reflux condenser and heated in a water bath at 75˚C for 1 hour [26].

The resulting residue was filtered through a sintered glass crucible and successively washed with ethanol, demineralized water, and ether. Finally, the extracted cellulose was dried at 105˚C for 12 hours, then cooled in a desiccator for 12 hours before being weighed. The cellulose content (%) was determined using Equation (7) [23] [25].

$$\%C = 100 \times \frac{m_C}{m_{HC}} \left(1 - \%HC\right) \tag{7}$$

2.2.8. Hemicellulose Content (%*HC*)

The hemicellulose content was determined using Equation (8) [21].

$$\%H = \left(\%HC - \%C\right) \tag{8}$$

2.2.9. Ash Content (%*Cs*)

The ash content was determined using Equation (9) [23]. The stem fibers were first ground and then calcined in an oven for 6 hours at a temperature of 600˚C.

$$\%Cs = \frac{m_{Cs}}{m_d} \times 100 \tag{9}$$

m_{Cs} : Mass of ash (g);

m_d : Mass of sample taken (g).

2.2.10. Wax Content (%Wax)

Wax content was determined by the Conrad method [20]. The 95% ethyl alcohol extraction method developed by Conrad has proved to be so effective in determining wax content [27]. Because residue 2 had already been extracted with ethanol-benzene and hot water, no separate untreated aliquot was used: the assay measures the residual 95% ethanol-soluble material remaining in residue 2, not the total wax content of the untreated fiber.

To determine the wax content, residue 2 (aqueous extract) was used as the sample. The waxes were extracted in the Soxhlet assembly. 5 g of residue 2 was placed in a sample holder cartridge and introduced into a Soxhlet, which was mounted between a flask charged with 250 mL of 95% ethyl alcohol and a cooler; then the assembly was fixed on a flask heating stand. It was then heated under reflux for two hours at a temperature of 55˚C. Siphoning took place every 5 minutes. The alcohol-extracted samples were rinsed several times with distilled water to remove the adhering solvent. The residue was dried at a temperature of 105˚C and weighed. The wax content (%) was determined by Equation (10) [28].

$$\%Ci = 100 \times \frac{m_{Ci}}{m_{res2}}\left(1 - \%Es\right) \tag{10}$$

2.2.11. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy is an electron microscopy technique based on the principle of interactions between electrons and matter. This analysis technique is capable of producing high-resolution images of the surface of a sample [29]. The scanning electron microscope works by reflecting excited electrons onto the surface of the sample [30].

The principle is to form an image of a sample from a very fine, almost parallel beam of electrons that scans the sample and, from the secondary electrons emitted, forms a point-by-point image [29]. Microscopic examinations were carried out using a scanning electron microscope of the HIRACHI-TM1000 type, which allows magnifications of up to 10,000 times. The samples of banana stem fibers were placed and fixed on the sample holder, and then the whole assembly was introduced into the SEM chamber in order to analyze the samples microscopically. The instrument is controlled by a microcomputer. The samples analyzed are metallized to allow the unscattered or reflected electrons to flow away from the object being observed so that morphological observations can be made. The fiber samples were analyzed at an acceleration voltage of 15 kV. A voltage higher than 20 kV could damage the material during exposure.

3. Results and Discussion

3.1. Chemical Composition of Banana Stem Fibers

The results of the chemical composition analysis are presented in **Table 2**. The ma-

jor measured constituents were cellulose, hemicellulose, and lignin, with smaller fractions of pectin and extractives. The chemical profiles of H1, H2, and H3 were broadly similar, but differences were observed in the proportions of the major constituents. Cellulose increased from 60% in H1 (20 days) to 64% in H2 (25 days) and remained at 64% in H3 (30 days), while lignin varied from 8.0% to 10.0% and 9.5%, respectively. These variations may be associated with the increasing duration of water retting, although the present data should be interpreted descriptively rather than as a statistically validated time-dependent effect.

Table 2. Chemical composition of H1 - H3 plantain banana stem fibers.

Sample	Total Extract (%)	EtOH-Benzene (%)	Aqueous Extract (%)	Pectin (%)	Lignin (%)	Holocellulose (%)	Cellulose (%)	Hemicellulose (%)	Ash (%)	Wax (%)
H1	10.9	0.4	8.5	3.5	8.0	80.0	60.0	20.0	0.00058	0.12
H2	11.5	0.5	11.0	4.5	10.0	83.0	64.0	19.0	0.0005	0.15
H3	11.4	0.8	10.6	4.0	9.5	84.0	64.0	20.0	0.00054	0.12

Legend:

- %*Ex*: Percentage of extracts;
- %*Es*: Percentage of ethanol-benzene extracts;
- *Ws*: Percentage of aqueous extracts;
- *Ps*: Percentage of pectins;
- *L*: Percentage of lignin;
- *HC*: Percentage of holocellulose;
- %*C*: Percentage of cellulose;
- %*H*: Percentage of hemicellulose;
- %*Cs*: Percentage of ash;
- *Ci*: Percentage of waxes.

Table 2 shows the chemical composition of the fibers, *i.e.*, the percentages of cellulose (%*C*), hemicellulose (%*H*), lignin (%*L*), pectins (%*Ps*), extracts (%*Ex* and %*Ws*), ash (%*Cs*), and waxes (%*Ci*). This composition is in line with that described in the literature, although the percentages are different.

The chemical profiles of H1, H2, and H3 were broadly similar, but differences were observed in the proportions of the major constituents. Cellulose increased from 60% in H1 (20 days) to 64% in H2 (25 days) and remained at 64% in H3 (30 days), while lignin varied from 8.0% to 10.0% and 9.5%, respectively. The ash and wax contents were almost identical. The moisture, ash, and wax contents were almost identical, while the other constituents differed by 0.5 to 5 units. These variations may be associated with the increasing duration of water retting, which can lead to the partial removal of non-cellulosic components and a relative increase in cellulose content. Cellulose is the main structural component that gives fiber its strength. Lignin is a highly cross-linked molecular complex and acts as a bonding agent between individual fiber cells and the fibrils forming the cell wall [20].

Figure 1 presents the measured cellulose, hemicellulose, and lignin contents for H1 - H3. Cellulose was the dominant component in all three samples. The differences among samples are discussed descriptively in relation to the increasing retting durations of 20, 25, and 30 days, rather than as a statistically validated effect of retting time.

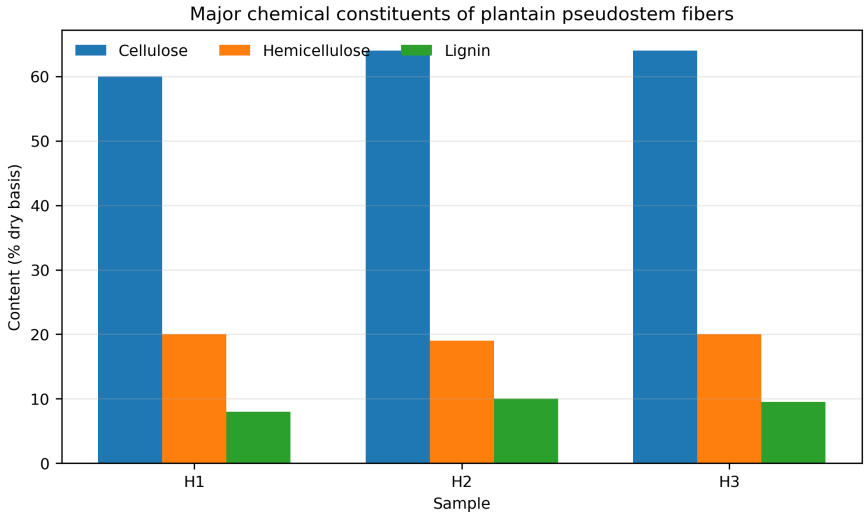


Figure 1. Major chemical constituents of H1 - H3 plantain pseudostem fibers.

3.2. Properties of Banana Stem Fibers Compared with Other Plant Fibers

Table 3 shows the chemical composition of the plant fibers most widely used in the literature, together with the chemical composition obtained in the present work.

Table 3. Chemical compositions of plant fibers.

Fibers	%*C*	%*H*	%*L*	%*P*	%*E*	%*WS*	%*CS*	References
Coton	85 - 90	5.7	0.7 - 1.6	0 - 1			0.6	[31]
Cupresus	48.4	21.6	34.3	3.4	-	3.2	0.57	[24]
RC	68.2	-	15.6	-		-		[32]
Jute	61 - 75	13.6 - 20	12 - 13	0.2			-	[24]
Lin	64.1	16.7	2	1.8	3.9		-	[33]
Sisal	65.8	12	9.9	0.8	1.2		-	[24]
AC	68.11	4.90	12.01	4.15	0.99	2.08	0.27	[26]
NA	36.08	15.33	25.15	7.69	3.20	9.57	1.53	[26]
RC	65.15	7.42	16.2	3.45	2.017	3.05	0.42	[26]
BF	59.153	14.42	10.70	3.7897	1.4189	11.3863	0.55	[34]
Mesocarp	66	-	19	-	-	-	2	[35]
BPSF	40	21.5	24	-	-	-	-	[5]
HB	60 - 64	19 - 20	8 - 10	3.5 - 4.5	0.4 - 0.8	8.5 - 11	0.0005	Present work

Legend:

- %*C*: Percentage of cellulose;
- %*H*: Percentage of hemicellulose;
- *L*: Percentage of lignin;
- %*P*: Percentage of pectins;
- %*Ex*: Percentage of extracts;
- %*Ws*: Percentage of aqueous extracts;
- %*Cs*: Percentage of ash.

The results of the chemical composition of plantain stem fibers of the false French Rouis variety are comparable with the chemical composition of fibers of plant origin.

The extract content of banana stem fibre varies between 8.5 and 11%, close to that obtained for Pseudo trunk (BF), which is 11.38%. The difference observed between the results of these studies and others is nothing new in the behaviour of plant fibers. However, the botanical origin of the plant and the fiber extraction process justify this slight difference.

The lignin content, which varies between 8% and 10%, is lower than the values found for fibers from *Rhecktophyllum camerunense* (RC) 15.6% - 16.2%, *Neuropeltis acuminata* (NA) 25.15%, and *Cupressus lusitnica* 34.3% [24] [26]. This content is also very close to that of jute fiber (12% - 13%), sisal (9.9%), and banana trunk (BF) (10.70%), and higher than flax fiber (2%) and cotton fiber (0.7% - 1.6%) [33] [34]. The theoretical lignin values obtained confirm the extraction method, since lignin is insoluble in water.

The pectin content varies from 3.5% to 4.5%, close to the content of Cupressus lusitanica fiber (3.4%), *Rhecktophyllum camerunense* (RC) fiber (3.45%), and banana trunk (BF) fiber (3.7897%), and lower than that of *Neuropeltis acuminata* (NA) fiber (7.69%) [24] [26].

The hemicellulose content, which varies from 19% to 20%, is higher than that of *Neuropeltis acuminata* (NA) fiber 15.33%, sisal fiber 12%, flax fiber 16.7%, and banana trunk (BF) fiber 14.42% [31]-[34].

The cellulose content varies from 60% to 64%, which is very close to the content of Pseudo banana trunk fiber (59%) and lower than the cellulose content of cotton fiber, which is mainly composed of cellulose [31] [34].

The results obtained show that cellulose is the most dominant compound in the chemical composition of banana stem fiber. The low ash content (0.0005%) is close to that reported in the chemical composition table for plant fibers and corresponds to the data available in the literature. Cellulose, hemicellulose, and lignin together account for 88.0%, 93.0% and 93.5% of the dry mass of H1, H2 and H3, respectively (mean 91.5%). They are the main constituents of all plant fibers. Extracts, pectin, and ash are the minor components. Ethanol-benzene extract and ash were calculated directly on the dry-fiber mass (Equation (2) and Equation (9)), whereas the aqueous extract, pectin, lignin, cellulose and wax fractions were calculated relative to the mass of the residue analyzed and multiplied by (1 − %*Es*) (Equations

(3)-(5), Equation (7) and Equation (10)); these fractions are therefore referred to the original dry-fiber mass only for the ethanol-benzene step. Pectin, lignin, holocellulose and wax were determined on separate aliquots of residue 2, and the extractive, pectin and wax fractions are operationally defined and may partly overlap (the wax assay used residue 2, which had already been extracted). They are therefore not additive, and the mass closure of 91.5% refers only to cellulose, hemicellulose and lignin.

The mean ± SD values pool the three samples obtained after different retting durations (20, 25 and 30 days); they describe the variation among retting durations and do not estimate the uncertainty within any single retting duration.

Figure 2. Mean composition of H1 - H3 fibers (mean ± SD, n = 3 characterized samples).

Descriptive statistics: cellulose 62.7% ± 2.3% (CV 3.7%), hemicellulose 19.7% ± 0.6% (CV 2.9%), lignin 9.2% ± 1.0% (CV 11.4%), pectin 4.0% ± 0.5%, total extract 11.3% ± 0.3%, and aqueous extract 10.0% ± 1.3%.

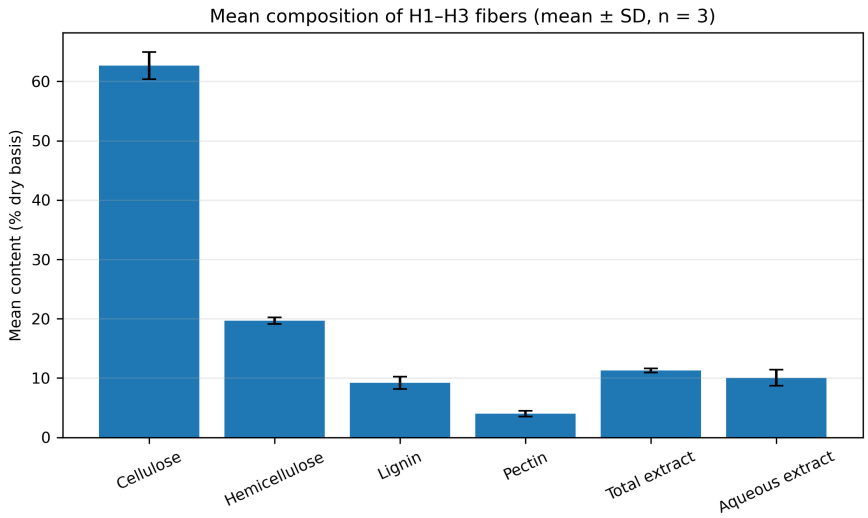


Figure 2. Mean composition of H1 - H3 fibers.

3.3. Morphological Study of H1, H2, and H3 Fibers

Microstructural analysis of H1, H2, and H3 revealed irregular and porous surfaces with filaments, cells, pores, and residual impurities. As shown in Figure 3, the SEM images of H1, H2, and H3 reveal these morphological features, highlighting the surface heterogeneity of the extracted fibers. The observations provide qualitative evidence of surface heterogeneity but do not provide quantitative pore size, fiber diameter, roughness, or density measurements.

The surface of H1 contains impurities and certain components expected to be residual lignin; this phenomenon can be reduced with appropriate combing. Observation of these microstructures also shows that the surface of the samples is irregular, with numerous filaments, alveoli, impurities, cells, and pores. It can also be seen that the surface of the H1 fiber is cylindrical. Each fiber is made up of an

assembly of fibrils, with the central part of each fibril, called the lumen, being hollow [36]. Despite the length of time the H1 fibers have been extracted, the elementary fibers are still bonded together and can be seen to be arranged longitudinally, with varying degrees of parallelism. This fiber, therefore, has a high porosity.

Observation of these microstructures also shows that the surface of the samples is irregular, with numerous filaments, impurities, cells, and pores.

The image of H3 shows a microstructure similar to the previous two (H1 and H2). H3 also has an irregular surface with numerous filaments, impurities, cells, and pores.

This porous nature is, in fact, the main characteristic of plant fibers.

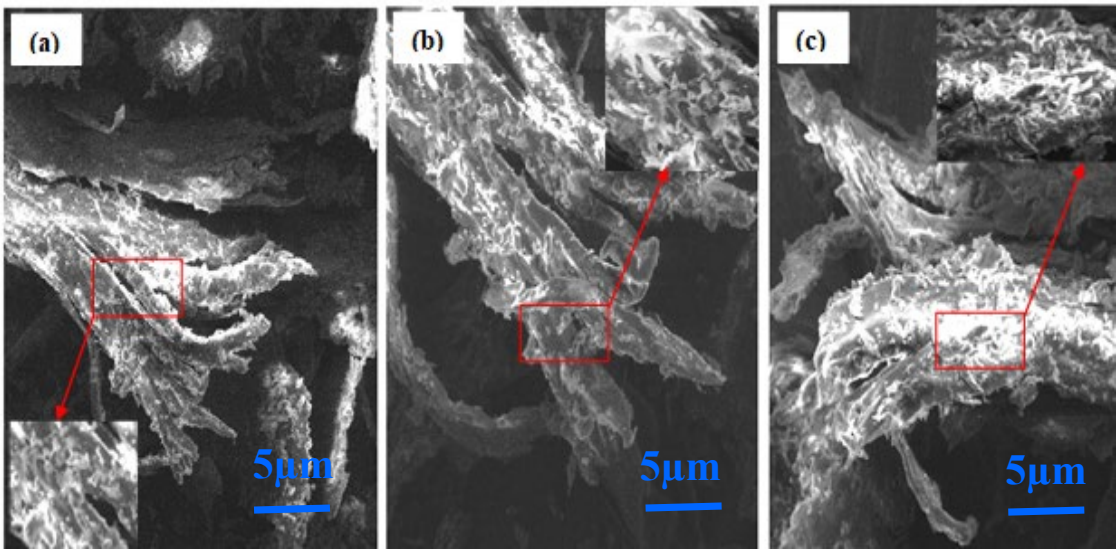


Figure 3. SEM images of H1, H2, and H3 plantain pseudostem fibers (5 µm scale bars; Hitachi TM1000, 15 kV).

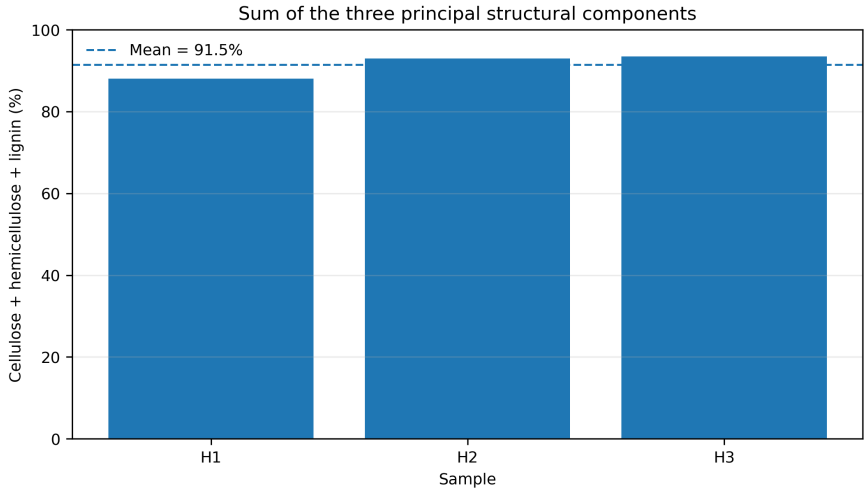


Figure 4. Sum of cellulose, hemicellulose, and lignin in H1 - H3 fibers.

Across the SEM images, H1 - H3 showed broadly similar irregular and porous surface morphologies. These observations are useful for describing the physical

appearance of the extracted fibers, but they should not be used to infer unmeasured mechanical, absorption, or density properties.

These samples have a porous character, which is the main characteristic of plant fibers. The porous morphology observed by SEM may contribute to the water affinity and low density reported for plant fibers; however, these relationships should be confirmed by dedicated measurements. These same observations are also reported in the literature for fibers extracted from date palms [37]. Similar observations have also been reported for other date palm fibers [38].

Figure 4 illustrates the sum of cellulose, hemicellulose, and lignin contents in samples H1, H2, and H3. These three major constituents account for an average of 91.5% of the fiber mass.

3.4. Data Quality and Study Limitations

The present manuscript focuses primarily on the chemical composition and morphological characteristics of water-retted plantain pseudostem fibers. The retting durations were documented as 20 days for H1, 25 days for H2, and 30 days for H3.

Previous work by the authors [10] has already established several physicochemical characteristics of these fibers, including their crystallographic structure by XRD, functional groups by FTIR, thermal behavior by TGA/DSC, as well as some of their physical and mechanical properties. These previously published results are therefore considered as reference and supporting evidence and are cited accordingly, rather than being presented as newly generated data in the present study.

In the present work, the chemical composition and SEM observations constitute the main experimental results.

The SEM observations provide qualitative information on the surface morphology of the fibers, including the presence of irregular surfaces, pores, filaments, and residual impurities.

However, no quantitative image analysis or in-depth statistical assessment of the morphological characteristics was performed. These aspects should be further investigated in future studies through independent biological batches, complete analytical replicates, and quantitative morphological analyses.

4. Conclusions

This study investigated the chemical composition and surface morphology of water-retted plantain pseudostem fibers (*Musa sapientum*) obtained from agricultural residues in Cameroon. The fibers were extracted using a biological extraction process based on water retting, with retting durations of 20, 25, and 30 days for H1, H2, and H3, respectively.

The chemical composition analysis showed that the fibers contained 60% - 64% cellulose, 19% - 20% hemicellulose, 8% - 10% lignin, and 3.5% - 4.5% pectin. SEM observations revealed irregular and porous surfaces, with filaments and residual impurities, providing qualitative evidence of the heterogeneous morphology of the extracted fibers.

These findings contribute to the characterization of plantain pseudostem as a lignocellulosic agricultural residue with potential for further valorization. Previous physicochemical characterization of these fibers, including XRD, FTIR, TGA/DSC, and selected physical and mechanical properties, has been reported by the authors [10] and provides complementary evidence supporting the present findings.

Further studies should focus on quantitative morphological analysis, independent biological replicates, and comprehensive mechanical, thermal, physical, processing, and durability assessments in order to better evaluate the potential of these fibers for different value-added applications.

Author Contributions

Zara Haman and Hambate Gomdje Valery: Conceptualization, methodology, software, formal analysis, investigation, and resources; **Desmond Mufor Zy and Nana Linus Ange:** Data curation, writing—original draft preparation, writing review and editing; **Zang Zang Arcene, Godwe Moïse, and Batchou Kamga Viviane Solange:** Visualization, supervision, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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