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Article

Comparative study of fibers extracted from the stems and roots of the Cameroonian pennissetum purpureum for their applications in compressed earth brick reinforcement and textile engineering

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Abstract: This work focuses on the extraction and experimental characterization of pennisetum purpureum fibers extracted from stems and roots, harvested in the Batié Kingdom, in the West Region of Cameroon. After extracting fibers using the boiling water technique, they are chemically treated to improve their properties and performance and to facilitate their incorporation into various composite materials. For the physical characterizations, it is measured: the absolute and apparent densities, the linear mass, the water absorption rate, and the diameter via the microscope. The mean values of the diameters and the measure of their frequency distributions are calculated, followed by the statistical analysis using the maximum entropy principle, in order to find the most probable diameter necessary for technological applications. For the mechanical properties, only the tensile tests are performed, with the determination of the young modulus of both the stems and roots. The results thus obtained showed that the fibers of the stems have an absolute density of (1.35 g/cm^3), a linear mass of (54.6 tex), an apparent density of (0.45 g/cm^3), a water content of (12.73%), an absorption rate of (142.46%), a porosity of (65.91%), a mean diameter of (7 mm), an elastic modulus of (3.98 GPa), a tensile strength of value of (1186.59 MPa) and an elongation of 16.17%, while the root fibers have an absolute density of (1.34 g/cm^3), a linear mass (16.76 tex), an apparent density of (0.37845 g/cm^3), a water content of (12.25%), an absorption rate of (193.16%), a porosity of (71.92%), a diameter of (4 mm), an elastic modulus of (1.55 GPa), a tensile strength of a value of (1960.35 MPa) and an elongation of 60.6%. Thus, the fibers of the stems have good mechanical properties, which make them an appropriate material in several applications, such as the reinforcement of composite materials.

Keywords: pennisetum purpureum; stem and root fiber; boiling water extraction; physical and mechanical characterization

1. Introduction

The rise of green technologies and the growing need for sustainable materials in the construction sector have sparked significant interest in harnessing renewable and eco-friendly resources [1]. Among these resources, natural fibers are emerging as a promising alternative to traditional synthetic materials because they have many advantages, such as biodegradability, renewability, wide availability, low density and low cost which provide greater opportunities to develop a new class of lightweight and eco-friendly natural fiber composites [2]. There are a wide variety of natural fibers that can be applied as reinforcements. The most used are linen, hemp, jute, kenaf and sisal, due to their properties and availability [3]. Some recent scientific works have shown the possibility of using other natural fibers as reinforcement for composite materials. Thus, Pennisetum purpureum (PP) commonly known as Napier grass or elephant grass, as we shall see further, presents itself as an ideal candidate due to its rapid growth, its adaptation to varied climatic conditions and its availability. PP is a monocotyledonous flowering plant belonging to the Poaceae family (the grass family) and the Pennisetum genus [4]. Pennisetum is a very diverse genus composed of a heterogeneous group of approximately 140 species [5]. It is used for the control of soil erosion [6]; resistance to a broad spectrum of pests and diseases [7]; and suitability for cellulosic biofuel production. It can then be used to make fences, as windbreaks, to demarcate boundaries between neighboring farmers, and the dried materials can be used as a fuel source [8]. In cropland management systems, it is used as a mulch to control weed infestation and soil erosion and as a trap plant in the push-pull strategy, a pest control practice that uses repellent plants and an attractive plant trap for insect pest control in Africa, particularly against the corn borer [9]. PP plants are also used to remove pollutants, such as heavy metals, and have been used in phytoremediation strategies, for example to clean up cadmium-affected soils, reducing the concentration of cadmium to a depth of 15 cm in the soil [10]. The only technique used until now to extract fibers from this plant was cold water retting. This is a technique that allows the fibers to be extracted after two weeks of soaking [11]. This technique is time consuming and there is a risk of air pollution due to the strong odor released, which can cause illness. Some authors have used an alternative extraction technique for other plant species using boiling water [12]. The studies of these authors showed that the boiling water technique allows rapid extraction of fibers without weakening their properties. In this present study the fibers are extracted from the stems and roots of the PP plant by the boiling water extraction method.

The characterization of fibers is an essential process that allows defining their physical and mechanical properties. These fibers, such as those extracted from plants such as PP, have been studied because of their potential to replace or complement synthetic fibers. The characterization of these fibers is therefore a step towards their successful integration into existing and new applications, allowing optimal exploitation of their unique properties. The physical characterization includes density, porosity, water content, water absorption rate and linear mass, allowing us to understand their behavior in various applications. At the same time, the mechanical characterization, including tensile strength, modulus of elasticity and elongation at break, provides valuable information on the capacity of these fibers to improve the properties of composites, particularly in terms of resistance to cracking and ductility. A few studies have been carried out by some researchers on the characterization of fibers derived from plant sources such as banana, sugarcane bagasse, Brazilian sponge gourd, Shwetark stem and raffia palm [13–20]. Such studies are being conducted worldwide to substantiate their potential for use in construction, packaging, sporting goods, furniture and lightweight applications.

The industrial use of fibers derived from natural plants as reinforcements in materials began in the early 20th century with the manufacture of large quantities of sheet metal, tubes and pipes for electronic purposes. One also has the seats, fuel tanks, the interior equipment and exteriors of automobiles [21,22], the manufacturing of fabrics, packaging, the manufacturing of high-strength paper or cardboard, the manufacturing of panels, the creation of art objects due to their excellent characteristics. To our knowledge, fibers from PP stems and roots have not yet been used in such applications. Thus, the major problem solved is to determine which of the stem and root fibers of PP have favorable properties for the creation of durable, profitable and environmentally friendly material. Let us remember that in [23] the fiber from the PP studied is extracted only from the stems, while in the present work, both fibers from the stems and roots are studied and compared. Moreover, it is the pioneering work for the Cameroonian PP, which is new since the properties of plants can vary according to geographic location and climate change. In addition, we use the statistical approach, usually used in energetic physics to evaluate the most probable fiber diameter to find the more realistic wind speed, which is new in the context of natural fibers. To address this theme, we seek to provide elements of answers to the following research questions:

- Do PP fibers have favorable physical and mechanical properties for reinforcing compressed earth bricks (CEBs)?
- Do the fibers extracted from different parts of the PP have different mechanical properties, thus influencing their performance in the CEBs?
- What would be the economic, environmental, and structural advantages of using PP fibers compared to other reinforcing materials in the construction of CEBs?

The specific objectives of our work are:

- Determine the physico-mechanical properties of fibers from PP stems and roots.
- Identify the most efficient extraction method for obtaining PP fibers.
- Compare the costs and environmental benefits linked to the use of PP fibers compared to other methods of reinforcing CEBs.

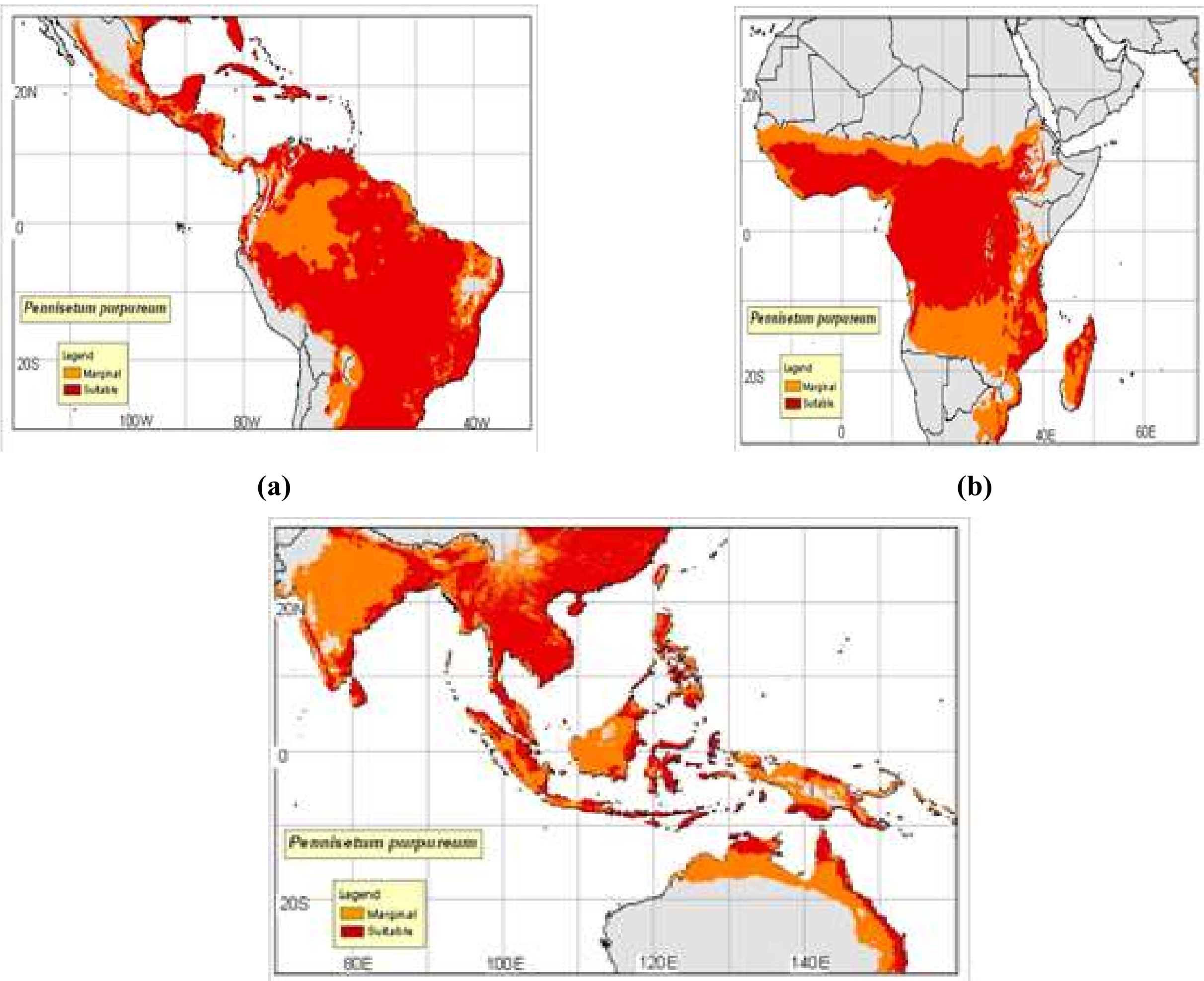
2. Materials and methods

Mastery of the materials and techniques used to properly carry out the study on the extraction and physico-mechanical characterization of fibers from PP stems and roots is of capital importance. This section describes all the methods and techniques used as part of our study as well as the materials and means implemented. After the extraction of the fibers and the collection of the different samples to be studied, we proceeded in turn to the physical characterization, to the mechanical characterization of the treated samples then to the presentation of the different tests carried out.

2.1. Origin of the material used and extraction site

2.1.1. Origin of the material used

PP is native to Africa, but has spread to many tropical and subtropical regions of the world. It is a perennial herb that can reach an impressive size of up to 3–4 m in height [24]. It is distinguished by its long, narrow leaves and feather-shaped purple or light brown inflorescences. **Figure 1** shows the distribution of this material across the world.



(a) **(b)** **(c)**

Figure 1. Distribution of PP in the world [24]. **(a)** Distribution in Caribbean, Central and Southern America; **(b)** distribution in Africa; **(c)** distribution in Melanesia, Southeast Asia and Surrounding regions.

2.1.2. Extraction site

The PP samples used come from the western region of Cameroon, more precisely in the Batié kingdom, in the Femgoum district. This Batié kingdom as shown in **Figure 2** is part of the large geographical area commonly called "the highlands of western Cameroon". It is one of the traditional chiefdoms of the western Cameroon region located on the national road No 2 to 210 km from Douala and 30 km from Bafoussam, the capital of the region. It is chosen based on its availability and abundance in the region.

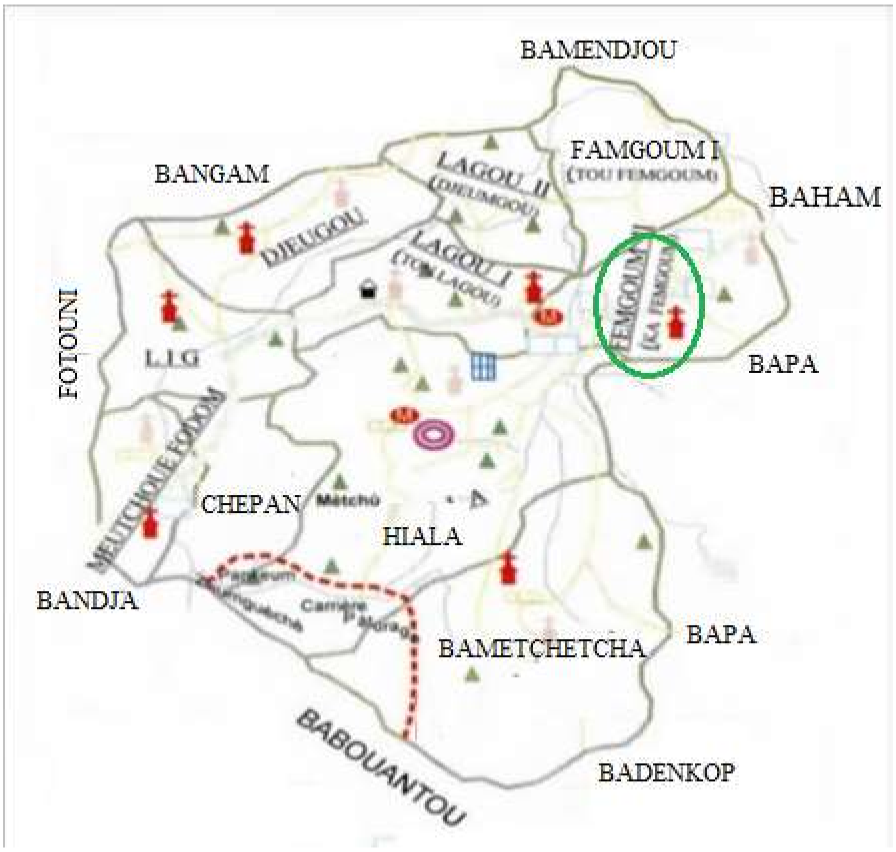


Figure 2. Location of the study area in Batié.

2.2. PP fiber extraction process and chemical treatment

2.2.1. PP fiber extraction process

In the present work, we study two elements: the stems and roots of the PP plant. **Figure 3** illustrates the plant under consideration.

Figure 3. PP plants showing their stem and root.

For this study, we opted for the chemical extraction method, as shown in **Figures 4** and **5**, because the execution time is relatively short and the process is hygienic. Firstly the stems are cut to the same lengths as well as the roots, ridding them of any impurities (**Figure 4**) and then introducing them in turn into a metal container and bringing them to a boil at a temperature of 100 °C for 1 h 30 min.

After this duration, one observes that the stems and roots have become soft and the fibers have been isolated from the stems and roots. The separated fibers were carefully washed under running tap water to remove any impurities (See **Figure 5**).

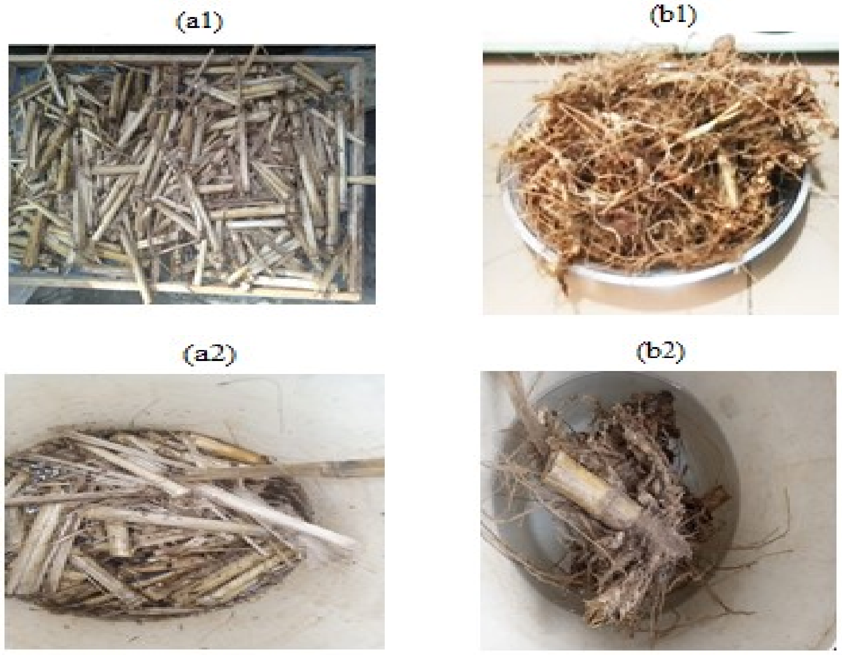


Figure 4. Cleaning stems and roots. **(a1)** and **(b1)** Stems and roots before any treatment; **(a2)** and **(b2)** Stems and roots cleaned.

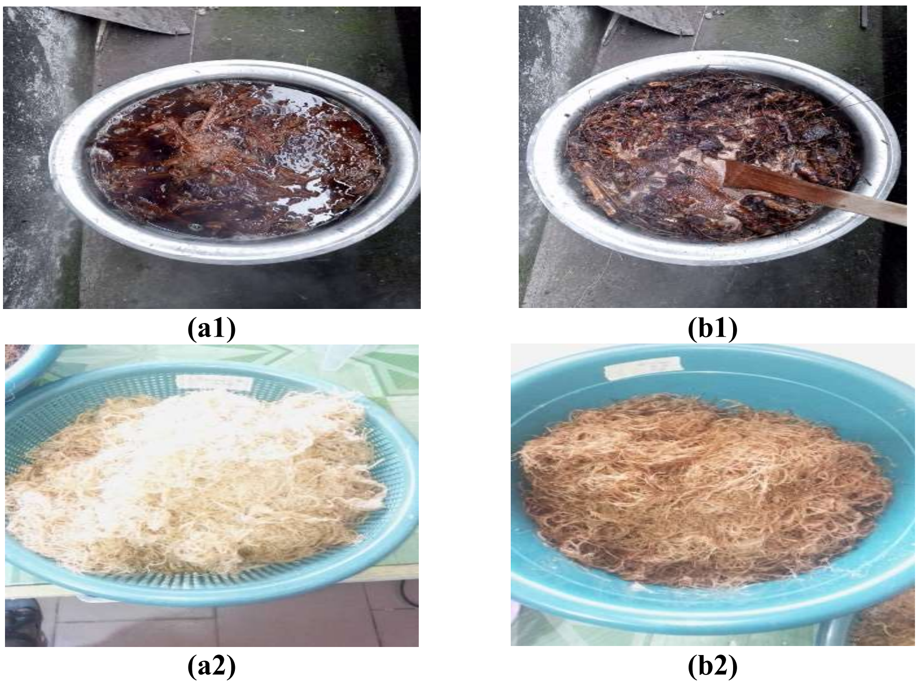


Figure 5. Fiber extractions. **(a1)** and **(b1)** cooking of the stems and roots; **(a2)** and **(b2)** Fibers obtained for the stems and roots.

2.2.2. Chemical treatment of fibers

It is a process that is generally carried out to improve the properties and performance of fibers as well as to facilitate their incorporation into various composite materials. The PP fibers were treated with sodium hydroxide (NaOH) solution. They are dehydrated in an oven at 60 °C for 24 h, and then weighed on a 0.001 g precision balance. Then they were immersed in distilled water and a 10% concentration of NaOH for one hour at a temperature of 105 °C. Then, the fibers were neutralized using a 0.001% acetic acid solution to obtain a PH = 7 (neutral) followed by water, and then the fibers were dried at 100 °C for 24 h. Finally, the fibers were dried in the open air for 24 h. Then stored in an oven for 24 h at 105ºC to ensure maximum moisture removal.

2.3. Determination of physical properties

2.3.1. Absolute density

The test aims to determine the natural density of a material. This test provides information on the internal structure of the fibers. The density of the fibers was carried out by the pycnometric method using ethanol ($\rho_{eth} = 0.789 g/cm^3$ in a room with a temperature of 27.4 °C) as immersion liquid, in accordance with standard NF EN 1097-6. Before the measurements, 03 fiber samples were dehumidified in an oven at a temperature of 105 °C for a minimum of 6 h. Measurements were made using a balance with a sensitivity of 0.1 mg and the following equation was applied to calculate the density ρ.

$$\rho_{abs} = \frac{m_0 \times \rho_{eth}}{m_0 + m_1 - m_2} \quad (1)$$

where

- m_0 (g) is the mass of the anhydrous sample;
- m_1 (g) is the mass of the pycnometer + ethanol assembly;
- m_2 (g) is the mass of the pycnometer + ethanol + sample assembly

2.3.2. Linear mass

Also called a measurement of the title (in tex) or the fineness of the fibers, this test aims to determine the mass per unit length of PP samples.

The linear mass of our fibers was determined gravimetrically according to the ISO 1973 2021 edition standard in a room with a temperature of 27 °C. To prepare the samples, they are first dehydrated in a ventilated oven at 105 °C for 24 h. Then five 5 mm samples are taken using a chisel and a ruler, and conditioned for 24 h in a desiccator whose hygrometry is 65% relative humidity. After 24 h of conditioning, the samples are taken and weighed on a 1 mg precision balance. The following equation was used to calculate the linear mass.

$$M_L(tex) = \frac{m(\mathrm{g})}{L(\mathrm{Km})} \quad (2)$$

where m (g) is the mass of the wire of length 1 m; L (km) is the length of the wire in km; $M_L(tex)$ is the calculated linear mass.

2.3.3. Apparent density

The purpose of this test is, to determine the compactness and porosity of our fibers. The apparent density of our fibers was determined according to standard NF EN 1097-3 (August 1998 Edition) in a room with a temperature of 27 °C. To obtain 03 samples, they are first dehydrated in a ventilated oven at 105 °C for 24 h. Then we carry out four successive weighings:

- The mass of the anhydrous sample m_0 (g);
- The mass of the assembly (pycnometer + distilled water) m_1 (g);
- The mass of the assembly (pycnometer + distilled water + fiber) after saturation m_2 (g);
- The mass of the saturated fiber with dry surface m_3 (g);
- The apparent density of the fiber is obtained from the formulas below:

$$\rho_{app} = \frac{m_0 \times \rho_{\text{water}}}{m3 + m1 - m2} \tag{3}$$

2.3.4. Water content

The purpose of the humidity level is to determine the quantity of water contained in our fibers; it is expressed as a percentage of the mass of the wet product. Three fiber samples with an initial dryness mass of $m_1 = 1 \pm 0.1$ g were weighed using a balance with a sensitivity of 0.001 g, and then dried in a ventilated oven for 24 h at a temperature of 105 °C. After drying, the mass m_2 was recorded using the balance, and the following equation was used to determine the humidity level according to the ISO 3344:1997 standard (room temperature: 27.6 °C).

$$W(\%) = \frac{(m_1 - m_2)}{m_1} \times 100 \tag{4}$$

where m_1 is the initial mass of the sample (g); m_2 the final mass of the sample (g).

2.3.5. Water absorption rate

The purpose of the current test is to determine how much water the fibers can absorb.

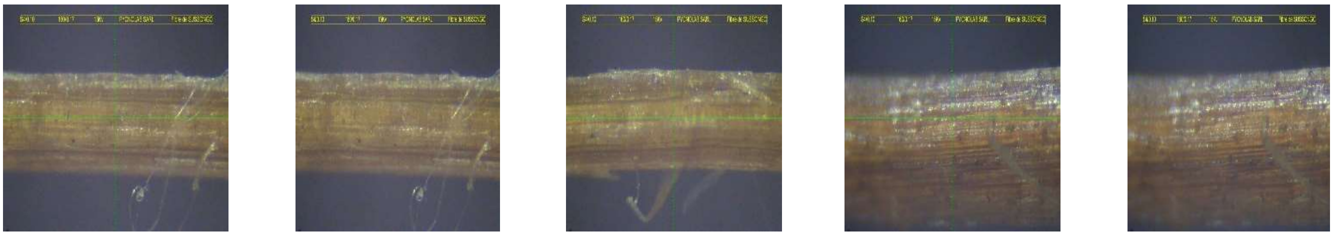
The test was carried out according to standard NF EN 1097-6 (room temperature: 27.4 °C). The samples were dried in an oven at 105 °C temperature, for a minimum of 6 h to make them anhydrous. Then, the fibers were weighed using a balance with a sensitivity of 1 mg to obtain their different initial masses. Finally, these samples (m_0) are introduced into pycnometers which are then filled with water up to 0 of the meniscus. After 24 h, the samples are extracted from the pycnometers, and the surface water is taken using a device to filter and extract the surface water. The saturated fibers at the dry surface are therefore weighed to obtain the mass mf. The following equation was used to determine the water absorption rate:

$$\text{Ab}(\%) = \frac{(m_f - m_0)}{m_0} \times 100 \tag{5}$$

2.3.6. Diameter under the microscope

$$\emptyset_{\mathrm{moy}} = \frac{\sum_{\mathrm{i}=1}^{5} \emptyset_{\mathrm{i}}}{5}, \tag{6}$$

where $\emptyset_{\mathrm{moy}}$: Average diameter; $\emptyset_{\mathrm{i}}$: Diameter at point 'i'. Since we are dealing with natural samples, we will observe a variation in diameter for each sample of these fibers (See **Figure 6**). In order to determine the most probable diameter of our fibers we will proceed as follows:



(a) **(b)** **(c)** **(d)** **(e)**

Figure 6. Measurement of fiber diameters. **(a)** Sample 1; **(b)** Sample 2; **(c)** Sample 3; **(d)** Sample 4; **(e)** Sample 5.

Determining the average

To do this, we will draw the diagram of the diameters of these fibers according to the different samples then average the 25 samples of each fiber in order to obtain the average value of the diameter of these fibers.

$$\phi_{\mathrm{moy}} = \frac{\sum \phi_i}{N} \tag{7}$$

ϕ_i is the unit diameter; N: is the total number of measurements.

Determining the median

To do this we will first group together in a table the different modal classes of fiber diameter and for each class we will determine its frequency of appearance. Finally, using the linear interpolation method, we will determine the median which will in this case be the value of the diameter.

$$F(\%) = \frac{M}{MT};\ Me = Xa + (Xt - X'a)\frac{Xb - Xa}{X'b - X'a} \tag{8}$$

From where F(%) is the frequency; M: modality; Mt: total modality; Me: the median; Xb−Xa: the modal class; $X'b - X'a$: increasing cumulative frequency; Xt: the total modality.

Statistical analysis using the maximum entropy principle

In order to study the principle of maximum entropy we took as a reference the work carried out by [25]. This study will allow us to determine the probability of appearance of our fibers depending on the diameter of the different samples obtained from our two fibers of the stems and roots. To do this, the probability density function of diameters has been introduced in the following form:

$$f(\phi) = \exp\left(\sum_{j=0}^{N} \alpha_j \phi^j\right) = \exp(\alpha_0 + \alpha_1\phi + \alpha_2\phi^2 + \alpha_3\phi^3 + \cdots) \tag{9}$$

where α_j are the Lagrangian multipliers, while N is the number of the low order moments used, and where P is the irradiance distribution. This density function is obtained by minimizing Shannon's entropy, following the well-known Carla et al principles [26], suggesting the following constraints:

$$\int_0^{\max(\phi)} f(\phi)d\phi = 1\,, \int_0^{\max(\phi)} \phi f(\phi)d\phi = \bar{\phi} \tag{10}$$

$\bar{\phi}$ being the m-low statistical orders, obtained empirically (as in [26] and references therein).

$$\bar{\phi} = \frac{1}{N}\sum_{j=0}^{N} \phi^j \tag{11}$$

The set of Equations (10) and (11) will be solved numerically, and the parameters α_j substituted into Equation (9) and plotted in the next section to give the probability distribution.

2.4. Determination of mechanical properties: Tensile test

The tensile test measures the maximum tensile strength of a fiber, indicating its ability to support a load without breaking. This information is crucial for assessing the strength and durability of fibers. By analyzing the traction curve, we can evaluate the elastic behavior of the fiber, that is to say its ability to return to its initial shape after being subjected to stress. This provides insight into the flexibility and deformation of the fibers.

The determination of Young's modulus, from strain to fiber breakage was carried out on 25 samples for each fiber, using a universal testing machine at a speed of 2 mm/mi. The fibers were previously dried in an oven at 105 °C for 24 h, then cut to a length of 50 mm, before being placed on a glass slide and measured using an electron microscope. The diameter of the fibers being obtained under a microscope, the fibers are subsequently mounted on cardboard supports, and numbered according to the order of the diameter measurements. Before mounting the samples on the traction device, they are conditioned in a desiccator formulated at 65% relative humidity. After 24 h, the fibers are successively installed on the jaws of the universal testing machine, where an installation tension is applied to them before starting the test. During the test, the Test Master software draws the curves and calculates all the test parameters. The following equations were used to determine Young's modulus, maximum tensile strength, and strain at break:

$$\sigma_{\max} = \frac{F\max}{S}, \varepsilon_{\text{rupt}} = \frac{A_r}{Lo}; E = \frac{\sigma 2 - \sigma 1}{\varepsilon 2 - \varepsilon 1}, \tag{12}$$

where

- Fmax (*N*) is the maximum tensile force;

- S (mm^2) is the section of the specimen;
- A_r (mm) is the elongation at break;
- Lo (mm) is the useful length of the test piece (here 20 mm);
- E (MPa) is the young module;
- $\sigma_{\max}$ (MPa) is the maximum tensile strength;
- $\varepsilon_{\text{rupt}}$ is the strain at breakage of the specimen.

3. Results and discussion

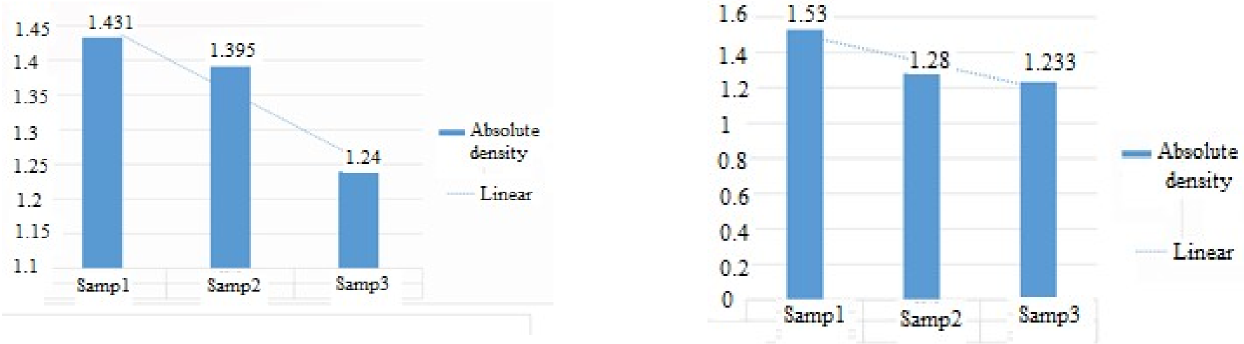
In this section, it will be a question of presenting the results of all the tests carried out and interpreting them in turn in order to have a clear vision of the properties of these fibers and their abilities to be used in various applications. These results correspond to the average of the different data obtained from each.

3.1. Appearance of fibers extracted and processed from PP stems and roots

According to our observation, it turns out that the fibers obtained after extraction retained their color after treatment with a 10% sodium hydroxide (NaOH) solution, which improved the mechanical properties of our fibers compared to others. However, we encountered difficulties during the process of extracting our fibers. In fact, the fibers harvested fresh, posed a problem during cleaning and segmentation into several batches because of their high density and their water content which was, however, relatively high. We therefore proceed to dry our materials in order to facilitate the process of extracting our fibers at room temperature. This result is in the same direction as that presented in [17] which showed that the treatment of Lemba leaf fibers with 10% NaOH improved thermal stability and tensile mechanical properties [27]. On the other hand, the study carried out in [23] shows that the alkaline treatment at 10%, 12% and 15% reduced the mechanical properties of the fibers studied, that is an elastic modulus with a value of 1.00 ± 0.17 GPa and a tensile strength of 50 MPa. This variation in results may be due to the nature and origin of the fibers studied and the extraction and treatment process used for each fiber. Thus, it is obvious that the extraction and treatment process used in our study are of high quality.

3.2. Absolute density

Table 1 presents the value of absolute densities obtained from the fibers of the stems and roots and calculated according to Equation (1). These results allowed us to draw **Figure 7**.



(a) **(b)**

Figure 7. Variation of the absolute density (ρ_{abs}) of fibers. **(a)** stems; **(b)** roots.

Table 1. Absolute density of stem fibers and root fibers.

	Sample 1		Sample 2		Sample 3	
	stem	**root**	**stem**	**root**	**stem**	**root**
m_0 (g)	1.034	1.006	1.049	1.008	1.011	1.013
m_1 (g)	62.638	62.641	62.409	62.121	62.758	62.228
m_2 (g)	63.103	63.131	62.863	62.509	62.153	62.593
ρ_{abs}	1.431	1.53	1.395	1.28	1.24	1.233

We have on average an absolute density of $1.35\ \mathrm{g/cm^3}$ for stem fibers and $1.34\ \mathrm{g/cm^3}$ for root fibers. It appears that the stem fibers are slightly denser than the root fibers. These results are identical to those of banana fibers ($1.35\ \mathrm{g/cm^3}$) w. Compared to other plants, these fibers have a density higher than that of date fibers ($0.99\ \mathrm{g/cm^3}$), coconut fibers ($1.15\ \mathrm{g/cm^3}$) and lower than that of sisal fibers ($1.45\ \mathrm{g/cm^3}$), flax ($1.53\ \mathrm{g/cm^3}$), [28]. Due to their lightweight, stem and root fibers can be used in composite and textile applications.

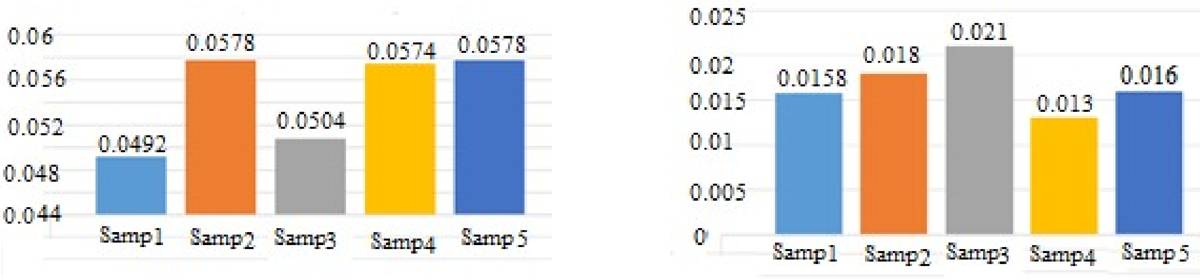
3.3. The linear mass

Table 2 presents the different values of the linear mass obtained from the stem and root fibers and calculated using Equation (2). These results allowed us to draw **Figure 8**. We have on average a linear mass of $0.0546\ \mathrm{g/cm}$ or 54.6 tex for the stem fibers and around $0.01676\ \mathrm{g/cm}$ or 16.76 tex for the root fibers. Stem fibers have a higher linear mass than root fibers.

Table 2. Linear mass of stem and root fibers, for the length L = 5 cm.

fibers		**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
Stem	ml (g)	0.246	0.289	0.254	0.287	0.289
	M_L *(tex)*	0.0492	0.0578	0.0504	0.0574	0.0578
Root	ml (g)	0.079	0.09	0.105	0.065	0.08
	M_L *(tex)*	0.0158	0.018	0.021	0.013	0.016

Compared to other plants, these fibers have a higher linear mass than the fibers of sida rhombifolia (SR) (11.23 tex ± 1.1–13.57 tex ±0.95) [11], to that of pineapple leaf (8.0–8.4 tex) [15]. This variation may be due to the treatment process of our fibers [11] so we can say that our fibers are of good quality.

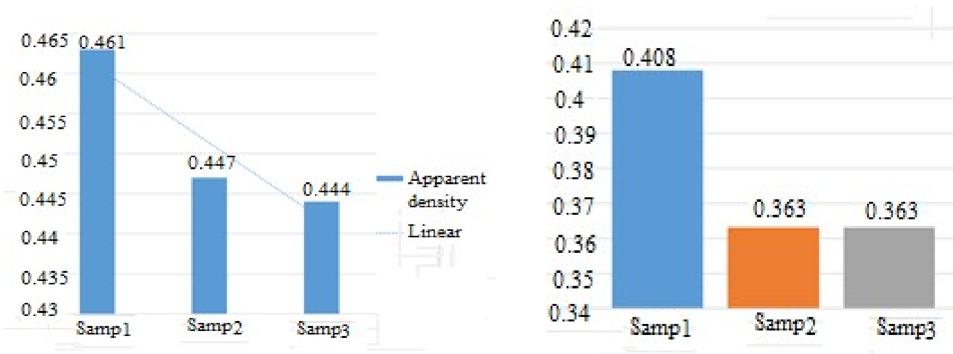


(a) **(b)**

Figure 8. Variation of the linear mass of the fibers. **(a)** Stems; **(b)** Roots.

3.4. Apparent density

Table 3 presents the different values of the apparent density obtained from the stem and root fibers, and calculated according to Equation (3). These results allowed us to draw **Figure 9**. We have on average an apparent density of 0.45 g/cm^3 for stem fibers and 0.37 g/cm^3 for root fibers. Stem fibers have a higher apparent density than root fibers, which means that stem fibers have fewer empty spaces. Compared to other plants, these fibers have a higher apparent density than that of hemp fibers (164.5 kg/m^3), sunflower fibers (20 kg/m^3), esparto fibers (99.4 g/cm^3) [29] and lower than that of amioca fibers (235 to 750 g/cm^3). Leading to the conclusion that the fibers in the stems are of high quality, having implications for the durability and longevity of the end products made from these fibers.



(a) **(b)**

Figure 9. Variation in apparent density of fibers. **(a)** Stems; **(b)** Roots.

Table 3. Apparent mass of stem and root fibers.

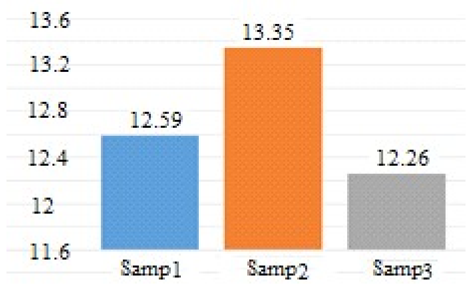
	Sample 1		**Sample 2**		**Sample 3**	
	stem	**root**	**stem**	**root**	**stem**	**root**
m_0 (g)	1.012	1.005	1.003	1.01	1.002	1.01
m_1 (g)	373.249	366.628	376.882	364.49	375.279	367.43
m_2 (g)	373.504	367.01	377.076	364.718	375.466	367.669

Table 3. (*Continued*).

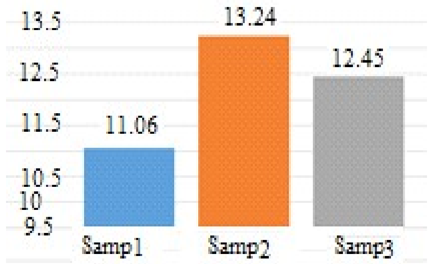
	Sample 1		Sample 2		Sample 3	
	stem	**root**	**stem**	**root**	**stem**	**root**
m_3 (g)	2.44	2.4841	2.433	3.01	2.442	3.018
ρ_{app}	0.461	0.408	0.447	0.363	0.444	0.363

3.5. Water content

Table 4 presents the water content values obtained from stem and root fibers using Equation (4). These results allowed us to draw **Figure 10**.



(a)



(b)

Figure 10. Variation in moisture content of fibers. **(a)** stems; **(b)** roots.

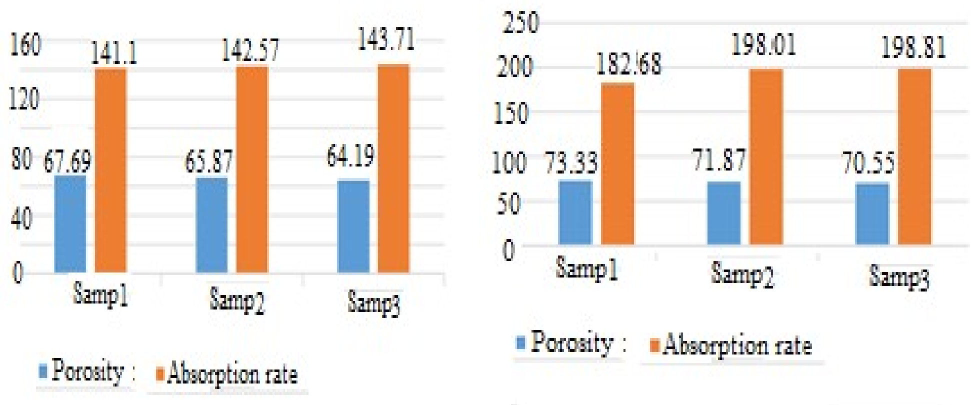
Table 4. Moisture content of stem and root fibers.

	Sample 1		Sample 2		Sample 3	
	stem	**root**	**stem**	**root**	**stem**	**root**
m_h(g)	1.008	1.004	1.011	1.009	1.003	1.002
m_s(g)	0.881	0.904	0.876	0.891	0.88	0.891
W(%)	12.59	11.06	13.35	13.24	12.26	12.45

We have on average a humidity rate of 12.73% for stem fibers and 12.25% for root fibers. Stem fibers have a higher water content than root fibers, which implies the rigidity of our stem fibers because they are responsible for maintaining and transporting water to the leaves. Compared to other plants, these fibers have a higher humidity level than that of flax fibers (10%); Hemp (10.8%); of bagasse (8.8%) [30] and lower than that of Abaca fibers (15%); Sida rhombifolia fibers extracted with boiling water (13.28%) [11]. This variation can be attributed to the different harvest sites.

3.6. Water absorption rate

Table 4 is also used to calculate, via Equation (5), the water content obtained from stem and root fibers. These results allowed us to draw **Figure 11**. We have on average an absorption rate of around 142.46%, with a porosity of 65.91% for stem fibers and of around 193.16% with a porosity of 71.92% for root fibers. Root fibers have a higher absorption rate and porosity than stem fibers, which means that root fibers have more empty spaces in their pores. This factor can therefore influence the durability and longevity of this fiber, most often leading to cracks and a reduction in stiffness in final products such as composite materials [31]. Compared to other plants, stem fibers have a higher absorption rate than Triumfeta Pentandra fibers (183.31%) [32]; Pineapple Comosus (188.64%) [15], and lower than that of SR fibers extracted by hot water retting [29] (225.12 ± 15.67%) [11]; Neuropeltis Acuminata (276.16%) [16].



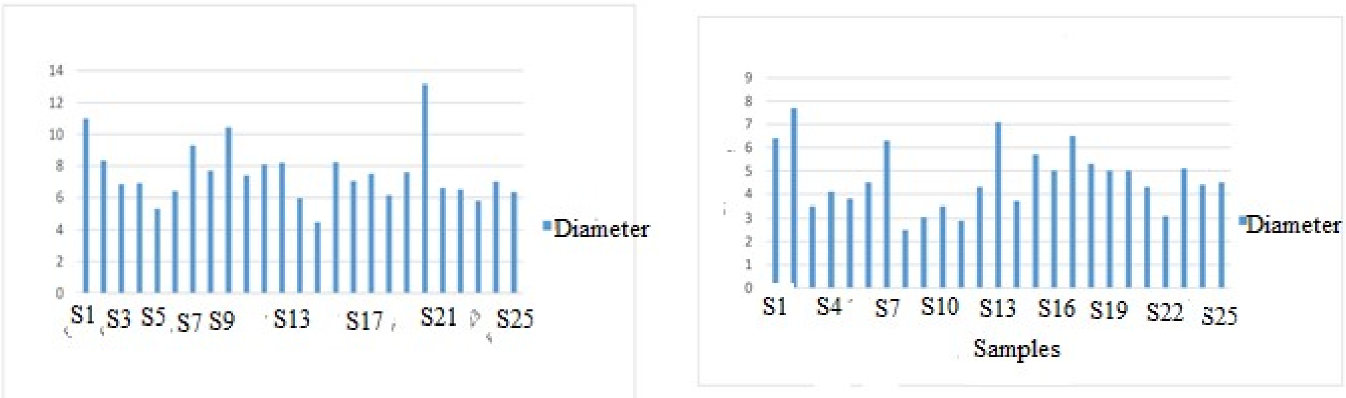
(a) **(b)**

Figure 11. Variation in fiber absorption rate. **(a)** Stems; **(b)** Roots.

3.7. Diameter under the microscope

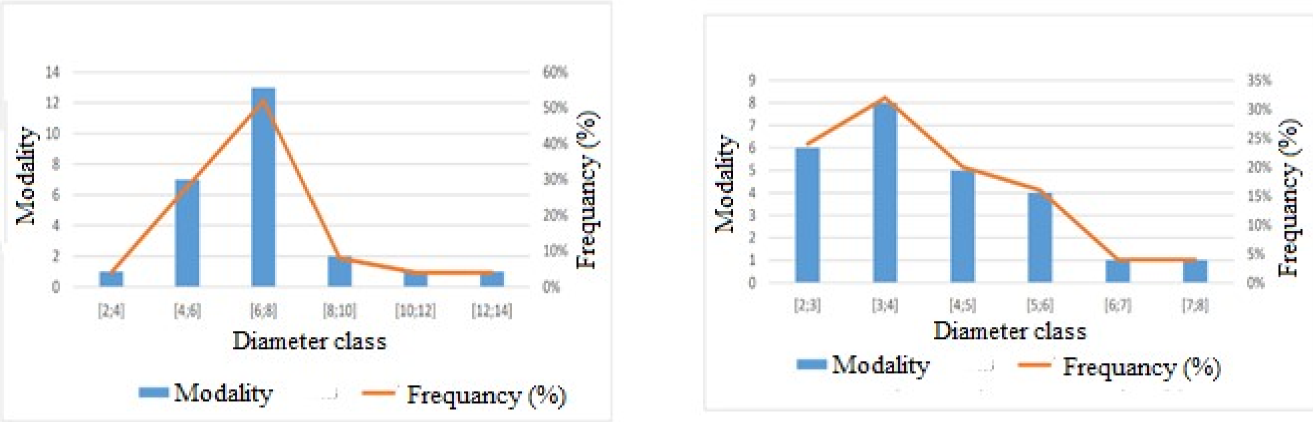
3.7.1 Diameter and frequency distribution

Table 5 and **Table 6** present the different values of the diameter obtained from the stem and root fibers, allowing to draw the curves in **Figure 12**. We have on average a diameter of 7.20 mm for stem fibers and 4.69 mm for root fibers. **Tables 7** and **8** present the different values of the appearance frequencies depending on the diameter, which allowed us to draw the curves in **Figure 13**. Thus, we obtain a diameter of 3.81 mm for the root fibers and 6.69 mm for the stem fibers.



(a) **(b)**

Figure 12. Variation in fiber diameter. **(a)** Stems; **(b)** roots depending on the samples.



(a) **(b)**

Figure 13. Variation in the frequencies of fibers. **(a)** Stems and; **(b)** Roots as a function of diameter.

Table 5. Diameter of stem fibers under the microscope.

Samples	ϕ_1	ϕ_2	ϕ_{moy}	ϕ_{moy}(mm)	Section (mm^2)
S1	11	11	11	0.44	0.151976
S2	8.2	8.5	8.35	0.334	0.08757176
S3	7.1	6.6	6.85	0.274	0.05893466
S4	6.8	7.0	6.9	0.276	0.05979816
S5	5.3	5.4	5.35	0.214	0.03594986
S6	6.4	6.4	6.4	0.256	0.05144576
S7	9.8	8.8	9.3	0.372	0.10863144
S8	7.4	8.0	7.7	0.308	0.07446824
S9	10.5	10.4	10.45	0.418	0.13715834
S10	8.2	6.6	7.4	0.296	0.06877856
S11	7.6	8.6	8.1	0.324	0.08240616
S12	8.4	8.0	8.2	0.328	0.08445344
S13	5.8	6.1	5.95	0.238	0.04446554
S14	4.5	4.5	4.5	0.18	0.025434
S15	8.4	8.1	8.25	0.33	0.0854865
S16	7.1	7	7.05	0.282	0.06242634
S17	7.5	7.5	7.5	0.3	0.07065
S18	5.9	6.4	6.15	0.246	0.04750506
S19	7.8	7.4	7.6	0.304	0.07254656
S20	12	14.6	13.15	0.526	0.21719066
S21	7.2	6.0	6.6	0.264	0.05471136
S22	5.8	7.2	6.5	0.26	0.053066
S23	6.4	5.2	5.8	0.232	0.04225184
S24	7.2	6.8	7	0.28	0.061544
S25	7.0	5.7	6.35	0.254	0.05064506

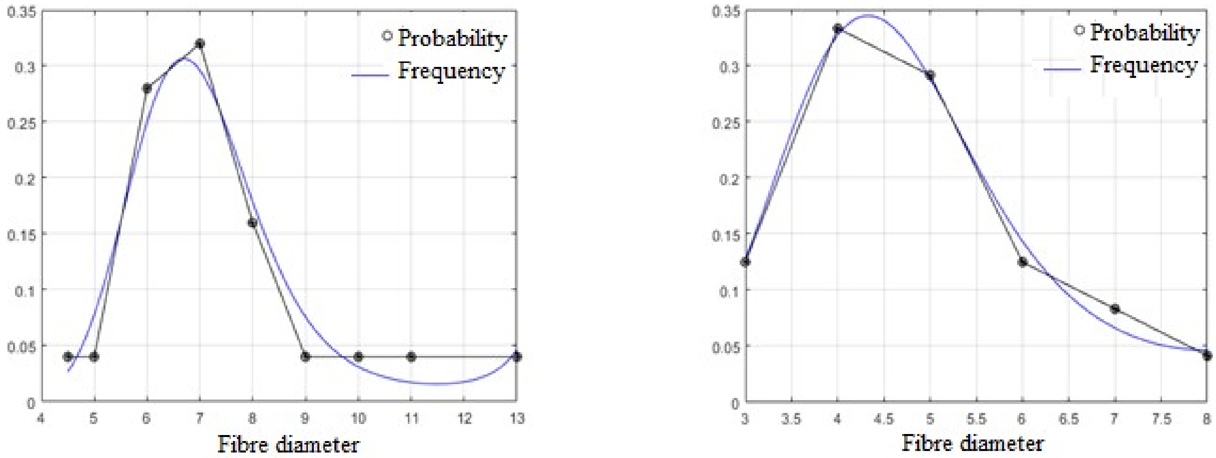
Table 6. Root fiber diameter under the microscope.

Samples	ϕ_1	ϕ_2	ϕ_{moy}	$\phi_{moy}(mm)$	Section (mm^2)
S1	7.4	5.4	6.4	0.256	0.05144576
S2	7.6	7.8	7.7	0.308	0.07446824
S3	3.2	3.8	3.5	0.14	0.015386
S4	4.0	4.2	4.1	0.164	0.02111336
S5	4.6	3.0	3.8	0.152	0.01813664
S6	6.0	3.0	4.5	0.18	0.025434
S7	6.8	5.8	5.3	0.252	0.04985064
S8	2.2	2.8	2.5	0.1	0.00785
S9	1.6	4.5	3.05	0.122	0.01168394
S10	2.2	4.8	3.5	0.14	0.015386
S11	2.8	3.0	2.9	0.116	0.01056296
S12	5.2	3.4	4.3	0.172	0.02322344
S13	7.0	7.2	7.1	0.284	0.06331496
S14	4.2	3.2	3.7	0.148	0.01719464
S15	4.6	6.8	5.7	0.228	0.04080744
S16	4.8	5.2	5.0	0.2	0.0314
S17	6.2	6.8	6.5	0.26	0.053066
S18	6.0	4.6	5.3	0.212	0.3528104
S19	5.2	4.8	5.0	0.2	0.0314
S20	4.6	5.4	5.0	0.2	0.0314
S21	4.6	4.0	4.3	0.172	0.02322344
S22	3.4	2.8	3.1	0.124	0.01207016
S23	5.6	4.6	5.1	0.204	0.03266856
S24	3.8	5.0	4.4	0.176	0.02431616
S25	4.6	4.4	4.5	0.18	0.025434

3.7.2. Probability distribution

The graphs of **Figure 14** present the probabilities of the appearance of fibers from PP stems and roots as a function of diameter by the method of statistical analysis using the maximum entropy principle. The peaks observed on these graphs designate the probable value of the diameter of our fibers. Thus, we obtain a value of 4 mm for the root fibers and 7 mm for the stem fibers.

In short, it is clear that the value of the fiber diameter obtained through these different diagrams and methods is approximately the same. Thus, we can conclude that this is due to the reliability and consistency of the results obtained, as well as to the quality of the fiber processing.



(a) **(b)**

Figure 14. Probabilities of appearance of fibers. **(a)** stems; **(b)** roots as a function of diameter.

Table 7. Frequencies of appearance of stem fibers.

Class of different diameters	Modes of appearance	Frequency (%)
[2;3]	6	24%
[3;4]	8	32%
[4;5]	5	20%
[5;6]	4	16%
[6;7]	1	4%
[7;8]	1	4%

Table 8. Frequencies of appearance of root fibers.

Class of different diameters	**Modes of appearance**	**Frequency (%)**
[2;4]	1	4%
[4;6]	7	28%
[6;8]	13	52%
[8;10]	2	8%
[10;12]	1	4%
[12;14]	1	4%

3.8. Mechanical properties

3.8.1. Tensile strength

Stress strain curves

Figure 15 shows the tensile results of the PP stem, while **Figure 16** shows that of the PP root fibers according to results shown in **Table 9**. The fibers of the stems have an average elasticity modulus higher than that of the fibers of the roots (1559 MPa or 1.556 GPa) or a value of 3982.506 MPa or 3.982 GPa. Compared to other plants, stem fibers have a higher elasticity modulus than that of spine fibers (2.31 GPa), date palm fibers (2.5 GPa) [33]. Furthermore, the root fibers have a higher tensile strength than the stem fibers (1186.59 MPa), that is an average value of

1960.35 MPa. Compared to other plants, this fiber has a higher tensile strength than hemp fibers (70 MPa); ramie fibers (400-938 MPa); kenaf fibers (930 MPa) [34].

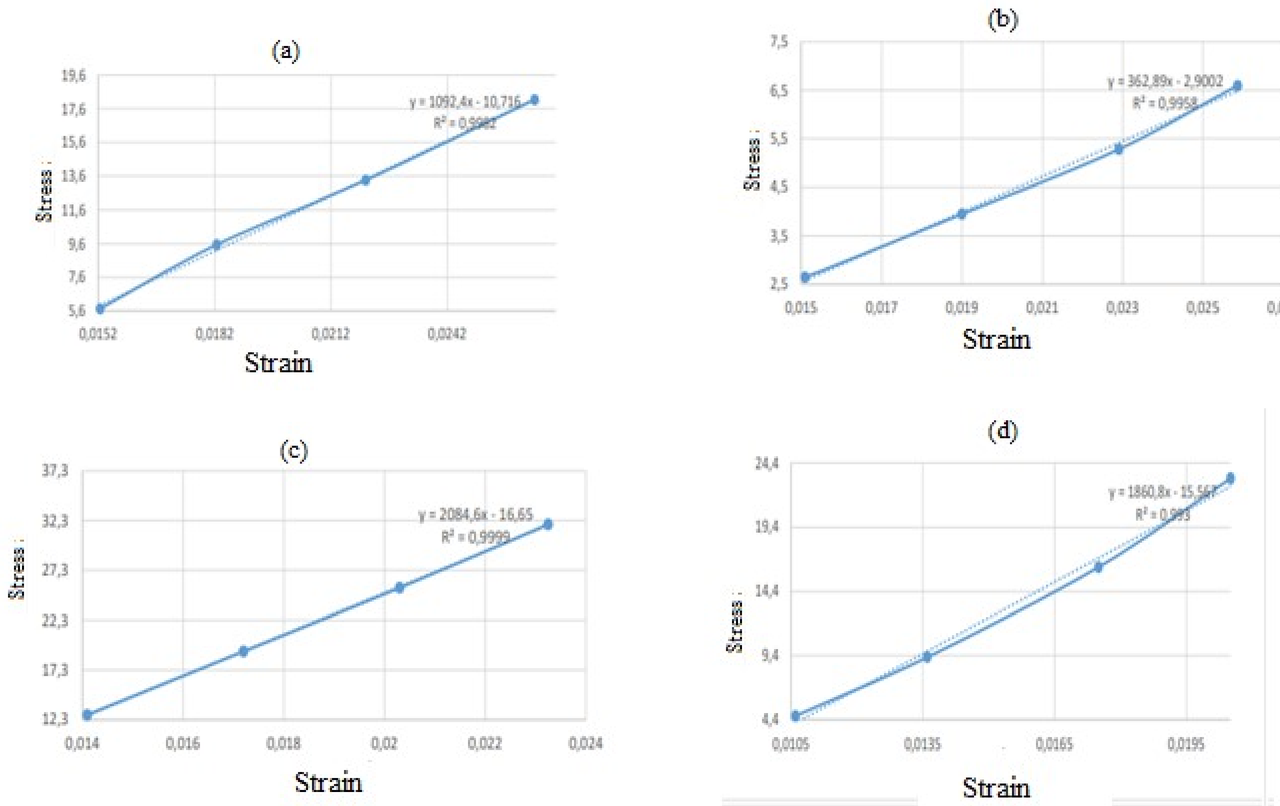


Figure 15. Curves of stress as a function of strain of the stem fibers. **(a)** Sample 1; **(b)** Sample 2; **(c)** Sample 3; **(d)** Sample 4.

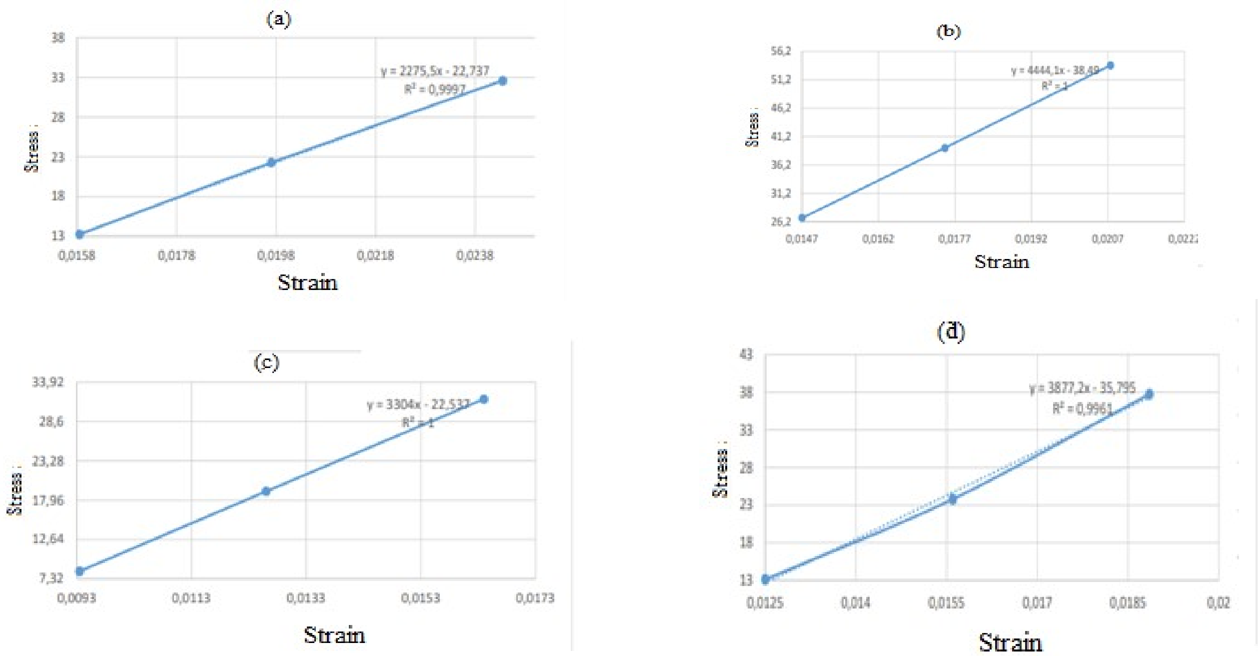


Figure 16. Curves of stress as a function of deformation of the root fibers. **(a)** Sample 1; **(b)** Sample 2; **(c)** Sample 3; **(d)** Sample 4.

Table 9. Mechanical properties of stem and root fibers.

Samples	Elongation (mm)		Stress (MPa)		E (MPa)	
	Stem	Root	Stem	Root	Stem	Root
S1	0.4355	1.1383	490.781	545.3874	2275.5	1092.4
S2	0.96435	1.76475	2212.9459	217.3954	4444.1	362.89
S3	0.2064	1.2692	181.4381	889.6399	3304	2084.6
S4	1.1384	6.335	2462.54	4104.817	3877.2	1860.8
S5	0.4015	4.6257	1005.3991	3340.078	7452.2	1720.8
S6	0.6398	5.7101	2132.2245	2215.853	7149.6	1416.3
S7	0.20255	3.2855	33.9491	2182.022	6447.9	1517.5
S8	0.7569	3.8625	1589.6046	2980.127	3031.5	2020.9
S9	0.37285	1.5984	449.4077	1280.64	1922.6	1111.8
S10	0.4281	8.27145	530.542	4624.984	285.2	2005.6
S11	0.5677	0.8346	1099.092	664.299	3532.2	1525.6
S12	0.7553	1.296	1400.4883	1651.854	3798.8	2412.7
S13	0.8566	3.3486	2182.5235	1705.646	6926.1	1200
S14	0.2295	4.07215	428.0883	1788.427	6417.6	1693
S15	1.0565	1.5333	1612.7337	766.9272	3104.9	1084.2
S16	0.6598	3.7796	985.8985	5444.299	2910.5	3470
S17	0.8153	2.6014	117.7384	1551.822	1862	1306.3
S18	1.2495	2.2255	1975.0753	1430.602	2961.7	1210
S19	0.39955	2.6358	221.2801	1352.834	955.29	1399.9
S20	0.74665	2.6615	1415.1948	1276.497	1925.4	472.41
S21	0.2805	1.7229	313.3079	1453.344	3525.5	2087.9
S22	0.8881	1.0687	4102.5471	1239.934	8761.7	1086.9
S23	1.35235	1.3147	167.9833	947.4119	1024	1971.9
S24	0.17665	6.98055	399.92	4227.628	7526.3	1433
S25	0.92685	1.7909	800.2079	1126.327	2074.06	1448.7

Elongation at break

On average, we obtained an elongation of around 16.17% for the stem fibers, which indicates a lower capacity to deform before breaking. Compared to other plants, stem fibers have a higher elongation than sugar cane bagasse fibers (5.5%), and pineapple fibers (14.5%) [35]. On the other hand, the fibers of the roots have an elongation of an average value of 60.6%; this value is higher than that of the fibers of the stems, which means that they are more ductile and can deform more before breaking up. This can be advantageous in certain applications such as textiles. Compared to other plants, root fibers have a higher elongation than coconut fibers (15–40%), date palm fibers (2–19%).

4. Conclusion

In this work, we examined the extraction and physico-mechanical characterization of fibers from the stems and roots of the PP plant with the aim of evaluating the possibility of using them as stabilizers in compressed earth bricks. This plant with ecological, economic and social virtues opens the way to new and very interesting applications. Based on the literature and the work carried out on this plant, our plant was harvested in West Cameroon, more precisely in Batié in the high plateau division. We first presented the different materials and methods used during the works, so we extracted the fibers using the boiling water method. This extraction method was used because of the advantages it provides, such as the relatively short time required for the extraction; there is no risk of pollution or infection and the process is hygienic. Once the fibers were extracted, they were treated with a 10% sodium hydroxide (NaOH) solution. Then the physico-mechanical characterization of the fibers was subsequently carried out from the stems and roots of the PP through, among which the determination of the absolute density according to the NF EN 1097-6 standard, the linear mass according to the ISO 1973 standard 2021 editions, the apparent density according to the NF EN 1097-3 standard, August 1998 edition, the water content according to the ISO 3344: 1997 standard, the water absorption rate according to the NF EN 1097-6 standard, the diameter under the microscope according to the ISO 137 standard and finally the determination of their mechanical properties (Young's modulus, tensile strength, etc.).

As results, the fibers of the stems have an absolute density of 1.35 g/cm^3, a linear mass of 54.6 tex, an apparent density of 0.451 g/cm^3, a content of water of 12.73%, an absorption rate of 142.46%, to determine the diameter of these fibers we proceeded by three steps. We first took the average of all our samples and obtained a value of 7.20 mm, secondly, we determined the frequency of appearance for each sample based on the diameter of our fibers and obtained a diameter of 6.69 mm, and thirdly we proceeded by the method of statistical analysis using the principle of maximum entropy thus obtaining a value of 7 mm. Finally, we obtained an elastic modulus of 3.98 GPa, a tensile strength of a value of 1186.59 MPa and an elongation of 16.17%.

While for the root fibers we obtained an absolute density of 1.34 g/cm^3, a linear mass of 16.76 tex, an apparent density of 0.378 g/cm^3, a water content of 12.25%, a absorption rate of 193.16%, a diameter of 4.69 mm by the average, 3.91 mm by the probability of appearing of each sample, and 4 mm, using the statistical analysis method via the maximum entropy principle. At the end we obtained an elastic modulus with a value of 1.55 GPa, a tensile strength with a value of 1960.35 MPa, and an elongation of 60.6%. From this study we can conclude that the fibers from stems are more suitable for industrial applications, since they have the greatest elastic modulus, and thus they are more resistant and thus suitable for compressed earth brick manufaturing. However, root fibers are lighter and are therefore more important for applications not requiring significant mass change, such as in the textile industries.

These fibers can also be used for several purposes, including the manufacture of absorbent materials such as sanitary paper and napkins, the manufacture of composite materials.

For future works, it would be interesting to:

- Determine the chemical and thermal properties of PP fibers, to have more information on this fiber.
- Incorporate the stem fibers with well-determined proportions into the CEBs with the aim of determining their behavior as a reinforcing material.

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Conflict of interest: The authors declare no conflict of interest.

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