



# Comprehensive characterization of Yanchama (*Poulsenia Armata*) fiber cloth from the Ecuadorian Amazon region: Towards sustainable reinforcement materials

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## ABSTRACT

Natural fibers are valued for their sustainability, low cost, and availability, positioning them as attractive alternatives to synthetic materials. This study comprises a comprehensive characterization of *Poulsenia Armata* fiber cloth (PAFC), focusing on its physical, mechanical and thermal properties. The fiber morphology was examined using scanning electron microscopy (SEM), thermal stability by thermogravimetric analysis (TGA), chemical composition through ANKOM procedures, crystallinity by X-ray diffraction (XRD), surface and chemical structure through Fourier-transform infrared spectroscopy (FTIR) and <sup>13</sup>C Solid State Nuclear Magnetic Resonance (NMR) spectroscopy. The mechanical performance was investigated via tensile testing. Results revealed a low lignin and hemicellulose content with percentages of 1.38 and 0.51 %, respectively, while the cellulose content was determined to be around 58 %. SEM micrographs showed that PAFC consists on a rough surface with several interconnected fibrils. The experimental density was measured to be 1.53 g/cm<sup>3</sup>. TGA showed a loss of approximately 5 % of weight due to moisture elimination and the beginning of thermal degradation at around 245 °C with a maximum decomposition rate at 371.8 °C. XRD analysis yielded a crystallinity index and a crystallite size of around 70 % and 2.76 nm, respectively. FTIR and NMR spectra confirmed the predominance of cellulose content relative to hemicellulose and lignin through the presence of several characteristic peaks. Tensile tests revealed an ultimate tensile strength of 30 MPa, a modulus of elasticity of 227 MPa, and an elongation at break of 15 %. Collectively, these findings highlight the potential of PAFC as a novel lignocellulosic material for diverse engineering applications.

## 1. Introduction

Ecuador is one of the 20 megadiverse countries worldwide, divided into four well-defined natural geographic zones: coast, highlands, Amazon, and Galapagos Islands. It has 91 types of ecosystems, which are divided into 65 forest ecosystems, 14 herbaceous, and 12 shrubby [1]. Forest ecosystems vary by geographic zone, including Amazonian lowland and flooded forests, coastal evergreen forests, and highland cloud and montane forests. These ecosystems are vital for capturing carbon, filtering air pollutants, preventing floods, and cooling temperatures. Most importantly, native forests play a crucial role in preserving

terrestrial biodiversity.

The practice of planting trees confers several environmental benefits, as well as a significant social impact on local economies. Forests provide wood, a material of paramount importance as a raw material of natural origin, which is primarily utilized in the production of furniture and its derivatives [2]. The main species planted in Ecuador are laurel, romerillo, cedar, and chonta, among others [3]. The tree trunk constitutes the primary raw material for wood processing; however, the bark is seldom employed for this purpose. Nevertheless, through the implementation of appropriate preparation techniques, it becomes possible to extract natural fibers that can be utilized in the production of yarns or ropes, which

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in turn find significant industrial applications [4].

Natural fibers of plant origin are defined as groups of cells characterized by high mechanical resistance. Their chemical composition is dominated by lignin and cellulose, which primarily function as structural support within the plant [5]. The high cellulose content of these fibers poses a challenge to microorganisms due to their insolubility and crystalline structure, thereby ensuring their durability. The substantial lignin content of these fibers contributes to their resilience to the mechanical stresses to which they are subjected during various stress-induced processes [6,7].

The utilization of natural fibers has played a pivotal role in the progression of civilization. Beyond their nutritional value and applications in the textile industry, these fibers are currently being employed to substitute synthetic materials such as fiberglass to reinforce polymer in composite materials [8]. Among the vegetable-derived fibers from the stem are flax, hemp, and jute, which are utilized to produce mats, linen, and packaging paper, respectively [3,9–11]. Given the considerable biodiversity observed within each region, there is a compelling need to undertake a comprehensive study to identify novel fibers that can be utilized for the fabrication and reinforcement in polymer composite materials, among other applications.

Polymer composite materials have been revolutionary for different sectors: aeronautics, construction, automotive, architectural, etc. [12,13]. They provide high mechanical strength and allow obtaining lighter parts, resistant to degradation and corrosion, design flexibility, improved aesthetic properties, and are environmentally friendly [14,15]. On the other hand, if a biodegradable matrix is used, it is feasible to develop 100 % biodegradable materials using fibers of natural origin [16].

The utilization of natural fibers in the development polymer matrix composite materials has garnered significant attention, primarily due to their minimal environmental impact, cost-effectiveness, low density, biodegradability, non-toxicity, and superior insulating, toxicological, thermal, and acoustic properties, along with their low health risks, cultivability and harvestability [16,17]. *Poulsenia armata*, a species within the Moraceae family, is of particular interest. Its common names include abababite (Guatemala), carnero (Mexico), tumu (Honduras, Nicaragua), cocua, mastate (Panama), corbon, cucua (Colombia), yanchama, majagua (Ecuador) [18]. It is characterized by its abundance in terms of volume per hectare, with a maximum height of 30 m and a diameter of 60–100 cm. Its primary exploitation is for the manufacture of furniture.

The morphology, dimensions, and mechanical properties of vegetable fibers are known to exhibit significant variations, which are contingent on the environmental factors during cultivation, geographical provenance, plant maturity, extraction methodology, and the manufacturing process [19]. A plethora of challenges have been identified in the utilization of plant fibers, with difficulties in achieving adequate adhesion between fibers and their respective polymer matrices being a prevailing concern [6,20–23]. The inherent vulnerability of fibers to moisture has been demonstrated to compromise their mechanical properties and dimensional stability, consequently affecting the integrity of the composites derived from them [23]. An alternative to this problem is to submit the natural fibers to chemical modifications to decrease the hydrophobic nature of the vegetable fiber, improving the interfacial bonding between the matrix and the fiber, decreasing the roughness, and increasing the wettability of the fibers [24].

Several investigations have been conducted to characterize natural fibers for composite applications [5,25–36]. It has been determined that significant alterations in properties occur due to the impact of fiber moisture absorption, fiber agglomeration/alignment/curvature/diameter variability, degree of wetting, interface reaction effects, and adhesion properties [26,27]. The chemical treatment of natural fibers has been shown to significantly enhance the performance of natural fiber composites [28,37,38]. However, to ensure a safer environment, it is essential to examine appropriate chemical removal methods in detail.

As reported by several authors [6,11,22,35], it is necessary to study new natural fibers in large volumes to improve the performance of composite materials they reinforce, as opposed to the commonly available natural fibers. According to the review of the state of the art, only two investigations performed with *Poulsenia armata* fibers have been identified; Daza-Gutierrez et al. [39] studied the effect of the orientation of Yanchama fibers as reinforcement in a polylactic (PLA) matrix. The former study focused on matrix reduction by utilizing fibers to reduce costs. Conversely, Obregón et al. [16] concentrated on morphological characteristics and mechanical properties to study the behavior of Yanchama fibers for their future use in the textile industry. Both investigations were carried out in Colombia; to the authors' knowledge, Yanchama, native to the Ecuadorian Amazon, has not yet been studied.

In this context, to determine the potential for engineering applications, it is necessary to know precisely the morphology and properties of the fibers. In this sense, the present research seeks to quantitatively characterize the chemical properties of *Poulsenia armata* fiber and evaluate its mechanical properties before using it as reinforcement for a polymer composite material.

## 2. Materials and methods

### 2.1. Raw material

Yanchama (*Poulsenia Armata*) fibers were procured in Puyo, Pastaza, Ecuador, in the shape of flat cloth obtained from the inner part of the tree bark. Fig. 1 shows a schematic process traditionally used to obtain the *Poulsenia Armata* fiber cloth (PAFC). Firstly, the bark from the Yanchama tree is extracted from the trunk (Fig. 1a). Then, the outer part of the bark is separated from its inner part, as depicted in Fig. 1b. Subsequently, the inner part of the bark is placed over a flat surface, and a mallet is used to mechanically flatten it until a uniform width is obtained, as illustrated in Fig. 1c. Once a uniform cloth is obtained, the cloth is subsequently washed to remove dust and impurities (Fig. 1d). Finally, the fabric goes through a sun drying process (Fig. 1e) until the moisture is removed, as shown in Fig. 1f.

The as received fiber cloth was washed with deionized water and soaked in a 2 % detergent solution for 15 min to remove any remaining impurities on the fiber surface [40]. Afterwards, the fibers were submerged in subsequent washes with deionized water to remove any remaining detergent. Subsequent to the cleaning process, the fibers were placed in a vacuum oven at a temperature of 60 °C for 72 h. Powdered samples were obtained using a Retsch Planetary Ball Mill and then sieved with a 100-mesh sieve to obtain a uniform particle size.

### 2.2. Chemical composition

Chemical composition (cellulose, hemicellulose, and lignin contents) of the Yanchama fibers was obtained through an ANKOM 200 Fiber Analyzer [41] in triplicates, and average values were reported. For the purpose, the standard acid detergent fiber (ADF) was performed using ANKOM 200 Method 5 which consisted of placing 0.5 g of ground PAFC in an ANKOM bag with cetyl trimethylammonium bromide (CTAB) and 1.00 N sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and heated to a temperature of 100 °C for 1 h. The remaining solid phase materials were obtained through filtration, and their ratio to the mass used to conduct the test was reported as ADF. Similarly, the neutral detergent fiber (NDF) was conducted using ANKOM 200 Method 6, which consisted of the digestion of the PAFC sample in a solution consisting of sodium dodecyl sulfate, ethylene diamine tetraacetic disodium salt, sodium borate, sodium phosphate dibasic, tri-ethylene glycol, alpha-amylase, and sodium sulfite at a temperature of 100 °C for 1 h. After the digestion procedure, a filtration process was performed to obtain the dried solid fraction, and its ratio to the original mass was reported as NDF. Correspondingly, the acid detergent lignin (ADL) analysis consists of seven subsequent 30-min stirring stages of the sample while submerged in a solution of 72 %

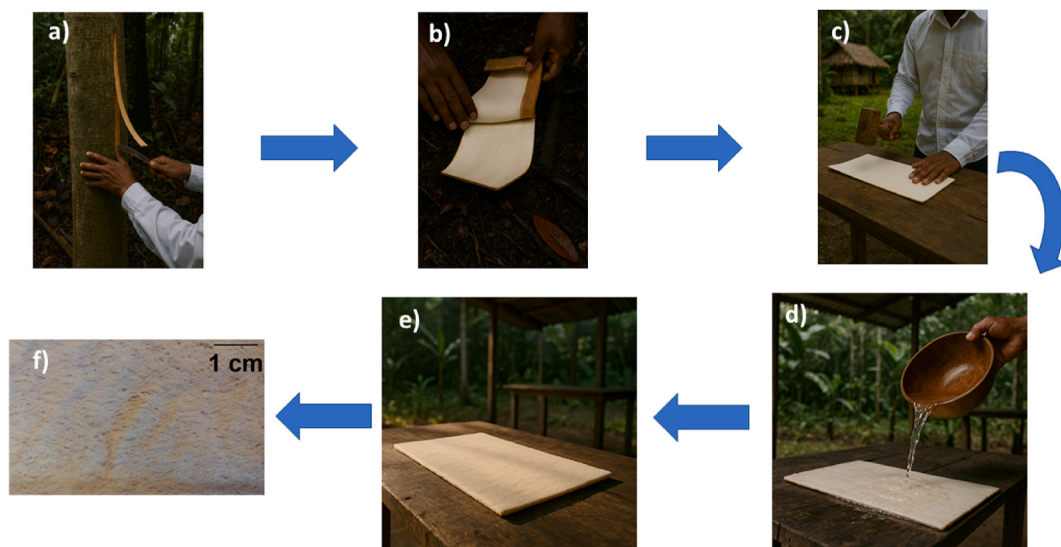


Fig. 1. Schematic process for the Poulsenia Armata fiber cloth (PAFC) obtained from the tree bark.

$\text{H}_2\text{SO}_4$ . After every stirring process, the solution was washed with deionized water until neutralization. Subsequently, the final solution was washed with acetone and then dried. The obtained solid residue was weighed, and its ratio to the original mass before the test was reported as ADL, which is the lignin content of the fiber (Equation (1)). The cellulose and hemicellulose content were obtained using Equations (2) and (3), respectively:

$$\% \text{ lignin} = \text{ADL} \quad (1)$$

$$\% \text{ cellulose} = \text{ADF} - \text{ADL} \quad (2)$$

$$\% \text{ hemicellulose} = \text{NDF} - \text{ADF} \quad (3)$$

### 2.3. Scanning electron microscopy

Scanning electron microscopy (SEM) was used to examine the PAFC morphology as well as the ground fiber [42]. A Thermo Fisher Scientific model Quattro Environmental Scanning Microscope (ESEM) (Waltham, MA, USA) was operated with an acceleration voltage of 2 kV. Before placing the fiber in the vacuum chamber, all samples were gold-coated, and conductive nickel paint was applied on the sample corners to ensure proper conductivity.

### 2.4. Density measurement

Poulsenia Armata fiber cloth density was measured utilizing a Micromeritics AccuPyc 1340 helium gas pycnometer (Norcross, GA, USA) whose working principle is based on Boyle's Gas Law [33], a method that has been widely used to determine the density of natural fibers due to its simplicity and accuracy [43–46]. Before the test, the fibers were vacuum dried at  $102^\circ\text{C}$  for 4 h. Then, an adequate amount of the material was weighed ( $m_s$ ) and placed in a sample cup holder with a known volumetric capacity of  $35\text{ cm}^3$ . After that, the sample cup holder containing the fiber sample was placed in the pycnometer and purged with helium gas to eliminate air and any moisture residue until an equilibrium chamber pressure of 19.5 psi was reached. At this moment, the values of pressure and volume were acquired and labeled as  $P_1$  and  $V_1$ , respectively. Afterwards, the helium gas was allowed to expand into the pycnometer reference chamber causing an increase in volume ( $V_2$ ), and a reduction in pressure ( $P_2$ ). When a pressure of 19.5 psi, the volume can be related to the volume of the chamber ( $V_C$ ) and the volume of the sample ( $V_s$ ) using Equation (4):

$$V_1 = V_C - V_s \quad (4)$$

Through Boyle's Gas Law, the initial volume ( $V_1$ ), and pressure ( $P_1$ ) can be related to the final volume ( $V_2$ ) and pressure ( $P_2$ ), as observed in Equation (5):

$$P_1 V_1 = P_2 V_2 \quad (5)$$

$$V_1 = \frac{P_2 V_2}{P_1} \quad (6)$$

Through substituting Equation (6) into Equation (4), the volume of the sample ( $V_s$ ) can be obtained:

$$\frac{P_2 V_2}{P_1} = V_C - V_s \quad (7)$$

$$V_s = V_C - \frac{P_2 V_2}{P_1} \quad (8)$$

After the volume of the sample has been successfully determined, the density of Yanchama fiber was calculated from Equation (9):

$$\rho_{Go} = \frac{m_s}{V_s} \quad (9)$$

The process was performed 5 times, and average values were reported.

### 2.5. Water absorption

Five square samples of PAFC with a weight of 0.5 g each were used to determine the water absorption of the samples. Before the test, the samples were dried in a vacuum oven for 48 h at  $70^\circ\text{C}$ , allowed to cool at room temperature, and weighed. During the test, taken at a temperature of  $23^\circ\text{C}$ , the samples were immersed in deionized water, removed periodically, lightly blotted with paper towel to remove excess surface water, weighed, and immersed again. Average values and their respective standard deviation were reported. The water content (WC) of the fiber by weight percentage (wt.%) was calculated using Equation (10):

$$\text{WC (wt. \%)} = \frac{W_t - W_0}{W_0} \times 100 \quad (10)$$

where,  $W_t$  is the weight of the fiber after being immersed in water during a specific time,  $W_0$  is the initial weight of the dry fiber.

## 2.6. Solid state nuclear magnetic resonance spectroscopy

$^{13}\text{C}$  Solid State Nuclear Magnetic Resonance (NMR) spectroscopy is a rapid and reliable characterization test used to provide advanced information on the molecular structure of lignocellulosic materials [47]. For this purpose, a DOTY Scientific Cross-Polarization/Magic Angle Spinning (CP-MAS) probe (Columbia, SC, USA) equipped with a Bruker AVANCE III HD spectrometer (Billerica, MA, USA) was used to obtain  $^{13}\text{C}$  solid state NMR spectroscopy while operating at a frequency of 125.77 MHz. The  $^{13}\text{C}$  Cross-Polarization with Total Suppression of Spinning Sidebands (CP/TOSS) spectrum was acquired with a sample spinning speed of 7500 Hz, a contact time of 2 ms, and a  $^1\text{H}$  90° pulse of 5  $\mu\text{s}$  with a ramp pulse on the  $^1\text{H}$  channel. A total of 2500 scans were performed using a recycle delay of 1 s with a 50 kHz SPINAL-64 decoupling sequence [48].

## 2.7. X-ray diffraction analysis

X-Ray diffraction (XRD) analysis was performed to obtain the crystallographic information of the PAFC [49,50]. A Rigaku Ultima IX X-ray diffractometer was operated with a Cu-K $\alpha$  radiation source ( $\lambda\text{-K}\alpha_1 = 1.5406 \text{ \AA}$ ). The XRD spectrum was obtained from 10° to 50° at 40 kV and 40 mA with a scan speed of 2°/min.

The crystallinity index of the fiber was obtained using Equation (11):

$$CI = \frac{I_{0.02} - I_{am}}{I_{0.02}} \times 100 \quad (11)$$

where  $I_{0.02}$  is the maximum intensity of the peak at a 2 $\theta$  angle between 22 and 23° that represents the (002) lattice peak from both crystalline and amorphous diffraction, and is  $I_{am}$  represents the minimum diffraction of the amorphous material located between a 2 $\theta$  angle between 18° and 19° from the peak (110) [51], [52].

Similarly, the crystallite size was calculated with Scherer's formula (Equation (12)):

$$CS = \frac{k\lambda}{\beta \cos \theta} \quad (12)$$

where  $k$  is the Scherer constant (0.945),  $\lambda$  is the X-ray wavelength (0.15406 nm for a Cu-K $\alpha$  source),  $\beta$  is the full width of the peak at half-maximum in radians, and  $\theta$  is the Bragg angle.

## 2.8. Fourier transform infrared spectroscopy

Fourier transform infrared (FTIR) spectroscopy was performed using a Bio-RAD FTS-40 IR (Hercules, CA, USA) to identify chemical functional groups in the PAFC [43,52]. An adequate amount of ground fibers was mixed with potassium bromide (KBr) in a weight ratio of 1:10. The spectrum was acquired over a range of 400–4000  $\text{cm}^{-1}$  using a resolution of 4  $\text{cm}^{-1}$ . A total of 128 scans were recorded, and a background spectral correction was applied for the KBr.

## 2.9. Tensile testing

Mechanical testing of the PAFC was performed using an Instron 600LX universal testing machine with a 2663-821 Advanced Video Extensometer. The tests were conducted using a strain rate of 5 mm/min, and the samples had an initial gauge length of 50 mm. Ten rectangular specimens with dimensions of 25 mm  $\times$  100 mm (length  $\times$  width) were tested, their thickness was obtained, and average results are reported.

The microfibril angle ( $\alpha$ ) was calculated using Equation (13) [31]:

$$\varepsilon = \ln \left( 1 + \frac{\Delta L}{L_0} \right) = -\ln(\cos \alpha) \quad (13)$$

where  $\varepsilon$  is the strain obtained from the stress vs strain curve,  $\alpha$  is the microfibril angle (°),  $L_0$  is the initial gauge length (mm),  $L_f$  is the elongation at break (mm).

## 2.10. Thermogravimetric analysis

Thermogravimetric analysis (TGA-DTG) can be usually performed to determine decomposition profiles of natural fibers when subjected to different temperatures [48]. Thermogravimetric curve (TG) and the derivative thermogravimetric curve (DTG) of PAFC were obtained using a Q50 TA Instruments thermogravimetric analyzer (New Castle, DE, USA). For the purpose, an adequate amount of ground fibers was placed in an open aluminum pan under a nitrogen ( $\text{N}_2$ ) gas atmosphere at a temperature of 30 °C for 60 s, and then heated until a temperature of 500 °C was reached with a heating rate of 10 °C/min.

## 3. Results and discussion

### 3.1. SEM microscopy

Fig. 2a and b show SEM micrographs of the top surface of the fiber cloth at different magnifications, while Fig. 2c and d show the morphology of the Yanchama fiber after the grinding process at different magnifications. Overall, the SEM micrographs of the PAFC display several fibrils bonded together [34] with a significant roughness on the surface, which might produce an outstanding binding effect with a polymer matrix, resulting in a composite material with improved mechanical resistance [27,53]. In addition, it can be observed that fibers are aligned with a longitudinal axis with some serrations or irregular shapes. This morphology is prone to be used for composite fabrication because it produces a locking effect that eases the load distribution in the resulting material [54]. Moreover, Fig. 2b shows the presence of amorphous materials present in the fiber, accompanied by some waxy impurities observed as white spots over the fibrils [55,56]. After the fiber cloth underwent a grinding process, it can be observed in Fig. 2c and d that the fiber particles possess a ribbon-like structure with a thickness of a couple of micrometers. Overall, the surface roughness appears to have decreased when the fiber is ground, but in contrast, the ground fiber offers a significant increase in the surface area between the fiber reinforcement and a polymer matrix, which may produce a composite material with improved mechanical properties [57].

### 3.2. Chemical composition analysis

Table 1 exhibits the chemical composition of PAFC along with a comparison with other natural lignocellulosic fibers (NLF) from the literature. PAFC is comprised of 58.03 % cellulose, 0.51 % hemicellulose, and 1.38 % lignin. It can be observed that PAFC possesses a significantly lower hemicellulose and lignin content when compared to other chemical compositions reported in literature, which can yield enhanced mechanical properties [58–60], thermal stability [61], and biodegradability [59,62] when used as a reinforcement for polymer composite materials.

### 3.3. Density measurement

The density for the PAFC was determined to be  $1.5318 \pm 0.001 \text{ g/cm}^3$ . This value is slightly higher when compared to other NLFs, such as *Thespesia populnea* bark [67], *Bauhinia vahlii* fiber [68], and *Cissus quadrangularis* stem [69] with a density of 1.41, 1.47, and 1.51  $\text{g/cm}^3$ , respectively. This phenomenon can be attributed to the positive correlation between cellulose content and density of an NLF due to its crystalline nature [70].

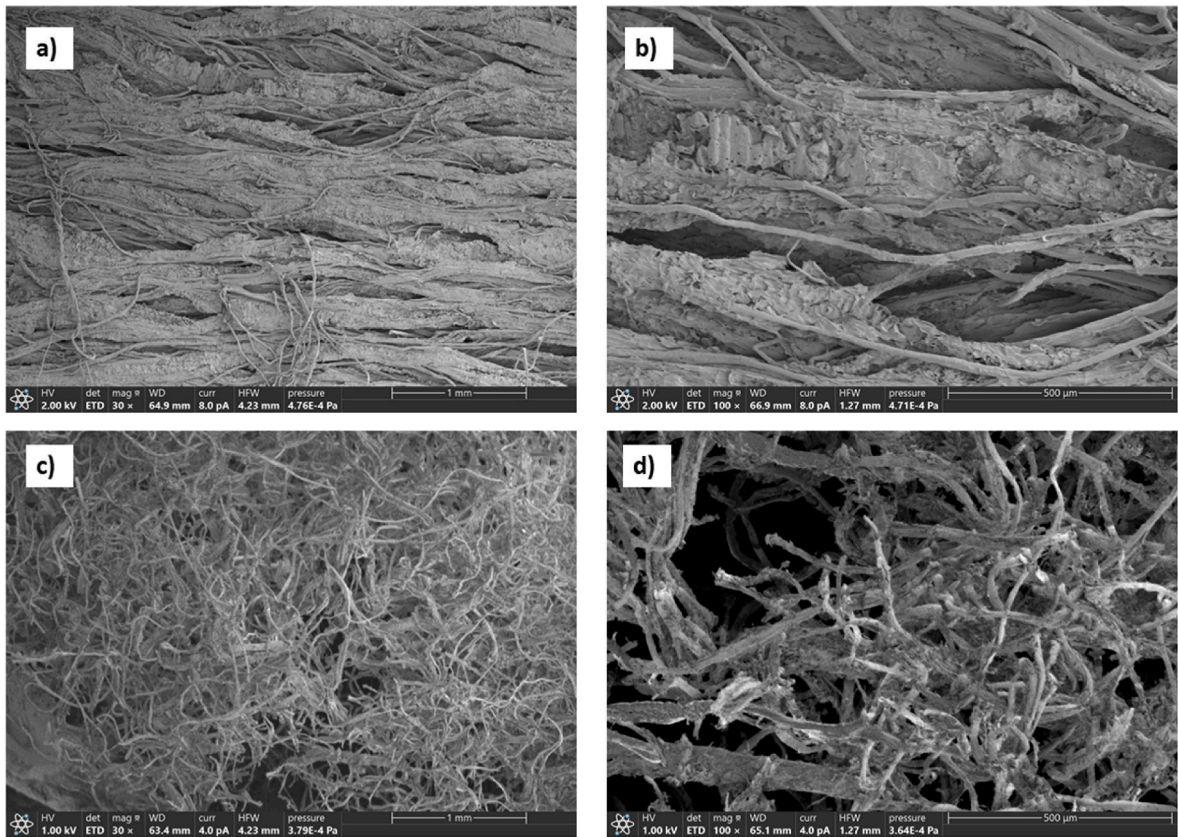


Fig. 2. SEM micrographs of a) PAFC with a magnification of 30×, b) PAFC with a magnification of 100×, c) Ground *Poulsenia Armata* fibers with a magnification of 30×, and d) Ground *Poulsenia Armata* fibers with a magnification of 100x

Table 1  
Comparative evaluation of the chemical composition.

| NLF              | Cellulose content (%) | Hemicellulose content (%) | Lignin content (%) | Reference |
|------------------|-----------------------|---------------------------|--------------------|-----------|
| Poulsenia armata | 58.0                  | 0.5                       | 1.4                | This work |
| Raphia vinifera  | 52.0                  | 13.0                      | 25.0               | [43]      |
| Acacia nilotica  | 56.5                  | 14.4                      | 8.3                | [63]      |
| Ferula communis  | 53.3                  | 8.5                       | 1.4                | [64]      |
| Hemp             | 70.2                  | 17.9                      | 3.7                | [65]      |
| Trinidad coir    | 48.6                  | 8.2                       | 30.4               | [66]      |

3.4. Water absorption behavior of PAFC

Fig. 3 shows the average variation of absorbed water as a function of time for PAFC. Natural fibers possess a hydrophilic nature and are prone to water and humidity absorption [40,43]. For PAFC, it can be observed that Yanchama absorbed approximately 360 % of its weight in water during the first hour of the test, which can be attributed to a capillary effect produced in the inner section of the *Poulsenia Armata* fiber due to the high cellulose content in the fibers [71–73]. Once this initial stage has been finished, an additional slight water uptake can be observed up to 168 h of the test, which is probably produced by the water absorption in smaller pores of the fibers [43]. After surpassing the 168-h threshold, it can be observed that a final saturation stage develops with a characteristic plateau [71,73].

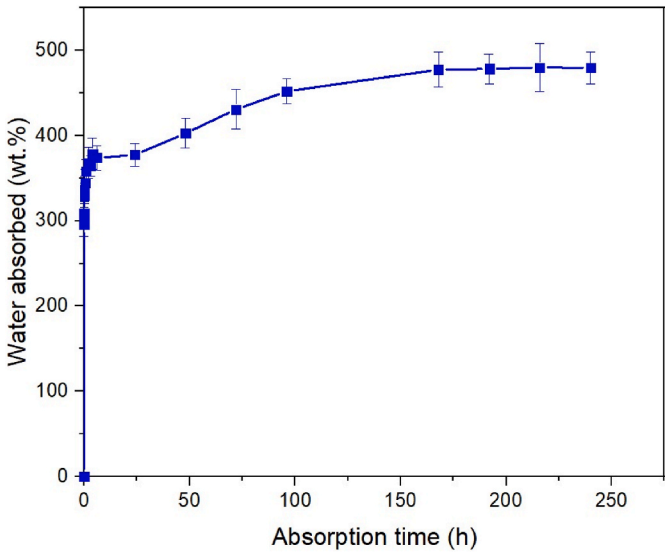


Fig. 3. Water absorption behavior of Poulsenia Armata fiber cloth.

3.5. Solid State Nuclear Magnetic Resonance spectroscopy (NMRS)

Fig. 4 depicts the high-resolution <sup>13</sup>C Solid-State NMR spectrum of the PAFC. Two smaller peaks can be observed at approximately 174.5 and 167.4 ppm, which correspond to aromatic resonance from lignin [66]. In addition, another peak is found at around 104.5 ppm, which indicates the presence of cellulose C-1 [74]. In the same way, different peaks can be found at 88.2 and 82.3 ppm, which correspond to cellulose

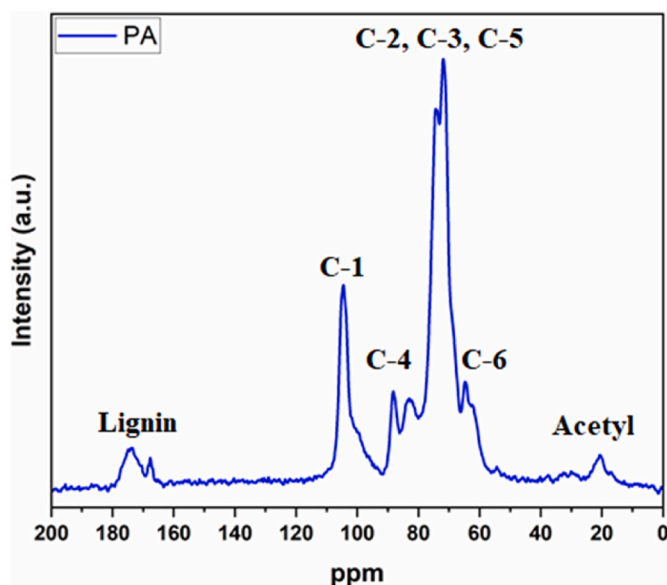


Fig. 4. High resolution  $^{13}\text{C}$  NMR spectrum of Poulsenia Armata fiber cloth.

C-4 with a more ordered and crystalline structure [74,75]. Two major peaks can be detected at approximately 74.2 and 71.8 ppm, which are allocated to C-2, C-3, and C-5 carbons from cellulosic structures [52,74]. A different peak is observed at 64.6 ppm, corresponding to the C-6 carbon atom resonance. Finally, a considerably minor peak can be found at around 20.9 ppm, which corresponds to acetyl carbons found in hemicellulose [75]. Overall, the NMR spectrum obtained for PAFC indicates a structure with an important cellulosic component and a slight presence of hemicellulose and lignin.

### 3.6. X-ray diffraction

Fig. 5 presents the XRD pattern for the PAFC. This analysis is commonly used for the study of crystalline materials. In that sense, the crystallinity index and crystallite size for PAFC was determined to be around 70 % and 2.76 nm, respectively, which is an indicative of the level of organization of the polymer chains []. The high cellulose content determines the higher crystallinity level. This is actually an indicator of a suitable material for polymer composite reinforcement [76].

Bragg's angles of  $15.68^\circ$  and  $23.22^\circ$  displayed the highest peak

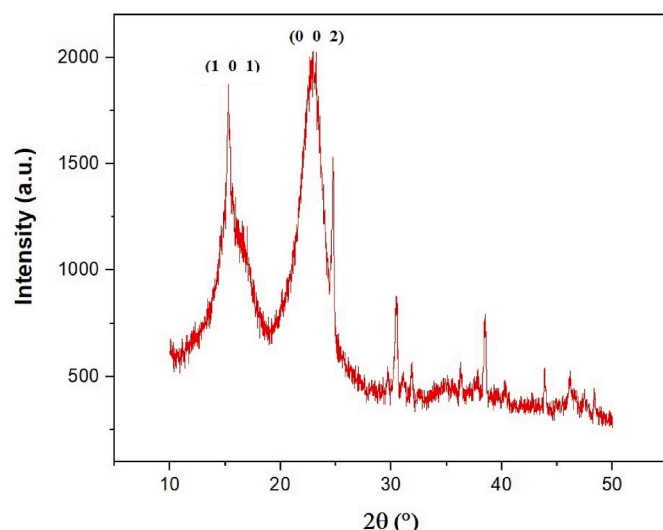


Fig. 5. XRD diffraction pattern of Poulsenia Armata fiber cloth.

intensity, pointing to (1 0 1) and (0 0 2) planes, respectively. The calculated lattice parameter of the PAFC corresponds to 7.82 Å. However, this parameter cannot be considered as an indicator that the material is crystalline, and only applies to areas where the presence of cellulose is higher. It is worth noting that the high degree of crystallinity, combined with the crystalline structure shown in those peaks, is considered a positive indicator of sound mechanical properties, which translates into better fiber strength results.

### 3.7. FTIR spectroscopy

Fig. 6 presents the FTIR spectra obtained for the PAFC, while Table 2 shows the FTIR absorption bands for the fiber. A major absorption band is observed at approximately  $3331\text{ cm}^{-1}$ , which corresponds to the stretching vibration of  $-\text{OH}$  found in cellulose and hemicellulose [62]. A different absorption band can be distinguished at around  $2905\text{ cm}^{-1}$ , which is characteristic of the stretching vibration from  $-\text{CH}$  and  $-\text{CH}_2$  found in cellulose and hemicellulose [32,34]. A minor peak can be observed at approximately 2250, which indicates a slight presence of double-bonded carbon ( $\text{C}=\text{C}$ ) found in wax [25,74] and the stretching of  $-\text{COOH}$  present in lignin [77]. Another absorption band can be noted at around  $1730\text{ cm}^{-1}$ , which is indicative of the stretching of  $\text{C}=\text{O}$  from acetyl groups found in hemicellulose [78]. A different peak can be observed at around  $1627\text{ cm}^{-1}$ , which indicates the presence of  $\text{C}-\text{O}$  stretching from acetyl groups from hemicellulose and lignin [74,78]. Another absorbance band can be observed at approximately  $1425\text{ cm}^{-1}$ , which corresponds to the stretching vibration of  $\text{CH}_2$  groups characteristic of cellulosic structures [59] and the  $\text{CH}$  bonding present in lignin [79]. A different peak around  $1367\text{ cm}^{-1}$ , which corresponds to the symmetric stretching vibration from the methoxyl group found in cellulose [80]. A different absorbance band can be observed at  $1061\text{ cm}^{-1}$ , which is characteristic of the vibration of  $-\text{CO}$  and  $-\text{OH}$  bonds in lignin [81,82]. Overall, the obtained spectrum indicates that the PAFC possesses a reduced lignin content when compared to the content of cellulose and hemicellulose.

### 3.8. Thermogravimetric analysis

Fig. 7 presents the thermogravimetric curve (TG) and its derivative (DTG) for PAFC, while Table 3 illustrates the main stages and parameters of the test. It can be observed that PAFC has an initial weight loss of

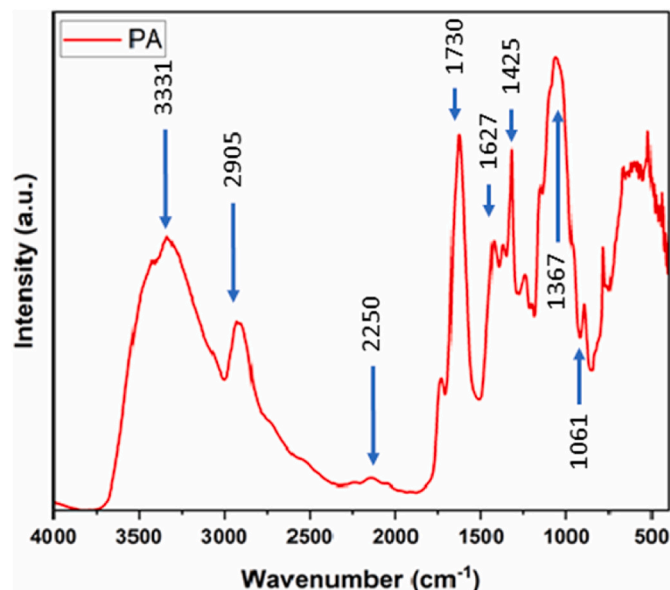


Fig. 6. FTIR spectrum of Poulsenia Armata fiber.

**Table 2**  
FTIR absorption bands of *Poulsenia Armata* fiber.

| Wavenumber (cm <sup>-1</sup> ) | Allocation                                                          |
|--------------------------------|---------------------------------------------------------------------|
| 3331                           | -OH bonds from cellulose and hemicellulose                          |
| 2905                           | -CH and -CH <sub>2</sub> vibration from cellulose and hemicellulose |
| 2250                           | C≡C found in wax and -COOH from lignin                              |
| 1730                           | C=O from acetyl groups from hemicellulose                           |
| 1627                           | C-O stretching from acetyl groups                                   |
| 1425                           | CH <sub>2</sub> groups characteristic from cellulose                |
| 1367                           | Stretching vibration from methoxyl group from cellulose             |
| 1061                           | -CO and -OH bonds in lignin                                         |

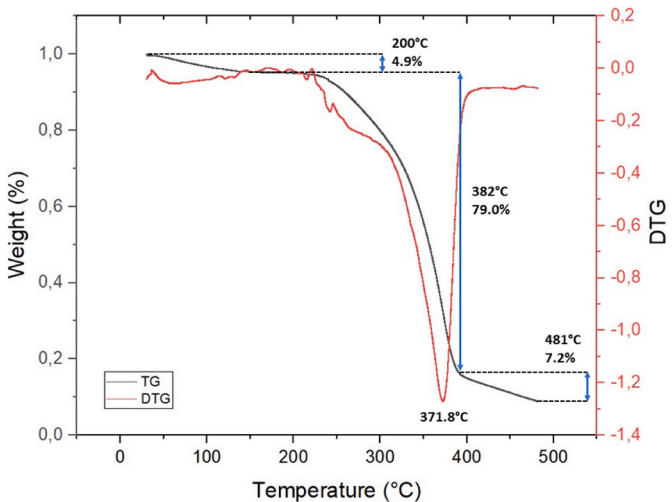


**Fig. 7.** TG and DTG curves for *Poulsenia Armata* fiber cloth.

**Table 3**  
Relationship between temperature and weight loss.

| Temperature                   | Weight loss                 |
|-------------------------------|-----------------------------|
| $T_{onset}$ (°C) <sup>a</sup> | $T_{max}$ (°C) <sup>b</sup> |
| 244.5                         | 371.8                       |
|                               | $W_{200}$ (%) <sup>c</sup>  |
|                               | $W_2$ (%) <sup>d</sup>      |
|                               | $W_{481}$ (%) <sup>e</sup>  |
|                               | 4.9                         |
|                               | 79.0                        |
|                               | 91.1                        |

<sup>a</sup> Temperature at which main decomposition begins.  
<sup>b</sup> Temperature at which the highest decomposition rate is achieved.  
<sup>c</sup> Weight reduction produced at temperatures up to 200 °C.  
<sup>d</sup> Weight reduction produced by the end of the second phase.  
<sup>e</sup> Weight reduction at a temperature of 550 °C.

4.9 % due to the evaporation of water in the fiber [26,83,84]. The main decomposition stage takes place within the range of 244–382 °C with a maximum rate at 371.8 °C during this stage a 79.0 % of the mass is decomposed, which is attributed to the degradation of hemicellulose and glycosidic links of cellulose [69,85]. In addition, two sharp decreases in weight can be differentiated within this region, the first one from 227 to 260 °C, which corresponds to the decomposition temperature range for hemicellulose, and the second one from around 240 to 350 °C which corresponds to a faster decomposition rate and is corresponding to the decomposition of cellulose [42]. From 382 °C up to 500 °C, a final decomposition stage occurs at which 7.2 % of the mass is decomposed due to the oxidative degradation of the carbonized residue of the PAFC [86].

### 3.9. Mechanical properties of the *Poulsenia armata* fiber cloth

Fig. 8 presents a representative stress vs strain curve for the PAFC. The experimental results indicate an ultimate tensile strength of  $28.95 \pm 0.96$  MPa, a modulus of elasticity of  $227.11 \pm 6.78$  MPa, and an elongation percentage at break of  $14.91 \pm 0.99$  %. In addition, the

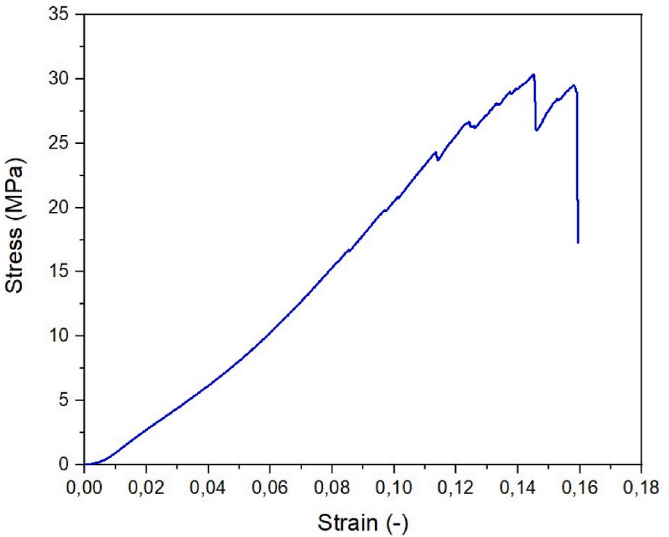


**Fig. 8.** Representative stress vs stress response for *Poulsenia Armata* fiber cloth.

microfibril angle was determined to be  $28.03 \pm 1.24^\circ$ . From the curve, three different zones can be differentiated. The first one, up to a strain of around 0.005, shows an increase in the strain without a distinguishable increase in the tensile stress, which is produced due to fiber crimp [87, 88]. This region is followed by a linear region that extends to a strain of approximately 0.115, from which the modulus of elasticity of the PAFC was calculated. From a strain of 0.115 up to failure, the tensile behavior of the fiber becomes more irregular, and different abrupt drops in the tensile stress are observed. This phenomenon is attributed to the partial collapse of weak primary cell walls of a single fibril and the rupture of smaller fibrils within the PAFC [89]. Table 4 presents the mechanical performance of PAFC along with a comparison with different natural lignocellulosic fibers (NLFs) reported in the literature. The results comparison shows that while *Poulsenia Armata* exhibits a slightly lower load-bearing capacity compared to other lignocellulosic fibers, its relatively high ductility highlights its potential in applications where energy absorption, toughness, and crack-bridging capacity are prioritized [90, 91].

## 4. Conclusions

In this study, the physical, thermochemical, and mechanical properties of *Yanchama (Poulsenia Armata)* fiber cloth from the Ecuadorian Amazon region were analyzed. The main conclusions can be summarized as follows.

**Table 4**  
Comparative evaluation of the mechanical properties of natural lignocellulosic fibers reported in literature.

| NLF                              | Ultimate tensile strength (MPa) | Modulus of elasticity (GPa) | Elongation at break (%) | Reference |
|----------------------------------|---------------------------------|-----------------------------|-------------------------|-----------|
| <i>Poulsenia armata</i>          | $28.95 \pm 0.96$                | $0.23 \pm 0.01$             | $14.91 \pm 0.99$        | This work |
| <i>Corypha taliera</i> fruit     | 43.24–53.55                     | 0.45–0.57                   | –                       | [92]      |
| <i>Tridax procumbens</i>         | 25.75                           | $0.94 \pm 0.09$             | $2.77 \pm 0.27$         | [93]      |
| <i>Vachellia farnesiana</i> bark | $33.08 \pm 1.3$                 | 1.5–1.7                     | 2.2–2.4                 | [94]      |
| <i>Manicaria saccifera</i>       | 54.98–81.67                     | 1.81–2.42                   | 4.97–5.42               | [95]      |
| <i>Leopoldinia piassaba</i>      | 22–23                           | 1.12–1.45                   | 5–7                     | [96]      |

- (1) The characterization of PAFC demonstrated that the fiber possesses different attributes that would constitute it a promising candidate for composite reinforcement applications. PAFC exhibited a density of 1.53 g/cm<sup>3</sup> and a high cellulose content of around 58 %, while its lignin and hemicellulose content were remarkably low, with 1.38 and 0.51 %, respectively. This chemical composition was confirmed through FTIR and NMR, and is directly associated with a favorable mechanical behavior was obtained.
- (2) SEM micrographs revealed that PAFC is composed by several unidirectional fibrils which forms a rough surface. This morphology can produce an enhanced interfacial adhesion with a polymer matrix leading to a favorable stress transfer in a composite material.
- (3) Through XRD analysis the potential of PAFC was further confirmed due to a high crystallinity index of approximately 70 % and a crystallite size of 2.76 nm. These parameters are typically correlated to improved mechanical performance.
- (4) The tensile tests yielded an ultimate tensile strength close to 30 MPa, a modulus of elasticity of 227 MPa, and an elongation percentage at fracture of 15 %, which is indicative of a positive correlation of mechanical strength and ductility. Despite its slightly lower mechanical resistance when compared to other natural fibers, its pronounced ductility would constitute PAFC as a suitable reinforcement when a crack-bridging behavior is required.
- (5) Water absorption tests allowed to determine that PAFC has an initial water uptake of approximately 360 %, reaching an equilibrium after 168 h. This behavior highlights that PAFC would be greatly favored through surface treatments in order to improve the fiber moisture resistance.
- (6) Overall, the present research demonstrates that PAFC is a viable natural fiber reinforcement for lightweight and sustainable composites. Future work should explore surface modification techniques to optimize its performance in demanding environments.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Akindele Odeshi reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Duncan E. Cree reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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