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Research Article

Extraction and Physicochemical and Thermomechanical Characterizations of Water Hyacinth Fibers *Eichhornia crassipes*

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The presence of floating plants is becoming an uncontrollable issue on the banks of Douala, Cameroon, notably in the city of Bonaberi, where the water hyacinth is expanding incredibly quickly. The aim of this study is to evaluate the mechanical and physicochemical performance of water hyacinth fibers for pulp manufacture. To this end, tensile tests on fiber bundles in accordance with ISO 13934-1:2013, thermogravimetric analysis (TGA), chemical composition evaluation in accordance with ASTM 1972 and 1977, and absorption rate were carried out. The results obtained indicate that the fiber is composed of a variety of fibrils with irregular cross-sections, with an average diameter ranging from 0.02 to 0.09 mm. The fibers absorb 42.03% of their weight in water, and their density ranges from 1.23 to 1.45 g/cm^3. According to mechanical tests, the fiber has a maximum tensile strength of around 0.64 MPa, a specific modulus of 6.45 MPa/g/cm^3, and an elongation at break of 1.8%. For the chemical characteristics of the fiber, cellulose, hemicellulose, and lignin contents are 68.3%, 11.3%, and 7.4%, respectively, while pectin and ash content concentrations are 4.8% and 7.8%, respectively. Thus, in order to determine whether the plant is suitable for making pulp and paper, this investigation was conducted to examine its fiber properties. It was found that the water hyacinth fibers were superior to flax straw and jute fibers in all qualities, but not as good as silk cotton and bagasse fibers. Given the information above, water hyacinth has been recognized as a potential raw material for the pulp and paper industries, though.

1. Introduction

In many regions around the globe, the water hyacinth is an invasive plant that is not welcome since it frequently clogs rivers and lakes with a lot of floating plant matter [1]. Up to 200 tons of water hyacinth can be found in a good acre [1]. It features spherical, leathery leaves that are linked to spongy stalks and lavender blooms that bloom in waters. The plant's roots are black and feathery. Water hyacinths may be a strong candidate plant for phytoremediation, which is gaining popularity as an environmentally beneficial alternative. Water hyacinth has been shown to be effective at cleaning up dirty lakes, sewage wastewater, and cattle effluent [2]. Water hyacinth often degrades water quality by impeding water flow, contributing to boating accidents, and occasionally killing fish. Because trees make up a larger amount of the raw materials used to make paper pulps, cutting them down damages the ecosystem by causing global warming to increase. In the current investigation, water hyacinth stalks were first processed in water at 60°C for 100 min to remove water-soluble materials, and then, they were refined at 20% (m/m) concentrations using refiner mechanical pulping (RMP). The pulp was beaten in a PFI mill to achieve optimum fiber fibrillation [3].

Recently, researchers have studied water hyacinth for more technical benefits such as health and medicines, renewable energy, agricultures and fisheries, and engineering applications [4]. The disposal of water hyacinth and maleates of *Eichhornia crassipes* fiber (MoECF) as reinforcing fillers in styrene-butadiene rubber (SBR) composites in terms of the mechanical, acoustical, thermal, and morphological properties could be the biggest obstacles for the application of water hyacinth [5]. Water hyacinth mixed with clay can be used in building which help in the reduction of acoustic emission [6, 7]. Natural fibers are chosen over synthetic fibers for a number of reasons, including the fact that they are biodegradable, light, and affordable and have high mechanical qualities. The demand for materials has increased due to the expanding global population and the desire for higher living standards, which has resulted in more postconsumer waste [8]. One of the plants that has been determined to be acceptable for use in the production of natural fibers is water hyacinth. In this study, we examined the water hyacinth fiber's mechanical, thermal, and physical properties. Good physical qualities of water hyacinth fibers contribute to the composite product's dimensional stability. As the literature does not provide the extraction process for water hyacinth fiber, this study will use other natural fiber extraction methods as a guide [9].

Applications for nonwoven fabrics include membranes, biomedical devices, thermal insulation in automobile (roofs of car), and acoustics. Natural and synthetic fibers are utilized as raw materials to make nonwoven fabrics [3]. Nonwovens have certain qualities such as being lightweight, flexible, and moldable; having cheap process and material costs; being fundamentally efficient; having high performance ratios; and being recyclable [10, 11]. By combining the water hyacinth fibers with any other fibers, which have excellent physical and mechanical qualities, a needle-punched nonwoven fabric has been created. Natural fibers can be used in the textile industry as reinforcement for synthetic fibers [12]. The plant is widely available, and by combining it into high-value goods like nonwoven for technological purposes, it can be successfully used as a substitute for other textile fibers and automobile applications [13, 14].

This study is aimed at assessing the water hyacinth fibers' physicochemical and mechanical performance. We describe the fiber extraction process in this article. To find out how much cellulose, hemicellulose in lignin, pectin in waxes, and minerals were present, a chemical analysis was conducted. The amount of moisture was computed. The structural functional groups were discovered using FTIR. Thermogravimetric analysis (TGA) was used to assess the fiber's heat deterioration. Finally, a COYON machine was used to measure the tensile characteristics of fiber bundles. These qualities have a significant impact on the most crucial chemical components that govern the pulping properties, including cellulose, hemicelluloses, and lignin.

2. Materials and Methods

2.1. Materials. In this work, analytical-grade materials were used. The primary chemicals employed in this investigation were ethanol 99.5%, sodium hydroxide, xylene, and sulfuric acid 98%. These experiments frequently made use of analytical balances, reflux condensers, crushing machines, thermometers, filtering crucibles, crucibles, magnetic stirrers, different size sieves, water baths, Whatman grade 1 filter paper, and Leica sliding microtomes.

2.2. The Study Area. The material used was water hyacinth plant and was collected at canals of Wouri River, in the Littoral Region of Cameroon. The sizes of water hyacinth are uniform in diameter and length.

2.3. Methods. TAPPI's standard method for pulp and paper industry was published in 2002 [15]. The petioles were separated from the roots and other parts of the plant and washed thoroughly in order to remove undesirable materials on the surface. Dried water hyacinth (WH) fibers were used for all the tests except for the internal structure observation. The WH fibers were sun-dried in the laboratory. The manual extraction of water hyacinth was performed by using two extraction techniques, including (a) retting and (b) chemical processes. The initial approach involved cutting the water hyacinth into strips, soaking them in water for three to five days to soften them, and then physically putting them through a mechanical process. In the second approach, the strips were mechanically processed after 72 hours of soaking in a NaOH solution [16]. WH fibers are extracted using mechanical methods that slowly remove the fibers followed by scrapping. From a variety of agricultural byproducts, plant fibers can be produced in large quantities and with ease. Targeting invasive species, however, would be even more environmentally friendly and economically advantageous. This would allow for the cost recovery of conservation efforts to eradicate these environmentally destructive plants. Samples of fiber are shown in Figure 1.

2.4. Physical and Chemical Properties of Water Hyacinth

2.4.1. Extraction of Water Hyacinth Fibers. Water hyacinth (WH) is extracted by choosing the stem of the plant, chopping off the roots, and soaking it in distilled alkali solution (NaOH with distilled water). They are then rinsed with water, dried in the shade, and then hand-washed to remove mucilage. Between 27°C and 30°C are the operating temperatures for these procedures. The mature stalks of the water hyacinth plant, which generate a greater quantity of fibers than the younger ones, are where the water hyacinth fibers were taken. By scraping the dried stalks of water hyacinth plants with needles, we were able to obtain the fibers [13, 14, 17].

2.4.2. Water Absorption. The method used to conduct water absortion test of water hyacinth stalk [18]. AATCC Test Method 79, developed by the American Association of Textile Chemists and Colorists (AATCC), is used to measure the water absorption of fibers. It involves determining the

Figure 1: Samples of water hyacinth fibers.

weight change of a sample before and after water immersion. Seven samples were prepared, and the equation was used to determine the mean % water absorption (1). Prior to being submerged in fresh water for 24 hours at room temperature, the samples were first weighed as $M0$. The samples were reweighed as $M1$ after being submerged for 24 hours.

$$\text{Abs} = \frac{M1 - M0}{M0} \times 100\%. \quad (1)$$

2.4.3. Fourier Transform Infrared Spectroscopy. On a Bruker Alpha spectrometer, a Fourier transform infrared (FTIR) study is carried out. On a diamond crystal, the samples were immediately examined using the ATR (attenuated total reflectance) technique.

2.4.4. Density Measurements. The fibers had previously been dried at 60 degrees Celsius for 24 hours and chilled to room temperature in a desiccator. Each of the seven sample's density is calculated by weighing the dry fibers with a precision balance set to 0.0001 g, which is then placed into the container of the Quant Chrome Helium Pycnometer MVP-6DC. The gas law [18], which is represented by the equation, serves as the foundation for the helium pycnometer's operation (2). By measuring the pressure variation that the fluid experiences as a result of the displacement of the fluid in a constant volume by the test sample, the volume of the fiber is ascertained. This approach complies with [19].

$$\rho = \frac{Vf}{Vp} \text{ where } Vp = Vo - \left(Vr\left(\frac{P1}{P2}\right) - 1\right), \quad (2)$$

where $P1$ is the pressure measured after pressurizing the reference volume (Vr) (PSI), $P2$ is the pressure measured after including the orifice volume (Vo), the density is measured in g/cm^3, Vf is the fiber weight (g), Vp is the sample volume (cm^3), Vc is the sample orifice volume (cm^3), and Vr is the reference volume (cm^3) (PSI).

2.4.5. Chemical Properties of Water Hyacinth. Fourier transform infrared spectroscopy (FTIR) is used to identify functional groups and chemical bonds present in fibers. It provides information about the chemical composition of the fiber and can help identify specific types of fibers. The fibers were collected and evaluated with [20, 21], and the ash content was determined [22]. TAPPI T212 om-982000c [23] measured the solubility of 1% alkali. The amount of total extractives was calculated using hot water under reflux after performing numerous Soxhlet extractions with different organic solvents (cyclohexane, acetone, and methanol). Each case was refluxed for six hours with this end in mind. The solvent was recovered using a spinning vacuum-operated evaporator. The methods described were used to measure the quantities of lignin, holocellulose, and cellulose in the extractive-free material [24–26], respectively. The hemicellulose concentration was calculated using the difference between cellulose and holocellulose [27].

2.5. Thermomechanical Properties

2.5.1. Thermogravimetric Analysis (TGA). From 25°C to 700°C at a heating rate of 10°C/min, the thermogravimetric analysis is carried out on an analyzer (TGA) utilizing the LENSEI 449F3 Jupiter (Germany). I selected representative fiber samples that accurately represent the material to analyze. Cut the fiber samples into small, uniform pieces. The size of the samples is sufficient to obtain accurate measurements but small enough to fit into the TGA instrument. Weigh each sample accurately using a balance. Ensure the samples are clean and free from any contaminants. The amount of sample used was about 10 mg. The pans or crucibles are loaded containing the fiber samples into the TGA instrument. Ensure they are properly positioned for accurate measurement and that the lids are securely closed. The experiment was conducted at the University of Yaoundé's Laboratory of Physical Chemistry of Mineral Materials, Faculty of Science 1.

2.5.2. Mechanical Properties. The machine used for the mechanical test was equipped with two jaws (Figure 2).

The single-fiber tensile test was performed using a COYON CJ-0820 outfitted with a 50 N load cell, and tension tests were performed on all specimens. Until failure, the samples were evaluated at a 2 mm/min (position-controlled) strain rate [28, 29]. Seven samples of water hyacinth fiber were examined. The fibers were not further preconditioned during any of the tension tests, which were all carried out at constant room temperature (22°C), and the mean diameter was determined by analysis of seven fibers which was 0.15 mm.

3. Results and Discussion

3.1. Physical and Chemical Properties of Water Hyacinth

3.1.1. Water Absorption. The mean value of water hyacinth fiber water absorption is 42.03% and a standard deviation of 530.51. The presence of hemicelluloses is responsible for this substance's extreme hydrophilicity [30] and the high

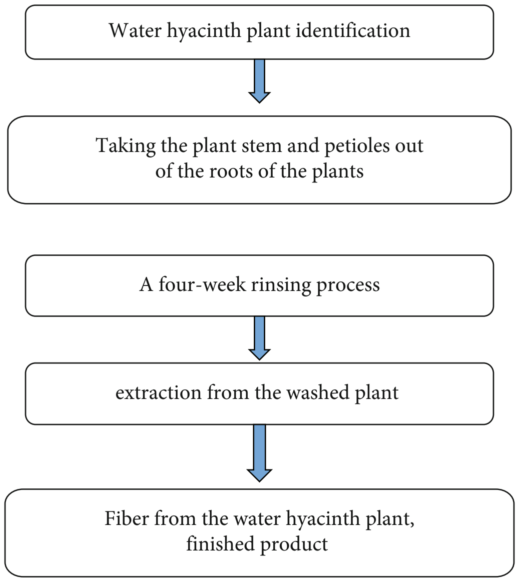

Figure 2: Schematic extraction of water hyacinth fibers.

content of free hydroxyl groups [31] and responsible for moisture sorption (Figure 2) and affects the physical and mechanical properties of the fibers [30]. In addition, the microstructure's significant porosity was noted; it should be mentioned that a surface treatment could potentially make this flaw better. The dried fibers contained an 8.16 wt% water content.

3.1.2. ATR-FTIR Spectrometry. The spectra from the ATR-FTIR analysis are shown in Figure 2. The parameters of its identification according to the wavenumber (cm^{-1}) are shown in Figure 3. Figure 2 shows the infrared spectrum, which ranges from 400 to 4000 cm^{-1} and is compiled from 32 scans with a resolution of 4 cm^{-1}.

The water hyacinth fiber's spectrum is depicted in Figure 4, and chemical compositions are represented by the peaks at 3737.4 cm^{-1} wavelength. The presence of liquid water that is more or less bound to the polymeric network that makes up the natural fibers is seen to be the cause of this absorption band [32]. The hydroxyl groups (O-H) present in cellulose and hemicellulose are shown by the second peak (3330.83 cm^{-1}). The third peak (2918.21 cm^{-1}) shows the shearing of an HH bond connected to the polymeric network that makes up natural fibers in open water [33]. The symmetrical aromatic elongation (C=C) inherent in lignin is typified by the fourth peak (2181.33 cm^{-1}), which is present in the sample [34]. The bend in CH2 in cellulose and symmetric deformation of CH in cellulose are shown by the fifth peak (1635.57 cm^{-1}). [35]. The aromatic group found in the polysaccharide and the wagging (cellulose and hemicellulose) C-O stretching vibration in the ester are represented by the sixth peak (1399.89 cm^{-1}), respectively [36]. The symmetrical elongation found in lignin is characteristically stretched in a C=C manner as shown by the seventh peak (1155.78 cm^{-1}) [37]. The eighth peak (1029.52 cm^{-1}) represents the elongation of -HH and MM=HH bonds of cellulose [36] and ester group

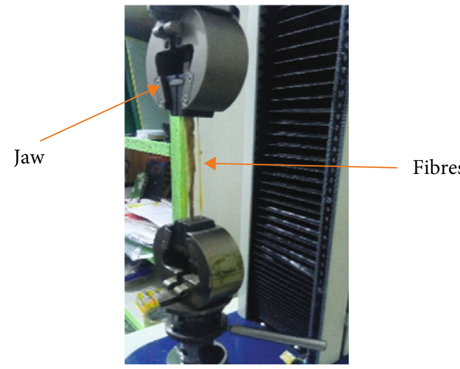

Figure 3: Tensile machine with WH fiber.

found in hemicellulose, waxes, and pectin. The ninth one (778.24 cm^{-1}) describes the symmetrical stretching of cellulose's C-H and O-H bonds [36].

These findings demonstrate that the main components of water hyacinth (WH) fibers are cellulose, hemicellulose, pectin, lignin, waxes, and polysaccharides. As a result, they resemble well-known plant fibers like sisal, coconut, and jute. The number of voids in a material is measured by its crystallinity index. The results demonstrate that water hyacinth fibers have a high crystallinity index and numerous vacancies, which support their hydrophilic nature. This outcome is in line with research on [38].

3.1.3. Density. Using the procedure described above, the density of water hyacinth fiber was ascertained. In comparison to some species, the mean density ranges between 1.23 and 1.45 g/cm^3 [39, 40]. It should also be mentioned that it is comparable to that of hemp fibers (1.47 g/cm^3) and banana fibers (1.50 g/cm^3), respectively [30], and as a result, WH fiber can be used in pulp-producing applications.

3.1.4. Chemical Composition. Noncellulosic substances like pectin and hemicellulose are eliminated from the WH fiber's chemical makeup during retting. In contrast to Senwitz et al.'s work [40], this chemical analysis goes so far as to separate the cellulose, hemicellulose, pectins, waxes, and minerals in terms of content, giving the holocellulose the techniques of getting the percentage of blast fiber (72.26%-87.90%) and extract content (0.70%-3.10%). It seems that the cellulose content of water hyacinth fiber is 68.4%, which is higher than that of banana or sisal fibers. Also, according to this content, its fibers could have excellent uses in textiles, papers, and composites. However, compared to ordinary fibers, the 11.3% hemicellulose concentration is lower [41] as shown in Table 1. This is because of its poor hydrophilic character, which prevents water from being absorbed because free hydroxyl groups are present in its structure [41]. The percentage of lignin (7.2%) is similar to that of banana and sisal [41], but it is lower compared to the work of Senwitz et al. [40]. The low lignin and high hemicellulose content likewise increases with retting time, according to these investigations. Due to the sizeable amount of pectins (4.8%) and hemicellulose that is left behind after retting, water hyacinth fiber stiffness and strength are significantly

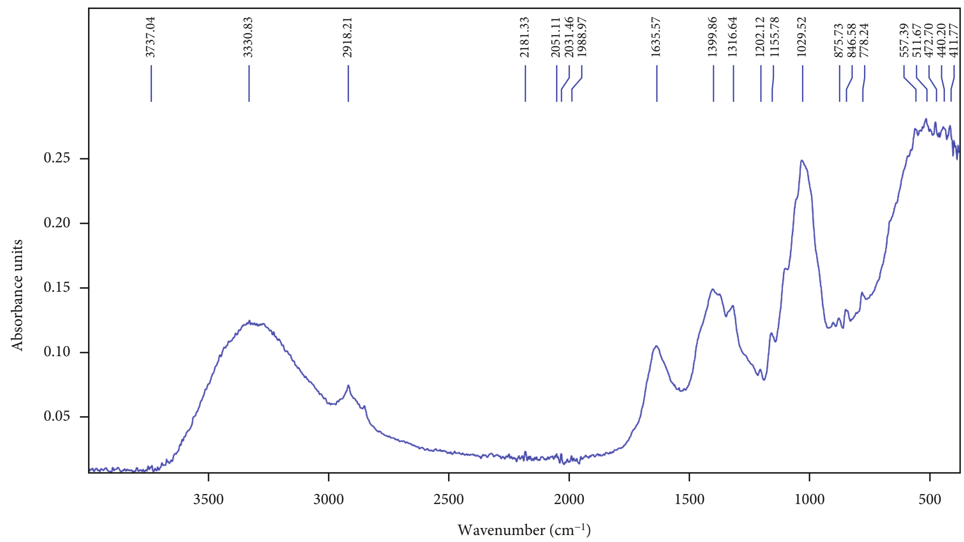

Figure 4: ATR-FTIR spectrum of water hyacinth fibers.

Table 1: Chemical composition of WH fibers compared to the fibers.

Fiber	Hemicellulose (wt.%)	Cellulose (wt.%)	Lignin (wt.%)	Wax content (wt.%)
Water hyacinth	11.3	68.4	7.2	0.6
Flax*	18.6-20.6	71	2.2	0.5
Jute*	16	67	9	0.5
Hemp*	17.9-22.4	70-74	3-5.7	0.7
Sisal*	10-14	66-78	10-14	02
Bamboo*	20.5	34.5	26	04

*Data republished from [44].

decreased [42]. As comparison to bamboo, water hyacinth fibers have a lower wax content (0.6%) and more minerals (7.8%) [43]. So considering these different chemical properties, it can be found that water hyacinth fiber is a potential candidate for pulp production.

3.2. Thermomechanical Properties

3.2.1. Thermogravimetric Analysis (TGA). The TG-DTG curves in Figure 3 are derived from the findings of the thermogravimetric analysis (TGA) of the fiber under investigation.

The TGA curve in Figure 5 demonstrates the breakdown of the studied fibers into five phases with accordance of ASTM 1972 and ASTM 1977 standards. Plant fibers typically experience this heat deterioration [41, 45]. The first obvious alteration is caused by the evaporation of the fibers' structural moisture and volatile extractives, and it lasts from 10 to 120 degrees Celsius. 5.99% of the mass is lost during this time. It can be shown that after these fibers are dehydrated, the mass variation is practically constant up to 180°C. According to this study, water hyacinth fibers can withstand a maximum working temperature of 180°C. This value is comparable to research on [3, 46] regarding some fibers. It could be considered when molding when water hyacinth fibers are used to reinforce the matrix during the creation of composite materials. Between 180°C and 580°C, the second phase showed a larger loss of mass (42, 97%) than the first. Between 180°C and 250°C, hemicellulose and pectin are responsible for this mass loss [47], than that of cellulose between 250 and 320 degrees Celsius. The third phase, which occurs between 587°C and 510°C, represents the cellulose's complete mass loss [46]. The aromatic structure of lignin and its thermal degradation occur in the fourth phase between 511°C and 680°C, when the mass loss is 9.59% [48]. 3.24% of the mass is lost. The ultimate degradation of lignin takes place between 680°C and 645°C; the mass loss of the water hyacinth fibers after heating at 655°C is (2. 08%).

3.2.2. Mechanical Properties. From our extraction, we successful extracted the fibers and performed our mechanical test on seven different fibers. Each stress-strain curve had a linear slope at first, followed by a curvature that showed how strain increased disproportionately with tension until the fiber broke. The initial linear slope of each graph was established, and this allowed us to calculate its modulus of elasticity. The dried fibers' stress-strain curve is depicted in Figure 6. Stress-strain curve for dried water hyacinth fibers is up to 4.53 MPa with Young's modulus of 10.60 MPa and

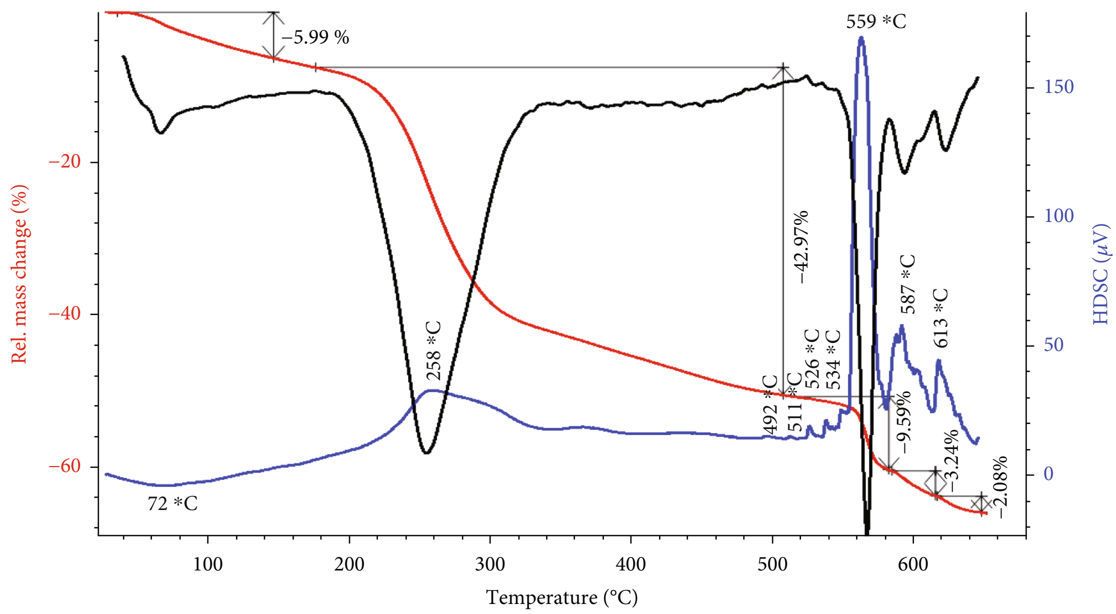

Figure 5: TGA and DSC curve of water hyacinth fibers.

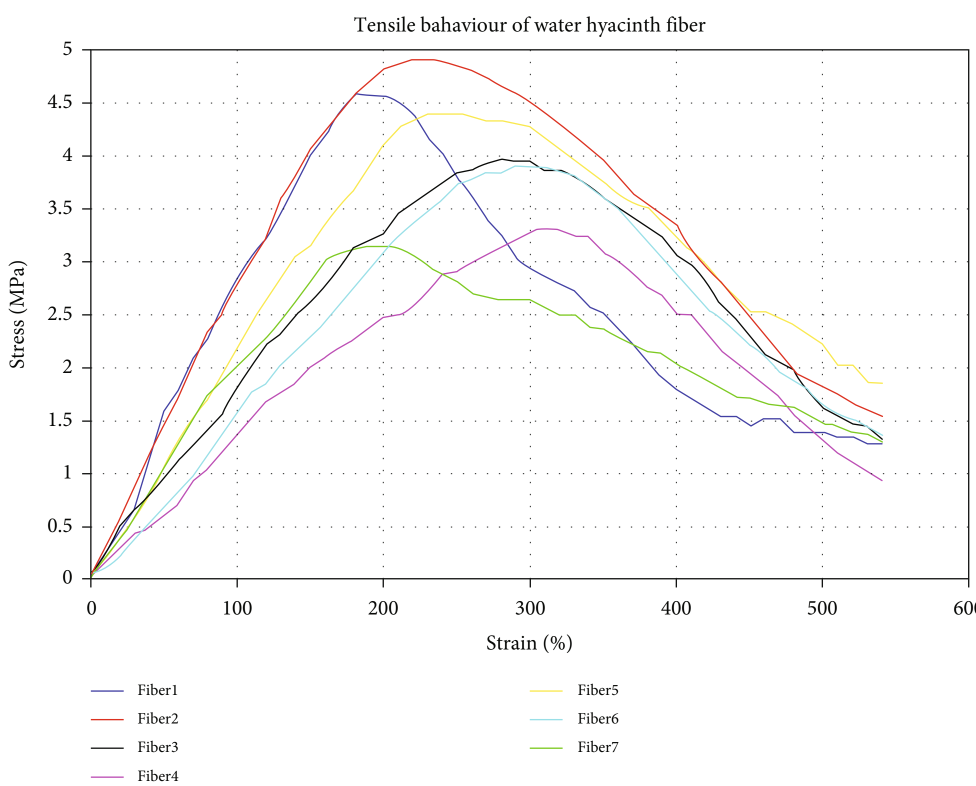

Figure 6: Tensile behaviour of WH fiber stress/strain curve.

a deviation of 2.92 MPa. The link between the diameter of fibers and their elasticity moduli was examined using a Fischer test and a fitted line model. The dried fibers indicate that the dried water hyacinth fibers arranged as a mat of numerous fibers would be more prone to fail gradually under pressure. Strength followed a similar pattern, with dried fibers having a maximum stress of 4.82 MPa and a tensile strength of 540 MPa with a deviation of 124 MPa. It demonstrates the relatively low tensile strength of the fibers made from dried water hyacinth. It has a regular distribution because it is a synthetic fiber. The mean modulus of elasticity for the seven examined specimens was 6.26 MPa. Figure 6 is

Table 2: Material properties of various biofibers.

Fiber	Young's modulus (MPa)	Tensile strength (MPa)	Breaking strain (MPa)	Density (g/cm^3)
Water hyacinth	10.60	540	1.3	1.23-1.45
Abaca*	12	400	3–10	1.5
Flax*	27.6	345–1035	2.7–3.2	1.5
Jute*	26.5	393–773	1.5–1.8	1.3
Kenaf*	53	930	1.6	—
Hemp*	70	690	1.6	1.48
Sisal*	9.4–22	511–635	2–2.5	1.5
Ramie*	24.5	560	2.5	1.5

*Data republished from [51].

comparable to other research [49]. As found in Table 2, it was confirmed that the tool and mounting grip technique yield trustworthy outcomes. This study's stiffness and strength tests were consistent with the tensile characteristics of other natural fibers [36, 41, 50]. Also, these researchers discovered a distinctive rise in strength with decreasing fiber diameter, suggesting that the effectiveness of fibers used as a pulp in papermaking will be significantly influenced by their size distribution. Fibers that have been dried are much stiffer and stronger. The findings of this study could be attributed to measuring errors in fiber dimensions and faults in the fiber that occurred either during plant growth, harvest, or the peeling process. Our findings may also be affected by variations in the tensile modulus and tensile strength of the stalks that were delivered on the strand rolls.

4. Conclusion

The research looked at how water hyacinth fibers may be suitable for pulp making. Materials have numerous applications, including packaging. The fibers of the water hyacinth were first assessed for density, water absorption rate, and moisture content. The findings demonstrate that water hyacinth fibers are smaller in diameter than other fibers and, as a result, can significantly contribute to lowering the volume of composites used in the fields of packaging, clothing, and textile. Additionally, water hyacinth fibers' density (0.23 to 0.45 g/cm^3) is low in comparison to other studies of other vegetable fibers, and they can significantly reduce the mass of composites used in the fields of leisure, clothing, and textile. Using the IPAT method on powdered fibers, the chemical composition of the water hyacinth fibers was determined. The number of polysaccharides (cellulose and hemicellulose) in these fibers, which is around 79.6%, suggests that they could be employed in an intriguing way as raw materials for the paper industry or as reinforcement materials for biosource materials. Low tensile strength may be obtained from the cellulose content (68.3%), and lignin (7.4%) could be recovered and used to make biofuels. The ATR-FTIR analysis of the spectra revealed the functions. The crystallinity index of cellulose in WH fibers is 69.8%, based on FTIR spectra. DSC and TGA were used to examine the thermal character of the water hyacinth fibers. Over 170°C, the components' thermal deterioration was seen. Six primary zones were related to the degradation of the fibers' structural moisture and volatile extractives (5.99% of mass loss). Hemicellulose/pectin, cellulose, and lignin were found in thermal transition phases as shown from DSC and TG/DTG thermograms. The fiber understudy's maximum working temperature was 170°C. Further research might be done on starch matrix composite reinforcement and the characterization of treated fibers. This source raw material's appealing paper may be used to create goods like cards, packaging, green composite materials, and printing papers and has good opacity as well. To make the qualities of water hyacinth pulps consistent across all locations and species, more effort must be done. In conclusion, the properties of water hyacinth stalk pulp make it an excellent option for composites and papermaking.

Data Availability

All data generated or used during this study are included in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] (IEA), International Energy Agency, *Biogas Production and Utilization*, IEA Bio-Energy, 2005, http://www.iea-biogas.net.

[2] D. Kim, Y. Huh, Y. Seong, S. Han, and C. Seo, "Characterization of water hyacinth biomass and evaluation of paper applicability," *Journal of Korea TAPPI*, vol. 46, pp. 79–87, 2014.

[3] K. Shaker, R. M. W. U. Khan, M. Jabbar et al., "Extraction and characterization of novel fibers from Vernonia elaeagnifolia as a potential textile fiber," *Industrial Crops and Products*, vol. 152, p. 112518, 2020.

[4] T. I. Virginie and P. R. Jules, "Répartition et valorisation des macrophytes envahissantes dans la region du littoral (Cameroun) : cas *d'Eichhornia crassipes* (Mart.) Solms-

Laubach," *Journal of Applied Biosciences*, vol. 100, pp. 9522–9534, 2016.

[5] A. E. A. El-Wakil, M. Abd-Elbasseer, and T. M. El-Basheer, "Mechanical and acoustical properties of Eichhornia crassipes (water hyacinth) fiber-reinforced styrene butadiene rubber," *Polymer Composites*, vol. 42, pp. 3732–3745, 2021.

[6] T. M. E. B. Hussein, "Calibration and uncertainty estimation for the reference sound source in reverberation room," *Romanian Journal of Acoustics and Vibration*, vol. 17, no. 2, pp. 118–127, 2020.

[7] A. Abdel-Hakim, E. H. Awad, K. F. El-Nemr, and T. M. El-Basheer, "Impact of gamma radiation and multi-walled carbon nanotubes on the mechanical and acoustical properties of reinforced sisal fiber/polyester resin composites," *Radiation Physics and Chemistry*, vol. 189, p. 109768, 2021.

[8] K. Shaker, M. Umair, S. Shahid et al., "Cellulosic fillers extracted from Argyreia speciose waste: a potential reinforcement for composites to enhance properties," *Journal of Natural Fibers*, vol. 19, no. 11, pp. 4210–4222, 2022.

[9] A. A. Ogunwusi and N. D. Ibrahim, "Advances in pulp and paper technology and the implication for the paper industry in Nigeria," *Industrial Engineering Letters*, vol. 4, no. 10, pp. 3-4, 2014.

[10] L. A. Worku, R. K. Bachheti, M. G. Tadesse, and A. Bachheti, "Proximate chemical analysis and effect of age and height of _Oxytenanthera abyssinica_ on fiber morphology and chemical compositions for pulp and paper production potential," *International Journal of Polymer Science*, vol. 2023, Article ID 5582854, 16 pages, 2023.

[11] V. K. Midha and A. Mukhopadyay, "Bulk and physical properties of needle punched nonwoven fabrics," *Indian Journal of Fiber & Textile Research*, vol. 30, pp. 218–229, 2005.

[12] A. Arivendan, W. J. JT, S. Irulappasamy, and B. N. Chris, "Water hyacinth (EichhorniaCrassipes) polymer composites properties-aquatic waste into successful commercial product," *Metallurgical and Materials Engineering*, vol. 28, pp. 157–169, 2022.

[13] S. Punitha, K. Sangeetha, and M. Bhuvaneshwari, "Processing of water hyacinth fiber to improve its absorbency," *International Journal of Advanced Research*, vol. 3, no. 8, pp. 290–294, 2015.

[14] M. Bhuvaneshwari and K. Sangeetha, "Investigation of physical, chemical and structural characterization of Eichhornia crassipes fiber," in *International Conference on Information Engineering, Management and Security*, pp. 92–96, Tamil Nadu, India, 2016.

[15] TAPPI, *Standards and Suggested Methods*, TAPPI Press, Atlanta, Georgia, USA, 2002.

[16] R. Robinson Gnanadurai, T. Guadie, and S. Mesfin, "Study on the mechanical properties of water hyacinth fiber reinforced high," *European Online Journal of Natural and Social Sciences*, vol. 10, pp. 379–390, 2021.

[17] M. Saha and A. M. Afsar, "Thermo-mechanical and morphological properties of water hyacinth reinforced polypropylene composites," *International Journal of Engineering Materials and Manufacture*, vol. 3, no. 3, pp. 151–161, 2018.

[18] S. Lowell, J. E. Shields, M. A. Thomas, and M. Thommes, *Characterization of porous solids and powders: surface area, pore size and density*, SPRINGER SCIENCE+BUSINESS MEDIA, LLC, Boynton Beach, U.S.A, 2004.

[19] E. L. Mari, "Parchment-like paper using water hyacinth pulp," *Philippine Journal of Science*, vol. 2, p. 141, 2012.

[20] W. Sandermann and M. Rothkamm, "Uber die Bedeutung der pH-Werte von Handelsholzern und deren Bedeutung fur die praxis," *European Journal of Wood and Wood Products*, vol. 17, no. 11, pp. 433–440, 1959.

[21] TAPPI T211 om-93, *Ash in Wood and Pulp*, TAPPI Press, Atlanta, GA, 2000.

[22] C. Tellez-Sanchez, H. G. Ochoa-Ruiz, R. Sanjuan-Duenas, and J. G. Rutiaga-Quinones, "Components quimicos del duramen de Andira inermis -W. Wright DC (Leguminosae)," *Revista Chapingo serie ciencias Forestales y del Ambiente*, vol. 16, no. 1, pp. 87–93, 2010.

[23] TAPPI T212 om-98, *One Percent Sodium Hydoxide Solubility of Wood and Pulp*, TAPPI Press, Atlanta, GA, 2000.

[24] R. O. H. Runkel and K. D. Wilke, "Zur kenntnis des thermoplastischen Verhaltens von Holz," *Holz als Roh-und Werkstoff*, vol. 9, no. 7, pp. 260–270, 1951.

[25] L. E. Wise, M. Murphy, and A. A. d'Addieco, "Chlorite holocelluse, its fraction and bearing on summative wood analysis and on studies on hemicellulose," *Paper Trade Journal*, vol. 122, no. 6, pp. 35–43, 1946.

[26] ASTM D 1103-60, *Annual Book of ASTM Standards, Standards Method for Determining Alfa-Cellulose in Wood*, American society for testing and materials, West Conshohocken, Philadephia, 1981.

[27] L. R. Carballo-Abreu, U. Orea, and Cordero, "Composicion quimica de tres maderas en la provincia de Pinard el Rio, Cuba, a tres alturas del fuste commercial. Partie 1," *Corymbia citriodira, Revista Chapingo serie ciencias Forestales y del Ambiente*, vol. 10, no. 1, pp. 57–62, 2004.

[28] G. Molero, D. Shuoran, M. Mamak, M. Agerton, M. M. Hossain, and H.-J. Sue, "Experimental and numerical determination of adhesive strength in semi-rigid multi-layer polymeric systems," *Polymer Testing*, vol. 75, pp. 85–92, 2019.

[29] D. Shuoran, Z. Zhu, C. Liu, Z. Tan, M. M. Hossain, and H.-J. Sue, "Experimental observation and finite element method modeling on scratch-induced delamination of multilayer polymeric structures," *Polymer Engineering and Science*, vol. 61, no. 6, pp. 1742–1754, 2021.

[30] S. Vidya Bharathi, S. Vinodhkumar, and M. M. Saravanan, "Strength characteristics of banana and sisal fiber reinforced composites," *IOP Conf. Series: Materials Science and Engineering*, vol. 1055, pp. 163–170, 2021.

[31] S. S. Sreedhara and N. R. Tata, "A novel method for measurement of porosity in nanofiber mat using pycnometer in filtration," *Journal of Engineered Fibers and Fabrics*, vol. 8, no. 4, 2013.

[32] B. Deepa, E. Abraham, B. M. Cherian et al., "Structure, morphology and thermal characteristics of banana nano fibers obtained by steam explosion," *Bioresource Technology*, vol. 102, pp. 1988–1997, 2011.

[33] B. Taallah, A. Guettala, and A. Kriker, "Effet de la Teneur en Fibres de Palmier Dattier et de la contrainte de compactage sur les proprietes des Blocs de Terre Comprimée," *Materials Science, Courrier du savoir*, vol. 18, pp. 45–51, 2014.

[34] H. Abral, D. Kadriadi, A. Rodianus et al., "Mechanical properties of water hyacinth fibers – polyester composites before and after immersion in water," *Materials & Design*, vol. 58, pp. 125–129, 2014.

[35] C. Parida, S. K. Dash, and C. Pradhan, "FTIR and Raman studies of cellulose fibers of luffa cylindrical," *Open Journal of Composite Materials*, vol. 5, pp. 5–10, 2015.

[36] U. Moonart and S. Utara, "Effect of surface treatments and filler loading on the properties of hemp fiber/natural rubber composites," *Cellulose*, vol. 26, pp. 7271–7295, 2019.

[37] K. Bilba, M. A. Arsene, and A. Ouensanga, "Study of banana and coconut fibers botanical composition, thermal degradation and textural observations," *Bioresource Technology*, vol. 98, pp. 58–68, 2007.

[38] B. O. A. Désiré, B. E. Fabien, M. Florian, J. J. Dumond Pierre, A. Ateba, and N. P. M. Anicet, "Physico-chemical and thermal characterization of some lignocellulosic fibers; Ananas cosmus (AC), Neuropeltis accuminatas (NA) and Rhecktophyllum camerunence (RC)," *Journal of Materials and Materials Characterization and Engineering*, vol. 8, pp. 205–222, 2020.

[39] R. M. Davies and U. S. Mohammed, "Moisture-dependent engineering properties of water hyacinth parts," *Singapore Journal of Scientific Research*, vol. 1, no. 3, pp. 253–263, 2011.

[40] C. Senwitz, A. Kempe, C. Neinhuis, J. L. Mandombe, M. F. Branquima, and T. Lau-Tenschläger, "Almost forgotten resources—biomechanical properties of traditionally used bast fibers from northern Angola," *BioResources*, vol. 11, pp. 7595–7607, 2016.

[41] S. Ouajai and R. A. Shanks, "Composition, structure and thermal degradation of hemp cellulose after chemical treatments," *Polymer Degradation and Stability*, vol. 89, pp. 327–335, 2005.

[42] W. Sridash, "The environmentally benign pulping process of non-wood fibres," *Suranaree Journal of science and Technology*, vol. 17, no. 2, pp. 105–123, 2010.

[43] M. R. Sanjay, G. R. Arpitha, L. Laxmana Naik, K. Gopalakrishna, and B. Yogesha, "Applications of natural fibers and its composites: an overview," *Natural Resources*, vol. 7, pp. 108–114, 2016.

[44] P. B. Sarkar, A. K. Mazumdar, and K. B. Pal, "The nature of the hemicelluloses of jute fiber," *Textile Research Journal*, vol. 22, no. 8, pp. 529–534, 1952.

[45] R. Nadlene, S. M. Sapuan, M. Jawaid, M. R. Ishak, and L. Yusriah, "Material characterization of roselle fibre (Hibiscus sabdariffa L.) as potential reinforcement material for polymer composites," *Fibers and Textiles in Eastern Europe*, vol. 6, pp. 23–30, 2015.

[46] S. Raghavendra, G. S. Kestur, and S. P. Balachandra, "Evaluation of structural, tensile and thermal characterization of banana fibers," *Journal of Natural fibers*, vol. 14, no. 4, pp. 485–497, 2017.

[47] R. Nadlene, S. M. Sapuan, M. Jawaid, M. R. Ishak, and L. Yusriah, "Material characterization of roselle fiber (Hibiscus sabdariffa L.) as potential reinforcement material for polymer composites," *Fibers & Textiles in Eastern Europe*, vol. 6, pp. 23–30, 2015.

[48] F. P. Teixeira, F. M. G. da Otavio, and A. S. Flavio, "Degradation mechanisms of curaua," *ThermalDegradation of Fibers*, vol. 14, pp. 1494–1511, 2019.

[49] D. R. H. Jones and M. F. Ashby, *Engineering Materials 1: An Introduction to Properties, Applications and Design*, vol. 1, Elsevier, 2012.

[50] A. V. R. Prasad, K. M. Rao, A. Gupta, and B. V. Reddy, "A study on flexural properties of wildcane grass fiber-reinforced polyester composites," *Journal of Materials Science*, vol. 46, no. 8, pp. 2627–2634, 2011.

[51] O. Faruk, A. K. Bledzki, H. P. Fink, and M. Sain, "Biocomposites reinforced with natural fibers: 2000-2010," *Progress in Polymer Science*, vol. 37, no. 11, pp. 1552–1596, 2012.