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Study of the Physical and Chemical Properties of Banana Peduncle Fibers of the Cultivar "William Cavendish": Influence of Extraction Techniques

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Highlights

What are the main findings?

- The fibres of the William banana peduncle are extracted by three methods and chemical analysis by Van Soest's dry biomass fractionation method has shown that its fibers have a cellulose content of over 70%.
- Thermogravimetric analysis shows that banana peduncle fibers are thermally stable at 82 °C, and X-ray diffraction reveals a crystallinity rate of over 50%.

What is the implication of the main finding?

- The method of extracting fibers from dew is advantageous and economical; chemical analysis results show that WBPF is a good candidate for the production of non-woven fabrics.
- In the case of textiles developed from banana peduncle fibers, they can be used in applications that can withstand temperatures of around 80 °C without damage and crystallinity levels predispose the fibers to better mechanical properties.

Abstract

This study deals with the physical, chemical, and thermal properties of William banana peduncle fibers in order to consider the possibility of using these new fibers in textile applications. The samples were collected in Cameroon, in the Littoral region, Njombe Penja district (agri-food industry). The fibers were extracted by three methods, including Water Retting (WR), Dew Retting (DR), and Mechanical Extraction (ME). The various resulting fibers were characterized by X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), Fourier-Transform Infrared Spectroscopy (FT-IR) and Scanning Electron Microscopy (SEM),

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respectively. The FTIR analysis confirmed the lignocellulosic structure of the fibers and revealed that the three extraction methods had not affected the chemical nature of the fibers. The extraction methods also had no significant impact on density and moisture content. Scanning electron microscopy showed bands of fibers bundles on all samples. Thermogravimetric analysis (TGA) showed that the fibers extracted were thermally stable at 82 °C. X-ray diffraction (XRD) analysis showed crystallinity levels ranging from 58.24% for (WR), 54.83% for (DR), and 69.53% for (ME). The results obtained on the chemical composition show that the extracted fibers consist mainly of 71.8%, 73.6%, and 74.8% cellulose for WR, DR, and ME, respectively, making them suitable for textile applications.

Keywords: William banana peduncle fiber; physical analysis; chemical analysis

1. Introduction

Tropical and sub-tropical countries grow bananas in large quantities. Approximately 13% of the weight of the banana bunch harvested represents waste (peduncle, pseudo-stem, and leaves), which is generally thrown away or incinerated [1]. The banana plant is a monocotyledonous plant belonging to the Musaceae family (order *Zingiberales*), of which nearly 70 species have been discovered [2]. Subsistence varieties are derived from the hybridization of *Musa acuminata (AA)* and *Musa balbisiana (BB)* [3]. The banana itself is one of the most popular fruits and one of the most important in diets due to its high nutrient content [4]. It is considered to be the third most consumed food [5]. Dessert bananas, marketed worldwide, are almost all hybrids of *Musa acuminata* with a triploid character, called AAA [6]. Plantain bananas (Musa AAB) and other bananas that can be used for cooking (Musa ABB) are also triploid and come from AA-B hybridization [5,7].

In Africa, Cameroon ranks 6th among banana-producing countries. According to the Cameroon Banana Association (ASSOBACAM), Cameroon exported 216,103 tons of dessert bananas from MBÔH Plantation Limited (BPL), Haut Penja Plantations (PHP), and Cameroon Development Corporation (CDC), all of the Grande Nain or William varieties. Figure 1 shows the different dessert banana harvesting sectors.

The peduncle is the part of the banana plant that supports the inflorescence and links it to the rhizomes and fruit. The work of Kamdem et al. [8] showed that the 'Williams Cavendish' cultivar is taller, more robust, and produces more waste. Numerous works in the literature show that fibers can be extracted from banana peduncles by biological, chemical, and mechanical retting. For example, the work of the authors of [9–11] on water-extracted banana peduncle fibers showed cellulose contents of 73.20%, 66.43%, and 72.90%, hemicellulose contents of 10.85%, 13.72%, and 11.01%, lignin contents of 15.32%, 16.85%, and 15.11%, moisture contents of 9.01%, 12.05%, 93.6%, and densities of 972 kg/m^3, 942 kg/m^3, and 990 kg/m^3. The work of Pitchayya et al. [12] on banana peduncle fibers extracted manually and then with water showed a cellulose content of 79.13%, a lignin content of 12.3%, a moisture content of 7.51%, and a density of 0.85 kg/m^3. The work of Pretti et al. [13] studied the physical and chemical properties of mechanically extracted fibers from the Grande Nain, Poovan, Monthan, and Nendran cultivars, revealing that the cellulose content of the Nendran cultivar was 60.41% higher, the hemicellulose content 10.20% higher, and the lignin content 17.56% higher. Zara et al. [14] worked on the analysis of certain textile properties of plantain stalk fibers and their results showed a fiber moisture content in the range 1.56–11.24%. Overall, the work presented in the literature on banana peduncle fibers shows interesting physical and chemical properties. Nevertheless, retting with water causes water pollution, a foul odor, and the development of microorganisms

that can degrade the fibers and consequently influence their properties [15]. In addition, chemical extraction is energy-intensive and requires the use of chemical products, making it expensive to obtain the fibers [12]. In addition, some authors carry out post-treatment of these fibers with a view to improving their properties [12]. To our knowledge, very few authors have conducted studies on the extraction of banana peduncle fibers using dew extraction. It seems interesting to apply this extraction technique to assess its effect on the properties of the fibers and compare it with other extraction methods. The objective of this study is to investigate the effect of tree extraction methods on the chemical properties of William banana peduncle fibers.

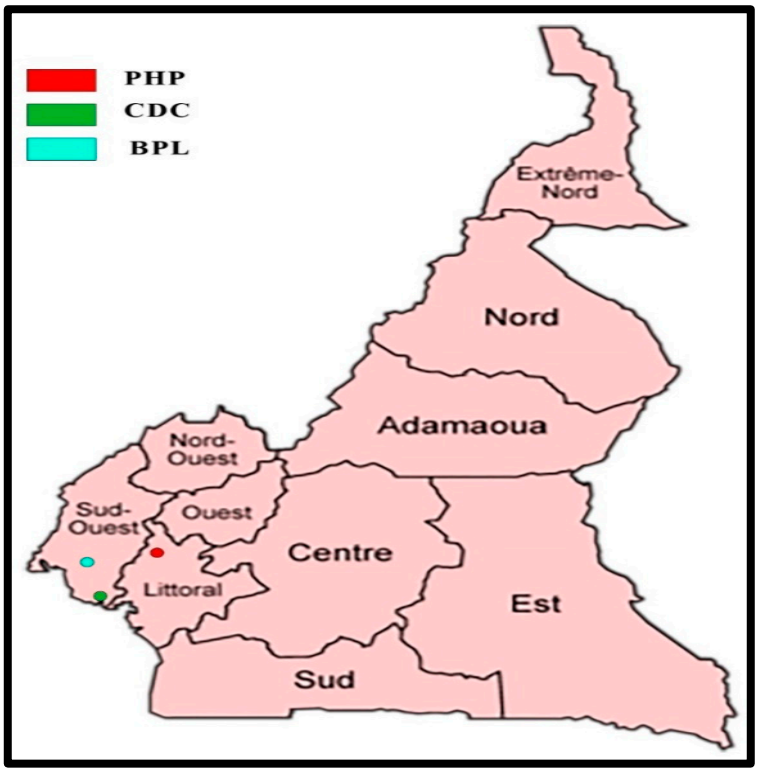


Figure 1. Main banana production sectors in Cameroon.

The physical–chemical and thermal properties of William banana peduncle fibers extracted by water retting, in dew, and by rolling will therefore be assessed. Physical–chemical characterization such as density, moisture content, chemical composition, Fourier-transform infrared spectroscopy (FT-IR), X-ray diffraction, and thermogravimetric analysis (TGA) of William banana peduncle fibers obtained by the three methods will be evaluated and compared with those of other plant fibers studied in the literature.

2. Materials and Methods

2.1. Origin of Samples

The William banana peduncle fiber is collected in the Littoral region, Mungo Department, and Njombe Penja Arrondissement, more specifically in the Kumbe sector of the PHP company, an agri-food industry located in Cameroon.

Banana peduncles were collected during the rainy season (from July to September). They are obtained after cutting the bunch from the mature pseudo stem (approximately 6 months old). Once the stems have been separated from the bunch, they are collected and stored in the laboratory (at approximately 27 °C) for water retting and mechanical

extraction. Another peduncle is left on the banks of a watercourse not far from the collection area for dew extraction.

2.2. Methods for Extracting Fibers from the Peduncle of William Banana (WBPF)

The William banana peduncle was cleaned with a knife to remove the green skin, regardless of the extraction method used. The following three fibers extraction methods were considered: water-retted, dew-retted, and laminated. The following codification (Table 1) was adopted for the different extraction processes.

Table 1. Coding of WBPF.

Code	Meanings
WR	Water retting
DR	Dew retting
ME	Mechanical extraction

The methods for extracting fibers from the William banana peduncle mentioned above have been described in previous work by (Anafack et al. 2023) [16] and are in agreement with many works in the literature [17–20].

2.3. Physical–Chemical Characterization of William Peduncle Fibers

The various fibers obtained underwent physical and chemical characterization, including chemical composition, scanning electron microscopy, moisture content, density, thermogravimetric analysis, X-ray diffraction, and Fourier-transform infrared spectroscopy to determine the lignocellulosic content, morphology, moisture absorption, crystalline phases, and functional groups of the fibers, respectively.

2.3.1. Study of the Chemical Composition of the Fiber

Van Soest's dry biomass fractionation method [21–23] was used in this work to determine the percentage of cellulose, hemicellulose, and lignin in accordance with the French standard XP U44-162. Before testing the sample must be in powder form; to achieve this, the fibers were dried at 105 °C for 24 h in an oven, then cut, crushed, and sieved to obtain a very fine powder [21]. The constituents are determined sequentially by treatment with neutral detergent, acid, and sulfuric acid.

Figure 2 shows the principle of this method, which is carried out in four stages, with different experimental conditions for each stage.

2.3.2. Scanning Electron Microscopy (SEM) Study of Extracted Fibers

The fibers were observed using a scanning electron microscope (JOEL JSM-IT100) at magnifications of ×200, ×300, and ×500. Five fibers samples were pre-coated with a gold film to make them conductive. The fibers samples were analyzed at different acceleration voltages between 15 and 20 kV.

2.3.3. Study of the Density and Moisture Content of WBPF

Fiber density is determined by using a pycnometer and the successive weighing method in accordance with ASTM D3800-99 (2010) and with a methanol solution. The fiber bundles are first introduced into desiccators filled with silica cells to remove the residual water present in the fiber bundles [9]. An analytical balance with a resolution of 0.001 g was used for this purpose. The density is calculated by Equation (1) as follows:

$$\rho_{(g|cm^3)} = \frac{(m_2 - m_1)}{(m_4 - m_1) - (m_3 - m_2)} \times \rho_m \quad (1)$$

where ρ_m is the density of methanol (0.791 g/cm^3), m_1 is the mass of the dried fiber sample, m_2 is the mass of the empty pycnometer, m_3 is the mass of the pycnometer containing methanol up to the lower meniscus of the gauge point, and m_4 is the mass of the pycnometer containing methanol and dried fibers.

The test took place in an environment with a temperature of 25 °C ± 2 °C with 65% ± 2% relative humidity. The fibers previously dried for 24 h in the oven at a temperature of 105 °C were tied into small bundles of about 0.5 g (±0.05) constant mass, as mentioned in the work of Ebanda et al. [24] and Athalie et al. [25]. These authors specify that in a jar saturated with sodium chloride (NaCl), the relative humidity is approximately 75% [26]. The moisture uptake (M_h) of banana peduncle fibers is determined by Equation (2), which is as follows:

$$M_C(\%) = \frac{M_f - M_i}{Mi} \times 100 \quad (2)$$

where

$M_C(\%)$: Moisture absorption in %;
Mi: Initial mass in the anhydrous state;
Mf: Final mass.

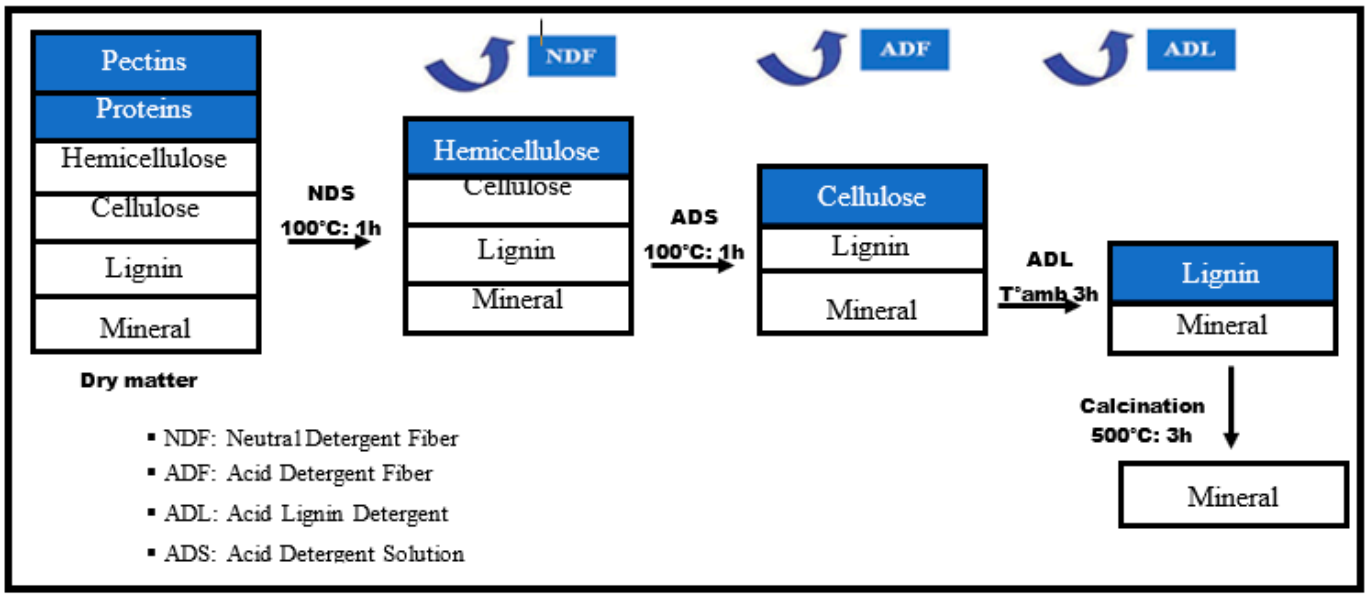


Figure 2. Schematic diagram of the fractionation of lignocellulosic biomass [21].

2.3.4. Thermogravimetric Analysis (TGA)

A NETZSCH STA 449F3 thermogravimetric analyzer (TGA) was used. A 100 mg sample was placed in an aluminum crucible and then introduced into the apparatus. The sample was subjected to a temperature rise from 20 to 900 °C, while maintaining a constant heating rate of 5 °C/min and an isotherm at 900 °C for 30 min in air. The device provides mass loss as a function of temperature.

2.3.5. X-Ray Diffraction (XRD) Study

The material analyzed was finely ground, homogenized, and then oven dried at 60 °C for 6 h. X-ray diffraction patterns of the fibers were recorded by X-ray diffractometry. An Empyrean diffractometer with radiation (CuKα = 1.5418 Å) was used. An angle interval of 2θ from 4° to 75° was scanned with a step size of 0.026261 at 8.67 s using a graphite monochromator, a voltage of 45 kV, and a current of 40 mA. The crystallinity ratio of the

William banana peduncle fibers was obtained as shown in Equation (3) [27], which is as follows:

$$I_C(\%) = \frac{A_{Cr}}{A_{C_r} + A_{am}} \times 100 \quad (3)$$

where I_C % is the crystallinity index, A_{am} is the area of the amorphous phase, and A_{cr} is the area of the crystalline phase.

2.3.6. Study Using Fourier-Transform Infrared Spectroscopy (FTIR)

The functional groups present in the banana stem fibers were analyzed using a BRUKER IR spectrometer. A mass of 2 mg of fine powder from the banana peduncle fibers extracted by the three methods was introduced into the diamond/ZnSe crystal and a manual force of approximately 150 N was exerted on the sample to ensure contact. The sample was scanned 5 times, and each spectrum was obtained after 32 scans at a resolution of between 4000 cm^{-1} and 500 cm^{-1} [28,29].

3. Results and Discussion

3.1. Study of Fiber Morphology

The fibers of the William banana peduncle were observed using a scanning electron microscope (SEM). Five fibers for each extraction method were observed using a scanning electron microscope (SEM), and the images are shown in Figure 3.

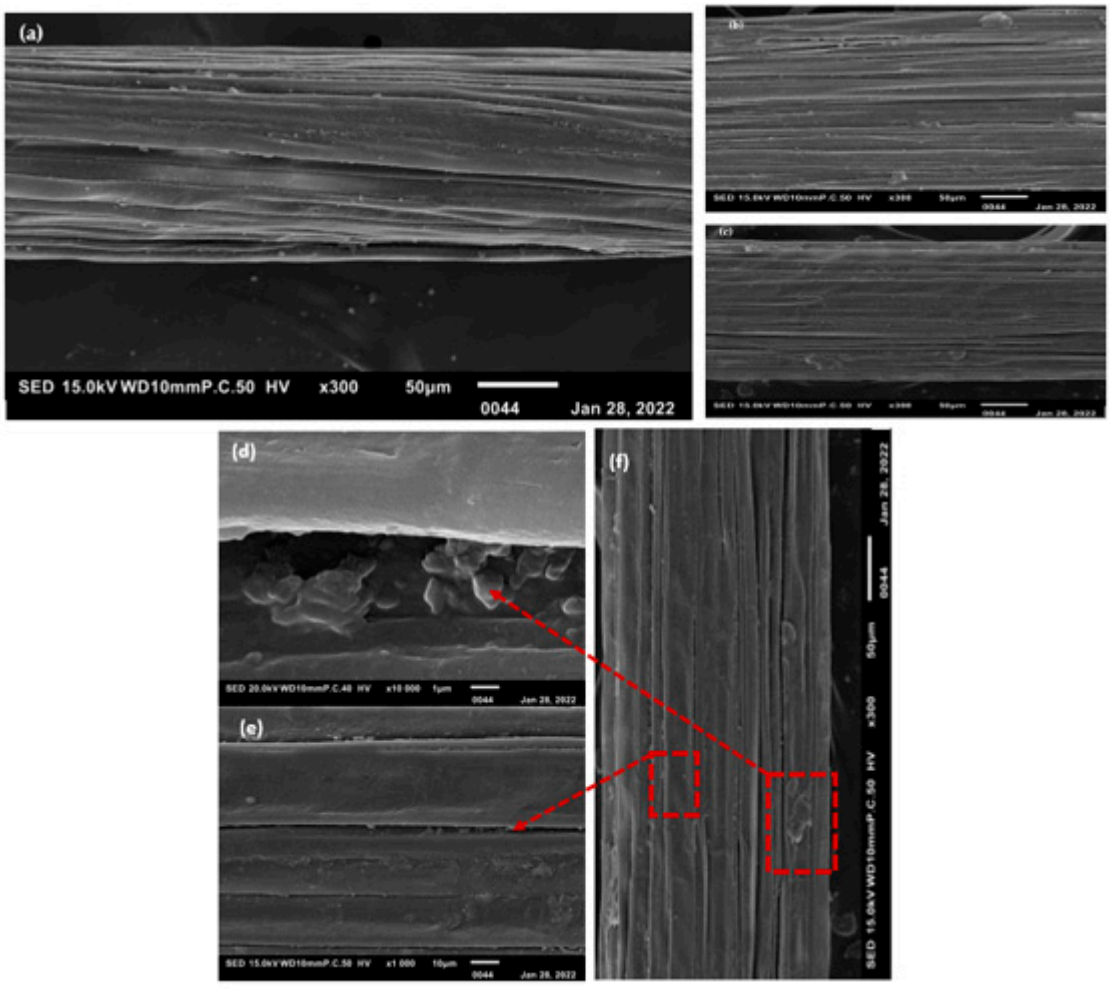


Figure 3. SEM images of longitudinal views of three extraction methods: (**a**) WR; (**b**) DR; (**c**) ME; (**d**) pectins; (**e**) bundle banana; and (**f**) expansion of fibers [16].

This figure shows that fibers extracted by rolling still contain impurities (pectins), unlike fibers extracted by retting, which are visibly smooth. [10]. The final fibers are more visible due to the retting action on the pectins that bind the fibers together (Figure 3b). We can see that the longitudinal structure is in the form of small flat ribbons, whatever the extraction method (Figure 3a).

3.2. Analysis of the Chemical Composition, Density, and Moisture Content of WBPF

The density, moisture content, and chemical composition of William banana peduncle fibers were determined and the results obtained are presented in Table 2. This table shows that the average density of the fibers studied is almost identical (0.934 g/cm^3), which is much lower than the fibers found in the work of Baley et al. [30] for which they had obtained densities of the order of 2.6 g/cm^3, 0.89 g/m^3, 0.97 g/m^3, 1.30 g/m^3, 1.45 g/m^3, and 0.942 g/m^3, respectively, for the fibers of Nendran banana peduncle, flax, jute, alfa, and the fibers of *Musa* acuminata peduncle [10,29,30]. The low density from the William banana peduncle fiber (WBPF) predisposes the fiber for industrial use as a reinforcement for bio-sourced composites. Additional contributions could improve the adhesion properties and make the fiber lightweight, improving its lightness properties [31].

Table 2. Comparison of the physical–chemical properties of William banana peduncle fibers with other natural fibers found in the literature.

Fibers	Extraction Methods	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Density $(g/cm)^3$	Moisture Content (%)	Ref
Hemp	Water retting	72	10	3.0	0.86	ND	[31,32]
Flax	Water retting	79	11	3.0	1.30	ND	[31,32]
Jute	Water retting	59–71	12–13	11.8–12.9	1.45	ND	[31,32]
Sisal	Water retting	60–67	10–15	8–12	1.26–1.33	ND	[31,32]
Ramie	Water retting	68.6–91	5–16.7	0.6–0.7	ND	ND	[31,32]
Kenaf	Water retting	44–57	21	15–19	ND	ND	[31,32]
Nendran banana	Water retting	73.20	10.85	15.32	0.97	9.01	[9]
Nain banana	Mechanical extraction	48.31	13.99	19.87	ND	ND	[13]
Poovan banana	Mechanical extraction	56.24	14.89	19.17	ND	ND	[13]
Monthan banana	Mechanical extraction	49.65	15.75	20.66	ND	ND	[13]
Nendran banana	Mechanical extraction	60.41	10.20	17.56	ND	ND	[13]
Musa acuminata	Water retting	66.43	13.72	16.85	0.942	12.05	[10]
Red banana	Water retting	73.20	11.01	15.11	0.99	9.36	[11]
Red banana	Chemical extraction	79.13	ND	12.3	0.85	7.51	[12]
Careya arborea treeJeevan	Retting extraction	71.8	21.86	14.95	1.40	ND	[33]
Abyssinia banana	Retting extraction	52.14	12.91	9.10	ND	ND	[34]
William banana peduncle	Water retting	71.8	14.6	8.6	0.933	9.62	This work
	Dew retting	73.6	12.8	5.7	0.938	6.66	This work
	Mechanical extraction	74.8	12.8	7.1	0.933	8.10	This work

ND: Not available.

With regard to the moisture content of extracted fibers, the moisture content of water-retted and laminated fibers was similar (9.62% and 8.10%, respectively), while the moisture

content of dew-retted fibers was low (6.66%). This may be due to the weather conditions and the colonization of the fibers by fungi during the retting process. This low moisture content of dew-retted fibers seems to be of interest for textile applications. The quantity of water present in the fibers of the William banana peduncle extracted by the three methods was confirmed by thermogravimetric analysis. A comparison of the moisture content of the dew-retted fibers with the moisture content of natural fibers in the literature shows that they are lower than the fibers from Nendran (9.01%), *Musa acuminata* (12.05%), and *Red banana* (9.36%). Comparing the chemical composition of the extracted fibers, it was found that their chemical nature (cellulose, hemicellulose, and lignin) was not affected by the different methods. However, the extraction methods had a significant effect on the lignin content of the WBPF. Water-retted fibers have a higher lignin content (8.6%) compared with the lignin content of dew-retted fibers (5.7%). The work of Praveen et al. [10] has shown that such a high lignin content protects the fibers against biological attack (bacteria and fungi). Compared to the three extraction methods, the cellulose content of the first two, ME and DR (74.8% and 73.6%), appears to be identical. According to the work of Yogesha et al. [32], this increase predisposes the fibers to better mechanical properties. However, water extraction gives a slightly lower result. Nevertheless, regardless of the extraction method, it can be noted that these fibers have a high cellulose content compared to certain natural fibers found in the literature, in particular Musa acuminata fibers (66.43%), Nendran fibers (60.41%), Poovan banana fibers (56.24%), and Abyssinia banana fibers (52.14%) [10,13,31,32]. In terms of chemical composition, it can be concluded that all fibers extracted by the three methods are very good candidates for use in various industrial applications, particularly in the textile industry.

3.3. Analysis by Fourier-Transform Infrared Spectrometry (FTIR)

Figure 4 and Table 3 show, respectively, the spectra and FTIR vibration bands of William banana peduncle fibers obtained by three methods, identifying the functional groups present in the molecular structure of the fibers. From the spectra of WR, DR, and ME fibers, the vibration bands observed around 3320 cm^{-1} are attributable to OH stretches of α-cellulose and the hydrogen-bonded cellulose structure [33]. Those located at 2898 cm^{-1} correspond to the C-H stretching of CH and CH_2 cellulose and hemicellulose in fibers [29,34]. The peaks also observed at 1629 cm^{-1} are attributable to stretching of $C = O$ of the amides present in lignin and hemicellulose. Finally, the peaks located at 1030 cm^{-1} are attributed to C-OH stretching of lignin [35]. This result confirms the lignocellulosic structure of WR, DR, and ME fibers and also correlates with their chemical composition. In addition, the extraction methods do not affect the chemical composition of the extracted fibers.

Table 3. FT-IR peak positions and chemical functional groups of William banana peduncle fibers.

Position of Peaks $(cm)^{-1}$	Functional Group	Chemical Composition	References
3320	O-H stretching	Cellulose	[33,36,37]
2898	Asymmetric stretching C-H and CH_2	Cellulose and hemicellulose	[9,29,34]
1629	Symmetrical stretching $C = O$	Lignin and hemicellulose	[9,35]
1030	C-OH stretching	Lignin	[9,35,37]

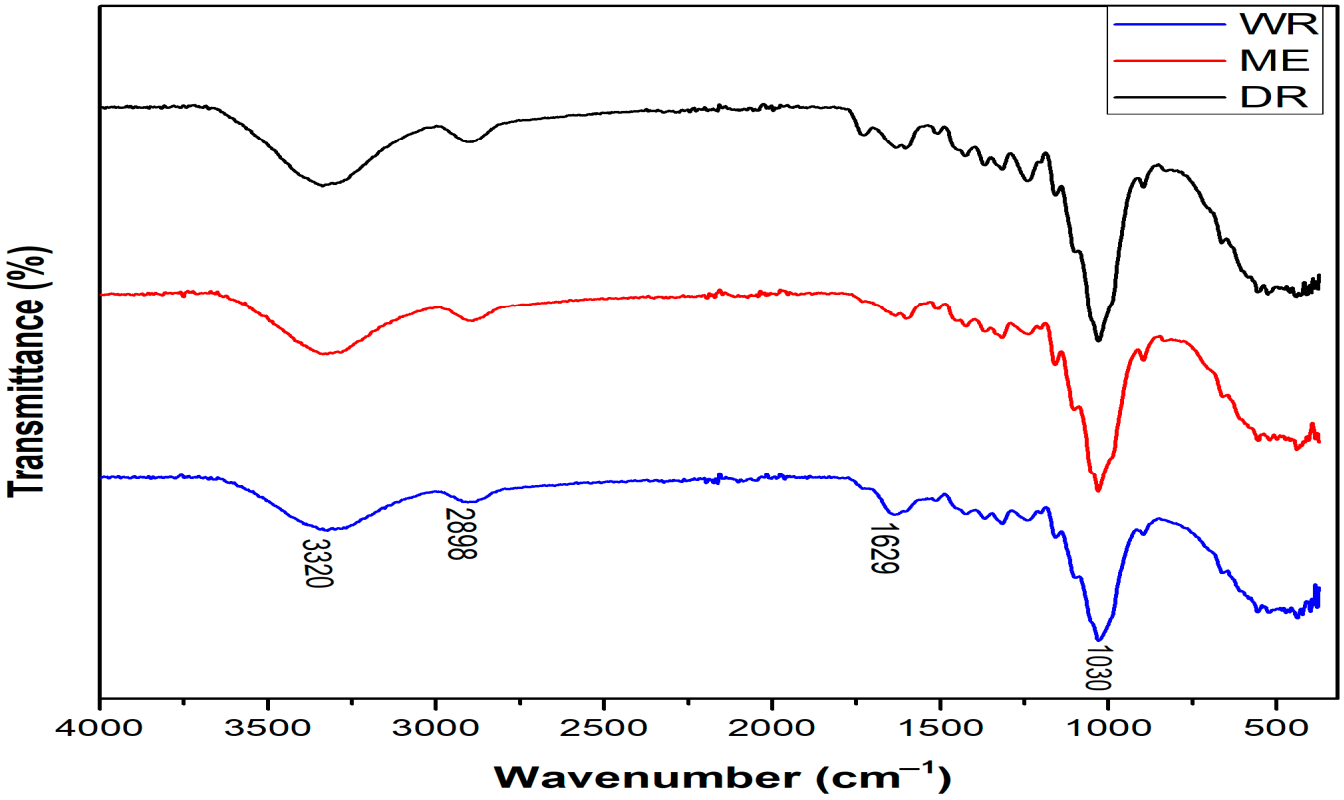


Figure 4. FTIR spectrum of WR, DR, and ME extracted from William banana peduncle fibers.

3.4. Thermogravimetric Analysis (ATG)

The combined thermograms (ATGs) of William banana peduncle fibers extracted by water retting, in the dew, and by rolling are shown in Figure 5. According to the various thermograms obtained (Figure 5), degradation occurred in the following three stages: The first stage of moisture evaporation takes place at 82 °C for water retting fibers, at 76 °C for dew retting fiber, and at 66 °C for fibers extracted by rolling. These degradations are due to the vaporization of moisture and the elimination of moisture from the fiber [38], which are (9.66%) for water retting fibers, (6.68%) for dew retting fibers, and (8.15%) for fibers extracted by rolling.

The second stage of degradation, which occurs at around 301 °C for water retting fibers, 319 °C for dew retting fibers, and 316 °C for fibers extracted by lamination, marks the decomposition of cellulose and hemicellulose. [39]. Mass losses of 74.51%, 49.97%, and 70.76% were recorded for water retting fibers, dew retting fibers, and fibers extracted by lamination, respectively. The final phase of cellulose degradation occurs from the temperature ranges of 426 °C for water retting fibers, 439 °C for dew retting fibers, and 457 °C for fibers extracted by lamination, with respective mass losses of (12.90%), (19.96%), and (4.80%) which corresponds to the degradation of wax as well as lignin and which leaves ash as residue [39]. Table 4 shows the thermal degradation values for the extracted fibers. These different interpretations correlate with the results of the chemical composition and FTIR analysis and show that fabrics made from William banana peduncle fibers can be ironed at temperatures of up to 82 °C.

Table 4. Thermal degradation values of William banana peduncle fibers.

Extraction Methods	Dégradation Température (°C)		
	1ère Phase	2ème Phase	3ème Phase
WR	[82 (9.66%)]	[301 (74.51%)]	[426 (12.90%)]
DR	[76 (6.68%)]	[319 (49.97%)]	[439 (19.96%)]
ME	[66 (8.15%)]	[316 (70.76%)]	[457 (4.80%)]

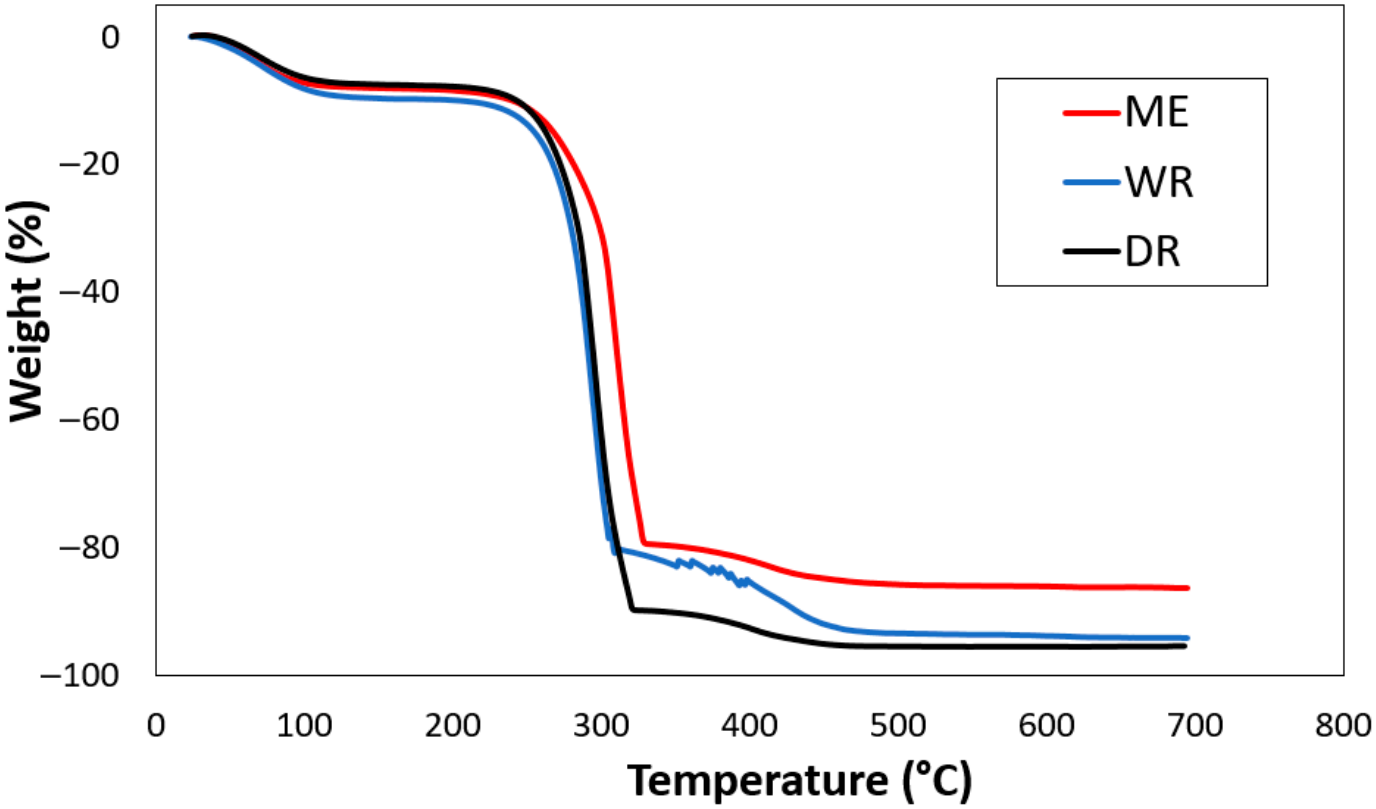


Figure 5. Thermogram of extracted by WR, DR, and ME fibers.

3.5. X-Ray Diffraction Analysis

Figure 6 shows the diffractograms of the fibers extracted by the three methods. The first peaks observed at around 2θ = 16.09° correspond to the different amorphous fractions. On the other hand, the second peaks observed at around 2θ = 22.67° correspond to the crystallographic planes of the cellulose. These results are similar to those found by Belouadah et al. [40] and Dallel [41].

A comparison of the crystallinity index values for William banana peduncle fibers with those in the literature (Table 5) shows that the crystallinity index for dew retting fibers is higher (54.83%) than for Nendran peduncle fibers (53.30%) and Musa acuminata peduncle fibers (36.47%). The value of the crystallinity index of the fibers extracted by lamination is more significant (69.53%) than those obtained with water and dew retting fibers (58.24 and 54.83%, respectively), which is in line with the results of the chemical composition of the fibers. Furthermore, according to the literature, its crystallinity rates predispose William banana peduncle fibers to better mechanical properties [42]. This is also confirmed in previous work by Anafack et al. (2023) [16].

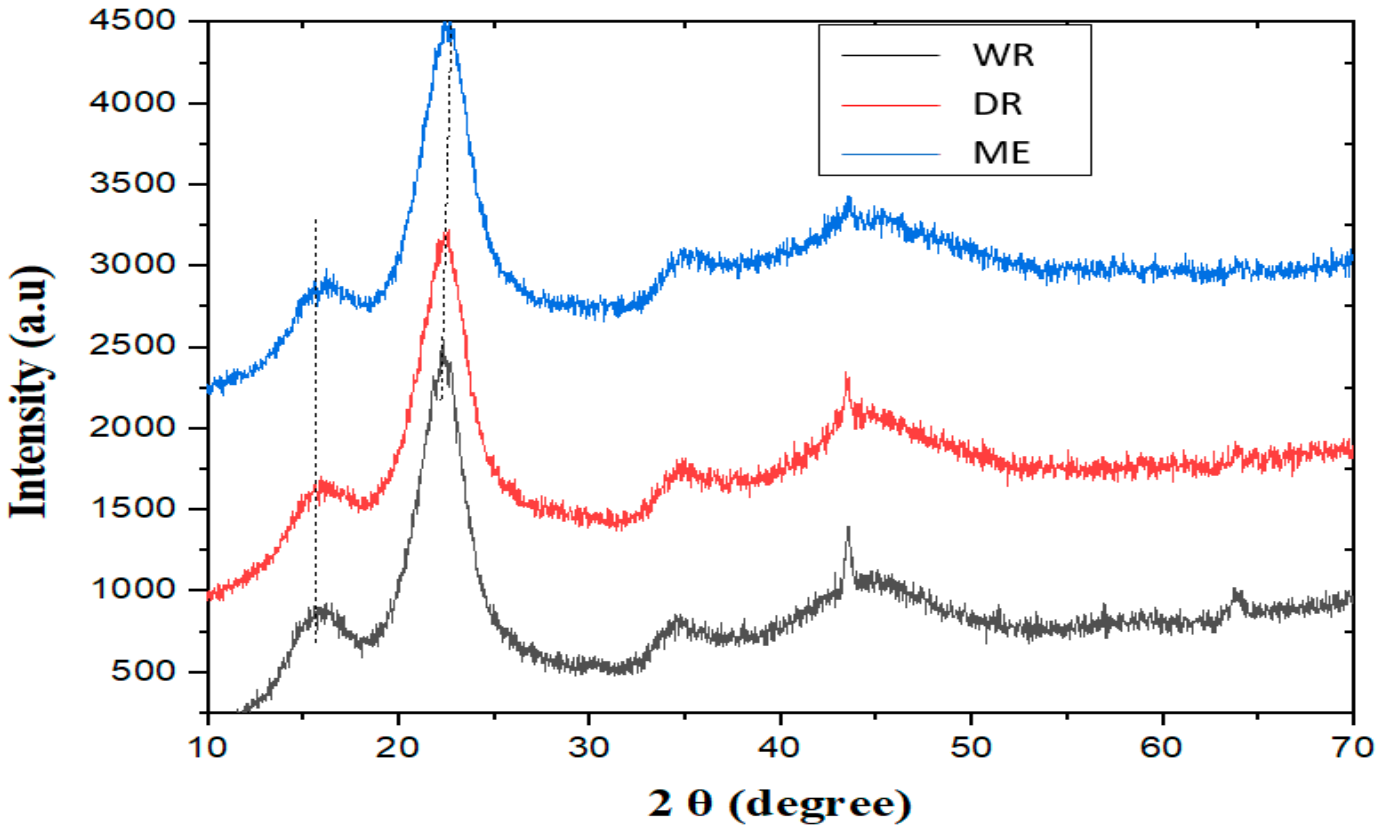


Figure 6. X-ray diffractograms of William banana peduncle fibers.

Table 5. Comparison of the crystallinity indices of William peduncle fibers with those found in the literature.

Natural Fibers	Amorphous Fractions at 2θ	Crystalline Fractions at 2θ	Crystallinity Index (%)	Reference
Nendran banana	15.34	24.16	53.30	[9]
Red banana	15.92	22.17	62.1	[11]
Musa acuminata banana	14.93	21.89	36.47	[10]
Red banana-treated	14.52	24.15	64.57	[12]
Linen	18	22	70	[42]
Ramie	18	22	58	[42]
Sisal	18	26	75	[42]
Hemp	16.6	22	87.9	[42]
Jute	18.5	22.5	58.90	[42]
WR	16.09	22.67	58.24	This work
DR	16.09	22.67	54.83	This work
ME	16.09	22.67	69.53	This work

4. Conclusions

This study focused on the physical, chemical, and thermal properties of William banana peduncle fibers, with a view to their use in textile applications. The samples were collected and extracted biologically (WR and DR) and mechanically (ME). The analysis of the physical characterization shows that the densities of the WBPF are almost the same, at around 0.93%, and that the moisture content of the WR is 9.62%, 6.66% for DR, and 8.1% for ME.

Analysis of the chemical composition shows that the fibers of the William banana peduncle are sufficiently rich in cellulose, with contents in the order of 71.8%, 73.6% and 74.8% for WR, DR, and ME, respectively. Scanning electron microscopy showed flat fibers bundles regardless of the extraction method used. FTIR analysis confirmed the lignocellulosic structure of the fibers and revealed that the three extraction methods had not affected the chemical nature of the fibers. TGA showed thermal stability at around 82 °C. This also indicates that the extracted fibers can be used in the design of clothing with a maximum ironing temperature of 82°C. XRD analysis shows that the crystallinity rates of WBPF are approximately 58.24%, 54.83%, and 69.53% for WR, DR, and ME, respectively. These crystallinity rates predispose William banana peduncle fibers to better mechanical properties. A comparison of the dew extraction method with other methods commonly used in the literature shows that it is cost-effective and economical (because it requires little water and does not require the use of containers), and that the fibers obtained are promising candidates for the textile industry. We suggest that future researchers focus on developing these fibers for use in nonwoven production given the cellulose content obtained.

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