Proximate chemical analysis and effect of age and height of Oxytenanthera abyssinica on fiber morphology and chemical compositions for pulp and paper production potential

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Research Article

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Abstract

This study examined the chemical composition, fiber morphology, and physical properties of *Oxytenanthera abyssinica* culm to assess its pulping potential. TAPPT and Franklin's methods have been used for experiments. The statistical analysis showed that the chemical composition of *Oxytenanthera abyssinica* is influenced by the age of the plant.The amount of cellulose in the culm increases with age, while ash and extractive content decrease with an increase in age. Thethree-year agedaverage chemical content of the plant was 49.26 ± 0.13, 21.31 ± 0.15, and 20.63 ± 0.12 cellulose, hemicellulose, and lignin contents respectively. There is a significant difference between one, two, and three-year-aged plants ($P < 0.05$) in cellulose, lignin, ash, and extractive content. The position of the culm also affectsthe fiber morphology of *Oxytenanthera abyssinica*. The fiber's length, diameter, cell wall thickness, and lumen diameter increase from top to bottom, whereas the flexibility and slenderness ratio decrease. The average fiber morphology of *Oxytenanthera abyssinica* was flexibility ratio (0.72 ± 0.10), Runkel ratio (0.35 ± 0.10), slenderness ratio (109.98 ± 0.21), lumen diameter (15.63 ± 0.03 μm), cell wall thickness (2.74 ± 0.03 μm), fiber length (2.40 ± 0.10 mm) and fiber diameter (21.83 ± 0.09 μm). The above data showed that the mean value of the fiber length of the plant is greater than 1.5mm, the Runkel ratio was less than 1, and the slenderness ratio was greater than 70 standard values. The result also showed that the average bulk density and the moisture content were 660 kg/m^3 and 9.6%, respectively. Although *Oxytenanthera abyssinica* is widely grown in the study area, no comprehensivestudies have been carried out on fiber morphology, chemical composition, and physical properties based on age and height. Thus, this research was carried out to study the plant's fiber characteristics to assess its suitability for pulp and paper production.Based on the above data, the three-year aged bottom part of *Oxytenanthera abyssinica* is recommended for moreyield of pulp and high-quality paper production than the first and second-year aged plant.

1. Introduction

Bamboo is one of the non-wood forest resources with significant potential as a substitute for wood resources due to its high productivity, rapid growth, and ease of reproduction [1]. It grows rapidly in tropical and subtropical regions and is called "green gold" because of its diversity [2]. Bamboo has received much ecological and economic attention in recent decades due to its rapid growth, compact inheritance, and superior mechanical strength compared to other plants [2, 3]. Around the world, more than 1,500 species of bamboo have been found in 90 genera, it covering 36 million hectares (ha) from latitudes 460 °N to 470 °S, 4000 meters above sea level [4]. It occurs in many countries, such as South America (Colombia, Ecuador, and Peru), Central America (Honduras, Mexico, and Costa Rica,) and Asia [5].

In Africa, Ethiopia has the largest bamboo forest [6]. *Oxytenanthera abyssinica*, a commercially and environmentally important bamboo species native to Ethiopia, accounts for around 85 percent of the country's total bamboo acreage [7, 8]. It covers around 850 000 hectares in the country's center, southwest, and south regions [8]. *Oxytenanthera abyssinica* is a fast-growing, high-yielding renewable resource. It is low-cost, quick-growing, and widely available, and it has physical and mechanical qualities similar to wood [9].

Bamboo fiber has been studied as a viable alternative pulp material in various places worldwide [10]. Bamboo's productivity and rapid growth, as well as its good fiber width (0.01–0.03 mm) and long fibers (1–4 mm), can be used to make a wide variety of papers and paper products [11]. Compared to other plants, bamboo has higher cellulose content; a study showed that one hectare of bamboo is estimated to contain 6–7 times higher cellulose content than those collected from deciduous or coniferous forests [12]. The tear strength of bamboo pulp is comparable to that of pulp obtained from softwood [13]. These properties have made bamboo fiber widely accepted as an excellent and alternative raw material base for paper and pulp production [14].

The pulping and bleaching process of bamboo fiber and the papermaking potential are directly affected by the chemical and physical properties of the raw material [15]. The most important aspects determining the characteristics of paper and pulp production are the bamboo species' type, age, and origin [16]. Using morphological characteristics of the bamboo species such as wall thickness, lumen width, fiber diameter, fiber length, and their derivative, such as flexibility ratio, theRunkel ratio, as well as slenderness ratio, determine its suitability for pulp and paperproduction [12, 17]. Chemical composition is another critical factor in determining the suitability of paper and pulpproducts. The content of the extractives directly affects the yield of pulp. Higher extractive concentrations reduce pulp yields.On the other hand, the concentrations of lignin, cellulose, and hemicelluloses are primarily involved in pulping behavior, and the fibers' morphology affects the paper's strength [18].

The rising demand for wood and fiber and the decreasing availability of wood supplies have prompted researchers to look for non-wood plants with fiber properties similar to wood. As a result, nonwoody plants like bamboo could serve as an alternate source of pulp and papermaking raw materials.The use of nonwoody plants as a source of raw materials for the pulp and paper industries has its own contribution to reducing the greenhouse gas emissions that cause climate change [19].

In order to use bamboo for pulp and paper qualities, it is critical to understand how its chemical composition varies with age and height. The age and height position of the plant affect its properties. Bamboo's chemical composition differs depending on the height of the culm, environment, age of the plant, type of the species, and region in which the plant is found [16]. However, *Oxytenanthera abyssinica* fiber morphological variation based on age and chemical property differences caused by culm location have yet to be reported in the study area (western part of Ethiopia, pawi woreda). Hence, this study is conducted on a detailed analysis of the pulping potential of *Oxytenanthera abyssinica* based on its physical properties, chemical composition, and fiber morphological characteristics.

2. Materials And Methods

2.1. Material

Analytical-grade substances were employed in this study. Ethanol (99.4%, Ethiopia), sodium hydroxide (ALPHA CHEMIKA, India), nitric acid (50%), safranin solution (Labchem), xylene, canada balsam (ALPHA CHEMIKA, India), and sulfuric acid (98%, India) were the main chemicals used in this study. All chemicals (Rankem, India) were purchased from Charcos, Addis Ababa, Ethiopia. Analytical balance, Reflux condenser, Crushing machine, Thermometer, Filtering crucible, Crucible, Magnetic stirrer, different size Sieves, Motic BA210 microscope, Water bath, Whatman grade 1 filter paper, Leica sliding microtome, and 3D light microscope were some of the common types of instruments and apparatus used in these experiments.

2.2. The Study Area

Lowland Ethiopian bamboo (*Oxytenanthera abyssinica*), one to three year age stems, were taken from the west part of Ethiopia, Metekel zone in Pawe woreda (Fig. 1). It is located at an elevation of 1120 meters above sea level, with longitudes of 36° 20' to 36°32' and latitudes of 11°12 to 11°21'. It has a humid and hot climate, with temperatures ranging from 19.4°C to 37.6°C [20].

2.3. Sample collection, identification and use

According to TAPPI standards 2002 [21], twenty *Oxytenanthera, abyssinica* plants with an average age of three years, were randomly selected from a natural forest found near village 7 town, pawe woreda for fiber characterization test. The plant's culms (9 meter) were cut above the second node, or around 30 cm, because cutting the culms below this height will slow the growth of the remaining culms. The culms were divided into three equal lengths, each measuring 3m, for the bottom, middle, and top segments to examine the culms' fiber characteristics.

For proximate chemical analysis, age (1, 2 and 3 year), *Oxytenanthera abyssinica* were randomly identified and selected based on age.The culms of identified *Oxytenanthera abyssinica* were cut with axes, after removing the branches and top parts of the plant, the culms were rinsed repeatedly with water and then chopped into chips with a planer machine. The chips were dried in the sun for 2 weeks. The dried chips of *Oxytenanthera abyssinica* were crushed, and the mesh size of over 60 mesh and under 40 mesh size were collected and stored in polyethylene bottle for proximate chemical analysis.

The identification of the plant species was carried out by taxonomists at Addis Ababa University, College of Natural Sciences Department of Biology and Biodiversity Management and the use of plant parts in the present study comply with international, national, and/or institutional guidelines [22]. A permission was received from the Pawe Woreda Agricultural and Rural Development Office to harvest plant material.

2.4. Physical properties of *Oxytenanthera abyssinica*

2.4.1. Moisture content

Sample blocks representing the 3 years *Oxytenanthera abyssinica*, at the top, middle and bottom position with 6 replicates were used to measure moisture content. All sample blocks were cut from fresh culms with a wall thickness of 10 x10 mm x culms. They were weighed and dried in a 105°C oven for 48 hours until a consistent weight was achieved. Afterward, the sample blocks were placed in a desiccator for 30 minutes to cool down before being re-weighed.The samples were weighed using a digital scale with a 0.001 gm precision and oven-dried at 105 ^{o}C for 72 hours to achieve a constant weight value. The moisture content was determined using ASTM 5229 using Eq. (1) [23].

Moisture content = $\frac{\text{GMoven}-\text{ODW}}{\text{ODW}} \times 100\%$………………(1)

Where: GW = green weight (the weight of sample before drying); ODW = the weight of a sample after drying with oven (Oven dry weight)

2.4.2. Basic density

Sample blocks representing the 3 years *Oxytenanthera abyssinica*, at the top, middle and bottom position (3 cm each) with 6 replicates were used to measure moisture content (Fig. 2). After removing the outer part of the plant samples, the middle region of each internode was taken fromthe top, middle, and bottom culms segments for basic density tests. Six sample block was cut to a culms wall thickness of 30cm x 30cm for each position. The sample blocks (18 samples) were oven-dried for 48 hours at 103°C until they attained a predetermined weight. The dry weight of the oven was calculated by measuring the weight of the sample block.The oven-dry weight and green volume were used to calculate density. The water displacement method was used to determine the green volume of the sample. Eq. (2) was used to compute basic density [23].

Basic density = $\frac{M_o}{V_2}$ ……………………………………(2)

Where M_o is the oven-dried mass of each sample in g, $V_2$is the fully saturated (maximum) volume in ml.

2.5. Fiber morphology of *Oxytenanthera abyssinica*

TAPPT standards performed proximate chemical analysis were used: TAPPI T203 om 99 for alpha-cellulose content, TAPPI T211 om-93 for ash content, TAPPI T207 cm-99 for water solubility, TAPPI T222 om-02 for lignin content, TAPPI T212 om-98 for 1% NaOH solubility and TAPPT T204 cm-97 for alcohol-benzene solubility. The wise technique was used to analyze holocellulose. The cell lumen, cell wall thickness, fiber breadth, and fiber length were all measured after fiber maceration using Franklin's method. Three derived values were also computed based on the fiber dimensions such as slenderness ratio (fiber length ÷fiber diameter), flexibility ratio [(fiber lumendiameter ÷fiber diameter)·100], and Runkel ratio [(2 ·fiber cell wall thickness)÷fiberlumen diameter] [24, 25]. The findings were then examined to see if *Oxytenanthera abyssinica* might be used to make pulp and paper.

2.6. Fiber dimensions measurement procedure

The width and length of the fibers were examined using the following methods (Fig. 3). The maceration processwas performed using amatch-size sample and nitric acid (50%). For fiber separation, matchstick-sized samples were placed in test tubes, and immersed in nitric acid solution, and kept at 70 ^{o}C for 5–6 hours. After cooling, the nitric acid was drained, and the fibers were rinsed in distilled water before being separated on the Whatman grade 1 filter paper [26]. A Motic BA210 microscope with a camera was used to take the images.

2.7. Cell dimension measurement

Slices with a thickness of 20m were cut with a Leica sliding microtome for cell measurement [27]. To eliminate excess safranin solution, the slices were soaked for one minute in a safranin solution (1 gram/100 ml water) and alcohol concentrations of 25%, 50%, and 75%, respectively. Slices were submerged in xylene for 1 minute before being placed on a standard 7.5cm x 2.5cm slide. Finally, a small amount of Canada balsam was dropped and left to dry before applying the slide cover. The lumen diameters and cell wall thickness were measured using Motic software and an image was recorded with a camera attached to a Motic BA210 microscope (Fig. 3).

2.8. Scanning Electron Microscopy (SEM) Analysis

Scanning electron microscopy (high-vac., SED PC-std, 15 kV) was used to obtain SEM images of extracted cellulose. ImageJ software analysis was used to examine the size image of the samples.

2.9. Statically analysis

Analysis of variance (one-way ANOVA), p-value, confidence limit (CI) and standard deviation (SD) on the results was performed using Origin 8 and Microsoft excels software. Measurements for cellulose, lignin, hemicelluloses, ash, extractives, solubility in alcohol, benzene, 1% NaOH, hot water, and cold water were performed three times (n = 3) for 1, 2, and 3 year age plants. For each sample, more than 14 readings were taken from the bottom, middle, and top positions of the plant to measure the fiber morphology (Table 2 and Table 3). Six repetitions of each experiment were utilized to measure physical properties such as basic density and moisture content. We put the average result with standard deviations (SD) in the manuscript. A 95% confidence limit of Pvalue less than or equal to 0.05 was used to determine significance. Mean comparisons were performed using Tukey Test.

3. Result And Discussion

3.1. Physical properties of *Oxytenanthera abyssinica*

3.1.1. Moisture content

The species type, the age of the culm, the place of growth, the length of the culm, and the thickness of the culm wall all affect how much moisture is present in a particular bamboo species [28]. This study measured the moisture contents at the top, middle, and bottom of a three-year-old *Oxytenanthera abyssinica* bamboo species. The result showed that 9.37 ± 0.24 percent mean moisture contentwas observed.The proportion of moisture content decreased from the bottom to the top as the culm height of *Oxytenanthera abyssinica* increased. The top, medium, and bottom parts of *Oxytenanthera abyssinica* moisture content were 8.73 ± 0.21, 9.4 ± 0.32, and 9.99 ± 0.21 percent, respectively. There was no significant variation ($p < 0.05$) in moisture content between the top, middle, and bottom parts of the plant. This showed that the position of the culm does not show a significant effect on the content of moisture. The moisture content of the culm dropped as the height of the culm increased, which is consistent with previous findings from other bamboo species [29]. In the current study, the average moisture content is significantly lower than other bamboo species, such as *Dendrocalamus asper*, *Bambusa vulgaris*, *Gigantochloa scortechini*, and *Schizostachyum grande*. For instance, the moisture content of the top section of the above bamboo species was found to be 20.83, 15.29, 16.09, and 23.36, respectively [30]. This shows that, in comparison to the other bamboo species described above, *Oxyrenanthera abyssinica* has a higher potential for paper production. This is because moisture reduces the bonds between the fibers formed in the papermaking process and reduces paper strength [31]. According to studies, paper loses 50% of its strength when it has a moisture level of 14%, which may be achieved by conditioning the paper at 90% relative humidity [31].

3.1.2. Basic density

Table 1 shows the basic density of *Oxytenanthera abyssinica's* at different heights. The average basic density was 0.66 ± 0.114 kg/ml, which varies between 0.362 to 1.245 g/ml. The table showed that, unlike moisture content, the basic density increased from bottom to top with values of 0.88 ± 0.25, 0.64 ± 0.034, and 0.42 ± 0.06 g/ml, respectively. There was no significant variation in basic densitybetween the top and middle as well as middle to bottom regions ($P < 0.05$). However, there was a significant difference between the top and bottom portions ($p < 0.05$) (Table 1). *Yushania alpine* (Ethiopian highland bamboo species), recorded the basic density at the top (704.033 kg/m^3**)**, middle **(**691.56 kg/m^3), and bottom (563.06 kg/m^3) parts [32]. It has a lower basic density at the top position than *Oxytenanthera abyssinica's*. The current plant's basic density was lower in the center and bottom than *Yushania alpina* (Table 1), indicating that it has a higher pulping capability than highland bamboo. Because a low-density basic wood creates a paper with a lower beating resistance, high folding strengths, bursting, and sheet density [33, 34].

Table 1
Basic density and moisture content of *Oxytenantheraabyssinica*

Location	Statically value	Mean basic density (g/ml)	Mean moisture content (%)
Top samples (TS)	N	6	6
	$\bar{x}$ ± STD	0.88 ± 0.30 ^{a}	8.73 ± 0.21^{a}
	95% CI_L	0.15	8.20
	95% CI_U	1.65	9.26
Middle samples (MS)	N	6	6
	$\bar{x}$ ± STD	0.64 ± 0.036^{b}	9.40 ± 0.32^{b}
	95% CI_L	0.56	8.61
	95% CI_U	0.74	10.2
Bottom samples(BS)	N	6	6
	$\bar{x}$ ± STD	0.42 ± 0.06^{c}	9.99 ± 0.21^{c}
	95% CI_L	0.27	9.64
	95% CI_U	0.58	10.34
The average value	N	18	18
	$\bar{x}$ ± STD	0.66 ± 0.11b	9.37 ± 0.24
	95% CI_L	0.46	9.01
	95% CI_U	0.86	9.73

Where: STD: standard deviation, CI: confidence interval, N: number of sample, and $\bar{x}$: mean value. All data were examined more than three times, and the mean value ± SD *was used. Values in the same column with the identical alphabetical letter are not significantly different (P ≥*

0.05), with a confidence limit of 95%.

3.2. Fiber morphology of *Oxytenanthera abyssinica*

An optical microscope, scanning electron microscope, and 3D optical surface profiler microscope were used to examine the surface of *Oxytenanthera abyssinica* fiber and its cross-sectional area. Fig.s 3 represent the cross-sectional area of the *Oxytenanthera abyssinica* bamboo block and the surface of its fiber. The cross-sectional structure of the bamboo culm is represented by many vascular bundles implanted in the scleral and parenchymal basal tissues (Fig. 4a). Parenchymalcells are characterized by thin walls and numerous simple holes that connect them. Pits can be seen mainly on the longitudinal walls. Sclerenchyma cells, on the other hand, have thick walls. Sclerenchyma produces bundles of fibers beneath and surrounding vascular bundles in most cases. The sclerenchyma surrounding the first cycle of peripheral vascular bundles is not obstructed by interfascicular parenchyma. The *Oxytenanthera abyssinica* possesses the longest interwoven fiber bundle coupled with cementing-like material to give great strength, as shown by SEM and optical imaging in Fig. 4.

Fiber characteristics are one of the most critical variables in determining a fiber's suitability as a pulp and paper raw material [35]. Thus, the purpose of this study component was to provide basic information on the morphological characteristics of *Oxytenanthera abyssinica* for the potential of pulp. Lignocellulosic materials have cell wall thickness, lumen width, fiber diameter, and fiber length. These factors determine if *Oxytenanthera abyssinica* fiber is acceptable for paper and pulp manufacture. The fiber characteristics features of the stem section of the *Oxytenanthera abyssinica* fiber are shown in Table 2.

Table 2
Fiber dimensions (Top, middle and bottom) of *Oxythenantera abyssinica*

Position	**Statically value**	**Fiber length (mm)**	**Fiber diameter (μm)**	**Cell wall thickness μm)**	**Fiber lumen diameter(μm)**
Top	N	14	14	22	20
	$\bar{x}$ ± STD	2.23 ± 0.01[a]	18.66 ± 0.22[a]	2.51 ± 0.11[a]	14.28 ± 0.04[a]
	95% CI_L	1.91	16.87	1.86	12.71
	95% CI_U	2.54	20.45	3.16	15.79
Middle	N	14	14	20	22
	$\bar{x}$ ± STD	2.38 ± 0.02[a]	21.98 ± 0.01[a]	2.90 ± 1.21[b]	15.54 ± 0.01[a]
	95% CI_L	2.02	18.76	2.55	12.80
	95% CI_U	2.75	25.20	3.25	18.28
Bottom	N	14	14	20	20
	$\bar{x}$ ± STD	2.59 ± 0.25[b]	24.87 ± 0.03[a]	2.91 ± 0.24[b]	17.09 ± 0.03[a]
	95% CI_L	2.22	23.12	2.11	16.34
	95% CI_U	2.96	26.62	3.71	17.86
Average for a plant	N	42	42	62	62
	$\bar{x}$ ± STD	2.40 ± 0.64	21.83 ± 0.09	2.74 ± 0.03	15.63 ± 0.03
	95% CI_L	2.20	20.18	2.53	13.84
	95% CI_U	2.60	23.48	2.95	17.42

All data were examined in triplicate, and the mean value ± SD was used. Values in the same column with the identical English alphabetical letter are not significantly different ($P \geq 0.05$), with the confidence limit of 95%. where: STD: standard deviation, CI_L: confidence interval lower, CI_U: confidence interval upper, N: number, $\bar{x}$: mean value

3.2.1. Fiber length

The fiber length is the number of binding sites available on fiber to create an interwoven network of fibers. It is calculated by measuring fiber from one end to the other [8]. In this study, fiber length of *Oxytenanthera, abyssinica* was measured, and the main result was recorded in Fig. 5. The result showed that the fiber length of *Oxytenanthera abyssinica* ranged from 1.32 to 3.55 mm, averaging 2.40 mm, with a 95% CI value of 2.20–2.60. Therefore, the expected fiber length is classified as long fiber(> 1.5 mm).The fiber length of *Oxytenanthera abyssinica* is comparable with the length of European red pine (2.15 mm), coniferous tree fibers (2.55 mm), jute (2.35 mm), kenaf (2.35 mm), and sisal (2.5 mm), [36, 37].The top and bottom parts of *Oxythenanteraa abyssinica* have significantly different ($P < 0.05$) fiber lengths. However, the length of the fibers in the top and middle parts is not significantly different (Table 2). The largest mean fiber length of *Oxytenanthera abyssinica* was found at the bottom of the plant, with a mean of 2.59 ± 0.25 mm, while the shortest (2.23 ± 0.01mm) was found at the top (Table 2). The plant`s fiber length decreased as it climbed from the bottom to the top. This result was comparable to the work of Wahab et al. (2009) [29]. According to their findings, the longest fiber was found near the bottom of the *Bambusa vulgaris* plant, while the shortest fiber was found at the top. However, according to Sharma et al. (2014) [38] and Aderounmu and Adelusi (2019) [39] finding, the axial section of the bamboo species, such as *Bambusa vulgaris* and *Dendrocalamu sstrictus* stems did not affect the length of the fibers. Differences in fiber lengths extracted from the axial section of *Oxytenanthera abyssinica* may be due to differences in internode lengths in different regions, asfiber lengthscorrelate with intermodal lengths [40].Because *Oxytenanthera abyssinica* has long fibers greater than 1.5 mm, it can build a stronger and larger network in the pulp than in short fibers, resulting in increased paper strength [41]. *Oxytenanthera abyssinica* possesses a higher fiber length when compared with a fast-growing grass called *Arundo donax* (fiber length of 1.73 mm), which has been used as an excellent raw material for handmade paper production [42].For the production of paper, long fiber lengths are preferred. Long fibers produce a sheet structure that is more open and less uniform. The stronger the paper's resistance to tearing, the longer the fibers are. The paper industry prefers long fiber materials for their excellent product [8, 43].Thus *Oxytenanthera abyssinica* can be a good source for the pulp industry.

3.2.2. Fiber width

Figure 6 shows the fiber width of *Oxytenanthera abyssinica* fibers. A fiber's width or diameter is usually measured from one end to the other, usually measured across thefiber length [8]. The data showed that theaverage width was 21.83 µm with a range of 13.38 to 29.78 µm with a 95% confidence interval of 20.18–23.48. Between the top and bottom parts, there was a significant difference in fiber diameter ($p < 0.05$). Fiber diameter increased from the bottom (24.87 ± 0.03 µm) to the top (18.66 ± 0.22 µm) (Table 2). This finding is different from the work of Wahab et al. (2009) [29]. According to their result, the middle part of *Bambusa vulgaris* had a larger fiber diameter (18.6 ± 0.20) than the top (16.5 ± 0.15) and bottom (15.8 ± 0.13) parts. *Oxytenanthera abyssinica* has a wider fiber diameter than other bamboo species, such as *Bambusa vulgaris* (14.8m) [44], *Dendrocalamus gignteus* (21.34 µm) [45], *Gigantochioa apus* (14.5 µm)[45], *Melocanna baccifera* (17.1 µm) [46]. *Eucalyptus grandis* (wood plant) and Bagasse of *Saccharum officinerum* (21.4 µm) (non-wood plant) have lower fiber diameters (19.00–20.00 µm) than *Oxytenanthera abyssinica* [47]. The fiber width of *Oxytenanthera abyssinica* (21.83 µm) is greater than that of two other plants that have been tested for pulp and paper properties such as *Melia azedarach* (hardwood plants with 13.45 µm fiber width) [48] and *Caesalpinia decapetela* (softwood plants with 18.63µm fiber width) [49]. This gives the idea that *Oxytenanthera abyssinica* also can be used as an excellent raw material for pulping.The increase in fiber diameter has been connected to the many chemical and physiological changes in cell walls during the growth processes and in the vascular cambium [50]. The paper's sheet density and surface properties are affected by the diameter of the *Oxytenanthera abyssinica* fiber.This is because paper made from fibers with a diameter of 20–40 µm frequently has high sheet density and surface properties [51]. According to the fiber diameters found in this work, the pulp will have few void spaces, resulting in fine-surfaced paper sheets with acceptable density [51, 38].

3.2.3. Cell wall thickness

Figure 7 shows the cell wall thickness of *Oxytenanthera abyssinica* fibers. The cell wall thickness of *Oxytenanthera abyssinica* ranged from 1.12 to 5.255 µm, with a mean value of 2.74 µm and a 95% confidence interval of 2.53–2.95. The thickest cell walls were found at the bottom, while the thinnest were found at the top. The top (2.51 ± 0.11 µm) and middle (2.90 ± 1.21 µm) sections have no significant ($P > 0.05$) change in their value. However, the top and bottom (2.91 ± 0.24µm) sections had significant changes in cell wall thickness ($P < 0.05$) (Table 2).*Oxytenanthera abyssinica* cell wall thickness is comparable to some wood plant cell wall thickness. It was demonstrated that *eucalyptus grandis* and *Ficus exasperate*, had average cell wall thicknesses of 2.94 µm and 2.0–3.0 µm, respectively [47, 52]. The plant's cell wall thickness is, however, less than that of *Rhizophora harrisonni* (~ 8.8 µm) and *Rhizophora racemosa* (~ 9.0 µm)[53]. Other bamboo species with thicker cell walls than the current plant, include *Bambusa beecheyana* (6.82 µm), *Bambusa vulgaris* (5.06 µm), *Ochlandra travancorica* (6.00 µm), and *Dendrocalamusasper* (5.69 µm) [54, 10]. *Arundo donax*, which has been utilized as an excellent raw material for producing handmade paper, has a cell wall thickness of 5.36 µm. In contrast, *Oxytenanthera abyssinica* has a smaller thickness of 2.74 µm[42]. This demonstrated the plant's greater potential for producing pulp and paper. Plants having thinner cell wall help to make high-quality paper [55].

3.2.4. Fiber lumendiameter

Figure 8 shows the fiber lumen diameter of *Oxytenanthera abyssinica* fibers. For several fiber sample measurements, the fiber lumen width for *Oxytenanthera abyssinica* ranged from 6.40 to 37.79 µm, with a pooled mean width of 15.63 µm with 95% confidence limit of 13.84–

17.42. The fiber lumen diameters at the top (14.28 ± 0.04μm), middle (15.54 ± 0.01 μm), and bottom (17.09 ± 0.03μm) were all of them were significantly different ($p \leq 0.05$). The sample with the greatest value was at the bottom, while the sample with the lowest value was at the top. The average fiber lumen diameter in our study is larger than the fiber lumen diameter of *Bambusa vulgar* a*s* reported by Wahab et al. (2009) [29]. However, the resulting value decreased from the top (2.6 ± 0.11) to the bottom (2.4 ± 0.15**).** *Oxytenanthera abyssinica* also possess a larger fiber lumen diameter than other bamboo species, such as *Dendrocalamus strictus* (4.33 μm), *Dendrocalamus latiflorus* (3.44 μm), *Dendrocalamus giganteus* (5.66 μm), *Dendrocalamus asper* (3.97 μm), *Bambusa vulgaris* (3.81 μm) and *Bambus abeecheyana* (3.55 μm) [10]. This showed that *Oxytenanthera abyssinica* has a greater potential for pulping than the bamboo mentioned above species becausethe bigger the fiber lumen width, the better the beating of pulp will be because liquids can permeate unoccupied holes in the fibers [8]. The width of the fiber lumen affects the beating of the pulp.The bigger the fiber lumen width, the better the beating of pulp will be because liquids can permeate unoccupied holes in the fibers. The difference in lumen diametercould bedue to the increase in physiological development and cell sizeof the wood as the plant grows in girth [53].

Because the species studied in this work had a broader lumen and thinner walls than the above bamboo species, They will quickly collapse during the beating process to generate pulp with stronger elasticity, burst strength, compression, and tensile. During the beating process, fibers with thinner walls and broader lumens collapse more quickly and form networks strongly with one another than those with thicker walls and narrower lumens beating process [56]. Thewall thickness, lumen diameter, and fiber diameter of *Oxytenanthera abyssinica* were generally larger at the bottom and smaller at the top. This showed that changes in fiber characteristics along the bamboo culm are caused by maturity; the older the culm segment, the better its morphological traits.Because the internodes at the bottom and middle of the bamboo plant spread and develop more quickly than those at the top, the fibers in those areas are often superior to those at the top [57].

3.2.5. Fiber-derived of *Oxytenanthera abyssinica*

3.2.5.1. Runkel ratio

The Runkel ratio of wood fiber is one of the characteristics of wood that has been recognized as essential for pulp and paper properties [58]. Table 3 showed that *Oxytenanthera abyssinica* had an averageRunkel ratio value of 0.35 with 95% confidence interval of 0.24–0.35.The maximum Runkel ratio was found in the middle of the plant (0.37 ± 0.01), and the minimum was found in the bottom (0.34 ± 0.01). No significant difference ($P \leq 0.05$) between the top, middle, and bottom regions.

A high pulp yield will be obtained if the Runkel ratio is less than one [59]. Low Runkel ratio fibers are often thin-walled and have greater strength properties, inter-fiber bonding, and greater conformability [60, 61]. The Runkle ratio of fibers from all portions of *Oxytenanthera abyssinica's* is less than 1, thus, it is satisfactory to recommend the plant for producing flexible pulp and paper with good mechanical properties [44, 62].

3.2.5.2. Flexibility ratios

The flexibility ratio indicates how easily fibers link and, as a result, how strong the tensile and bursting strength are generated [63]. Table 3 showed that *Oxytenanthera abyssinica* had an averageflexibility ratio value of 0.72 with 95% confidence interval of0.64-0.80. There was a significant variation in the flexibility ratio between the central and lower parts of *Oxytenanthera abyssinica* ($P \leq 0.05$). The results also showed that it decreased from the top (0.76 ±0.1) to the bottom (0.69 ± 0.1) along the culm.The flexibility ratios of *Oxytenanthera abyssinica* fibers werebetween 0.50 to 0.75 in all portions of the plant; this showedthat the plant possesses elastic properties [43]. Elastic fibers commonly recommend for manufacturing packing papers [47, 64]. According to studies, the higher the fiber length-to-width ratio, the more flexible the fiber is and the more likely it is to produce a well-bonded paper [65].

3.2.5.3. Slenderness ratio

Table 3 showed that *Oxytenanthera abyssinica* had a Slenderness ratio mean value of 109.98 with 95% confidence interval of104.2-115.76.The difference in the slenderness ratio was significant (P 0.05) between the bottom (104.14±0.31), the middle (108.28±0.12), and the top (119.00 ±0.22) sections. The slenderness decreased from the top (119.00±0.22) to the bottom (104.14±0.31) along the culm.The fibers from all parts of *Oxytenanthera abyssinica* have a slenderness ratio greater than 70.This suggests that the fibers create high-quality sheets for packing and other applications [63].

Table 3
Fiber-derived (top, middle and bottom) part of *Oxytenanthera abyssinica*

Position	Statically value	Flexibility ratio	Slendernessratio	Runkelratio
Top	N	14	14	14
	$\bar{x}$ ± STD	0.76 ± 0.10[a]	119.0 ± 0.22[a]	0.35 ± 0.01[a]
	95% CI_L	0.66	104.96	0.32–0.38
	95% CI_U	0.86	133.04	
Middle	N	14	14	14
	$\bar{x}$ ± STD	0.71 ± 0.10[b]	108.28 ± 0.12[a]	0.37 ± 0.01[a]
	95% CI_L	0.47	96.8	0.22
	95% CI_U	0.95	119.75	0.59
Bottom	N	14	14	14
	$\bar{x}$ ± STD	0.69 ± 0.10[b]	104.14 ± 0.31[a]	0.34 ± 0.01[a]
	95% CI_L	0.46	80.4	0.26
	95% CI_U	0.92	127.91	0.42
Mean	N	42	42	42
	$\bar{x}$ ± STD	0.72 ± 0.10	109.98 ± 0.21	0.35 ± 0.10
	95% CI_L	0.64	104.2	0.24
	95% CI_U	0.80	115.76	0.35

All data were examined in triplicate, and the mean value ± SD *was used. Values in the same column with the identical English alphabetical letter are not significantly different ($P \geq 0.05$), with a confidence limit of 95%. Where: STD: standard deviation, CI_L: confidence interval lower, CI_U: confidence interval upper, N: number, $\bar{x}$*: mean value.

3.2.6. Comparison of fiber characteristics with other bamboo species

In comparison to two well-known bamboo species such as green bamboo and Moso bamboo, *Oxytenanthera abyssinica* has a longer fiber length (2.40 mm) and diameter (21.83 mm), as well as a smaller Runkel ratio (0.350) (Fig. 9)[66]. However, the Runkel ratio of green bamboo and Moso bamboo were greater than one (> 1), with values of 2.96 and 4.53, respectively. This indicates that the papermaking potential of *Oxytenanthera abyssinica* is higher than the two bamboo species because a low Runkel ratio means larger fiber lumen width and a thin fiber wall. A thin fiber wall is desirable for high-quality, strong, well-formed paper. Moreover, the beating of pulp, which involves liquid penetration into gaps within the fiber, is positively influenced by large lumen size. Thus, fibers having a high Runkel ratio are less flexible, stiffer, and produce bulkier, low-bounded-area paper [67]. For the production of high-quality paper, long fiber lengths are preferred. Long fibers produce a sheet structure that is more drainable and less uniform. The flexibility, tensile, and burst strength of paper are all improved by thin cell walls[67, 68]. This also indicates that *Oxytenanthera abyssinica* has a higher potential for papermaking properties than the other two bamboo species (Fig. 9).

3.3. Chemical Composition

The results of the proximate chemical analysis of *Oxytenanthera abyssinica* at 1, 2, and 3 years of age were reported in Table 4. The average cellulose, hemicelluloses, and lignin content in three-year-old *Oxytenanthera abyssinica* were 49.26 ± 0.13, 21.31 ± 0.15, and 20.63 ± 0.12, respectively. The percentage of cellulose content increase when the ages of *Oxytenanthera abyssinica* become older. Themean cellulose content at ages 1, 2, and 3 were 49.26 ± 0.13, 48.87 ± 0.15, and 48.21 ± 0.15, respectively. The mean cellulose content of the 3-year-old, 2-year-old, and 1-year-old *Oxytenanthera abyssinica* samples differed significantly ($P < 0.05$). However, the average cellulose content of the 2 and 1-year-old bamboo samples did not differ significantly. The current studies have shown that the cellulose content of *Oxytenanthera abyssinica* is higher than that of all hardwoods and softwood plants[69].

The hemicellulose content of *Oxytenanthera abyssinica* in the ages of 1,2 and 3 years old are 21.31 ±0.15, 23.17 ±0.11, and 21.05 ±0.22% respectively. The hemicellulose content of the 3-year-old and 2-year-old bamboo samples did not differ significantly (P≥ 0.05). However, the content of the 1 and 2-year-old and 1and 3-year-old bamboo samples differed significantly (P $\leq$0.05). As can be seen in Table 3, the hemicellulose content was highest at 2 years old compared to *Oxytenanthera abyssinica* at ages 1 and 3. The hemicellulose content in the current study was lower than the softwood content [69]. The average percentages of lignin content in *Oxytenanthera abyssinica* at ages 1, 2, and 3 are 20.63±0.12, 23.54±0.33, and 23.03±0.24, respectively. There was a significant difference in lignin content between bamboo samples aged 3 and 2, and 3 and 1 years. Like hemicellulose, *Oxytenanthera abyssinica* has the highest lignin content at 2 years of age. The average percentages of extractives and ash content at ages 1, 2, and 3 are (6.8 ± 0.15, 7.16 ± 0.15 and 7.67 ± 0.15) and (2.645 ± 0.11, 4.505 ± 0.17 and 6.63 ± 0.153) in a respective manner. As the plant becomes older, the percentage of ash and extractive content decrease.

The content of cellulose, hemicelluloses, and lignin of the *Oxytenanthera abyssinica* is in the range of hardwood content. The content of lignin in the plant in this study showed a lower value than softwood and hardwood [69] when compared to wood; this showed a more efficient delignification under the same cooking conditions. This means that to achieve a suitable kappa value, *Oxytenanthera abyssinica* would require milder pulping conditions (lower chemical charges and temperatures) than hardwoods and softwoods, which could reduce chemical consumption and energy usage.

Three aged *Oxytenanthera abyssinica bamboo* species has got higher solubility in hot water(11.67 ±0.15), cold water (9.56 ±0.15), alcohol benzene (4.51 ±0.15), and 1% NaOH solubility (20.4 ±0.15) than two and one-year aged bamboo species. There was no significant difference (P > 0.05) in value of cold water and alcohol-benzene solubility between one, two and three year samples (Table 4).*Oxytenanthera abyssinica* has a greater alcohol-benzene solubility of 4.51 ±0.153 than green bamboo (*Dendrocalamopsis oldhami*) species (3.3–3.9%)[66] which is used for pulp and paper-making. This indicated that *Oxytenanthera abyssinica* has a higher concentration of salts, low molecular weight carbohydrates, non-volatile hydrocarbons, phytosterols, resins, lipids, waxes, and other water-soluble substances than green bamboo. This information confirmed that the study plant has higher pulp and paper potential.Solubility in 1% NaOH solution of *Oxytenanthera abyssinica* was (20.4 ±0.15). The value is higher than the other solubility such as cold water solubility (9.56 ±0.15), hot water solubility (11.67 ±0.15), and alcohol-benzene solubility (4.51 ±0.15). Solubility in a 1 percent NaOH solution indicates the degree of fungal decay or degradation of wood. 1 percent NaOH solubility also indicates the degree of solubility of extractive chemicals, some lignin, and low molecular weight hemicellulose [70].

Table 4
Chemical composition value of *Oxytenanthera abyssinica* at1, 2 and 3 year aged

Age of the Plant	Statically value	Cellulose	Lignin	Hemi cellulose	Ash	Extractives	Solubility			
							Hot water	1% NaOH	Alcohol benzene	Cold water
3 year	N	3	3	3	3	3	3	3	3	3
	x̄ ± STD	49.26 ± 0.13[a]	20.63 ± 0.120[a]	21.31 ± 0.15[a]	2.64 ± 0.11[a]	6.8 ± 0.15[a]	11.67 ± 0.15[a]	20.4 ± 0.15	4.51 ± 0.15[a]	9.56 ± 0.15[a]
	95% CI_L	47.39	18.73	16.06	2.09	5.18	9.25	16.89	1.02	3.30
	95% CI_U	51.13	22.52	26.55	3.19	8.41	14.08	23.90	7.99	15.82
2 year	N	3	3	3	3	3	3	3	3	3
	x̄ ± STD	48.87 ± 0.21[b]	23.54 ± 0.33[b]	23.17 ± 0.11[b]	4.50 ± 0.17[b]	7.16 ± 0.153[b]	9.11 ± 0.93[b]	17.42 ± 1.03	4.40 ± 0.71[a]	9.49 ± 0.71[a]
	95% CI_L	44.21	21.21	20.03	3.78	6.28	5.92	11.33	2.46	6.48
	95% CI_U	53.53	25.87	26.30	5.23	8.03	12.30	23.50	6.34	12.50
1 year	N	3	3	3	3	3	3	3	3	3
	x̄ ± STD	48.21 ± 0.12[b]	23.03 ± 0.24[b]	21.05 ± 0.22[a]	6.62 ± 0.15[c]	7.67 ± 0.153[c]	7.54 ± 0.76[c]	14.56 ± 1.42	4.21 ± 0.55[a]	9.01 ± 0.71[a]
	95% CI_L	44.17	19.00	17.43	1.68	3.89	1.86	10.19	4.14	7.07
	95% CI_U	52.25	27.00	24.66	11.57	11.44	13.21	18.92	4.27	10.32

All data were examined in triplicate, and the mean value ± standard deviation *was used. Values in the same column with the identical English alphabetical letter are not significantly different (P ≥ 0.05), with a confidence limit of 95%.STD: standard deviation, CI_L: confidence interval lower, CI_U: confidence interval upper, N: number,* $\bar{x}$: mean value.

The alpha-cellulose content of 3 year aged *Oxytenanthera abyssinica* was (48.8 ± 0.23) (Table 5). This value is higher than the value of seven Indonesian bamboo species studied by Maulana et al. (2020) [70]. According to their study, the alpha-cellulose content of Ando bamboo and Ampel bamboo is less than 40%, and the alpha-cellulose content of Senbiran bamboo and Kunin bamboo is 40–45%. Begun bamboo, Hitam bamboo, and Tari bamboo have high alpha-cellulose content greater than 45%. This showed that *Oxytenanthera abyssinica* couldhave a higher potential for pulping and paper production than Indonesian bamboo species. Because α-cellulose has a positive effect on the pulp yield [71]. Further research has been conducted to link the amount of cellulose to pulp yields. For instance, according to Dillner et al. (1970) [72], cellulose contents and kraft pulp yields of *Eucalyptus globulus* wood were closely connected and Wallis and coal.(1996)[73] demonstrated that eucalypt wood samples with a high cellulose content produced more pulp.

3.4. Chemical composition comparison to the other bamboo species

The chemical composition of other bamboo species with the current study were compared in Table 5. The table showed that the cellulose content (49.26wt%) of three year age of *Oxytenanthera abyssinica* was higher than other bamboo species such as *Dendrocalamus brandisii* (47.24wt%)[74], *Bambusa blumeana* (40.3–45.1 wt%) [75], *Bambusa tuldoides* (35.2 wt%**)** [76, 45], *Gigantochloa levis* (33.8wt%) [76], *Passiflora edulis* (44.64%)[77] and *Daphniphyllum oldhami* (47.1 wt%) [66]. This showed that *Oxytenanthera abyssinica* has a great potential for pulp yield and papermaking properties than the mentioned bamboo species.

Table 5: Chemical composition of *Oxytenanthera abyssinica* to other bamboo species

Samples	Alpha cellulose	Holocellulose (wt %)	Lignin (wt %)	Hemicellulose (wt %)	Cellulose (wt%)	Ash (wt %)	Reference
Oxytenanthera abyssinica	48.8± 0.23	70.57± 0.28	20.63± 0.12	21.31± 0.15	49.26± 0.13	3.30± 0.11	This study
Phyllostachys heterocycla	—		26.1	—	49.1	1.3	[78]
Phyllostachys nigra	—		23.8	—	42.3	2.0	[78]
Phyllostachys reticulata	—		25.3	—	25.3	1.9	[78]
Bambus ablumeana	—	65.70	20.50	—	40.3	—	[75]
Bambus atuldoides	—	67.20	25.5	32.0	35.2	3.70	[76]
Dendrocalamus asper	48.60	68.25	25.27	—	—	2.13	[79]
Dendrocalamus brandisii	—	—	23.84	23.85	47.24	1.37	[74]
Dendrocalamus giganteus	46.88	65.96	23.85	—	—	3.70	[79]
Gigantochloa apus	47.56	63.23	22.41	—	—	6.09	[79]
Gigantochloa brang	51.18	79.94	24.83	—	51.58	1.25	[80]
Gigantochloabrang(outer part)	56.94	80.05	38.75	—	—	0.78	[81]
Gigantochloa levis	33.81	85.08	26.50	—	33.8	1.30	[77]
Gigantochloa levis (outer part)	36.96	89.80	35.98	—	—	1.19	[81]
Gigantochloa robusta	44.36	56.81	23.86	—	—	1.66	[79]
Goniothalamus scortechinii	46.87	74.62	32.55	—	46.87	2.84	[80]
Goniothalamus scortechinii (outer part)	61.31	75.35	43.68	—	—	1.50	[81]
Melocanna baccifera		73.5	25.2	21.1	52.78	2.45	[82]

Many researchers have claimed that cellulose concentration and pulp production are directly related. Kiaei et al. (2014) [68] found a positive link between cellulose concentration and pulp quality. High cellulose concentration yields high pulp yield, according to Khoo and Peh. (1982) [83]. The hemicelluloses content *of Oxytenanthera abyssinica* is higher than that of *Dendrocalamus brandisii* [74], *Bambusa vulgaris* [83], *Phyllostachys edulis* [77], and *Daphniphyllum oldhami* [83]. This also explains why the plant has a higher potential for pulp yield than the plants mentioned above.The amount of hemicellulose has a positive relationship with pulp yield. Higher hemicellulose values, for example, lead to increased pulp yield and paper strength (mainly fold strength, burst, and tensile) [84]. The current study's lignin content of *Oxytenanthera abyssinica* exhibited the lowest lignin content among the other ten bamboo species listed in table 10 except *Bambusa blumeana.* This provides information on how suitable the plant is for pulp and paper production because the amount of lignin negatively affects pulp yield [85, 47]. Lignin causes fiber-to-fiber bonding to be delayed in the paper, and all of its properties have a negative impact on paper production; as a result, high-quality papers are made from lignin-free fibers [86]. Extractives from raw materials are undesirable because they can interfere with the pulping and bleaching processes. High extractive concentration, according to Ates et al. (2008) [50], will indicate low pulp production as well as increased chemical usage in pulping and bleaching [87]. Different soil types, age and maturity levels, and raw material sources could explain the variances in cellulose, lignin, hemicelluloses, ash, and extractives reported in this bamboo species (Table 5). Genetics, age, location, growth conditions, anatomic structure, and plant maturity level also influence the chemical composition of lignocellulosic materials [88].

Conclusion

In this study, we examined the chemical composition and fiber characteristics of *Oxytenanthera abyssinica* to assess its compatibility for pulp and paper production. The result indicated that the average Runkel ratio was 0.350 (< 1) with 95% CI of 0.24 to 0.35, the slenderness ratio was 109.98 (> 70) with 95% CI of 104.2 to 115.76, and the fiber length was 2.40 (> 1.5) with 95% CI of 2.20 to 2.60. The experimental data showed that the amount of cellulose in the culm increases and the amount of ash and extractive decreases as it becomes older (from 1 year to 3 years). However, the highest amount of lignin and hemicellulose content was found in two years, followed by 3 and 1 year. The three-year aged average chemical content of the plant was 49.26 ± 0.13 (95% CI of 47.39 to 51.13), 21.31 ± 0.15 (95% CI of 16.06–26.55), and 20.63 ± 0.12 (95% CI of 18.73 to 22.52) cellulose, hemicellulose, and lignin contents respectively. The bulk densities of *Oxytenanthera abyssinica* were 660 kg/m3, and its moisture content was 9.37%. Thus, the above data showed that *Oxytenanthera abyssinica* could have pulp and paper-making potential.The three-year-aged bottom part of the plant is more preferable to the middle and top part of one-year and two-year-aged *Oxytenanthera abyssinica.* The current study employed samples up to three years old; therefore, future research should focus on samples older than three years because a plant's characteristics rely on its age, culm height, environment (whether it is farmed or natural), type of soil it grows in, and the area in which it is found.

Declarations

Ethical Approval

Not applicable

Competing interests

The authors declare no competing interests

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Limenew Abate Worku. The draft of the manuscript was written and checked by Rakesh Kumar Bachheti, Mesfin Getachew Tadesse and Limenew Abate Worku, Archana Bachheti. All authors read and approved the final manuscript. All authors also worked on revision of the article

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Figures

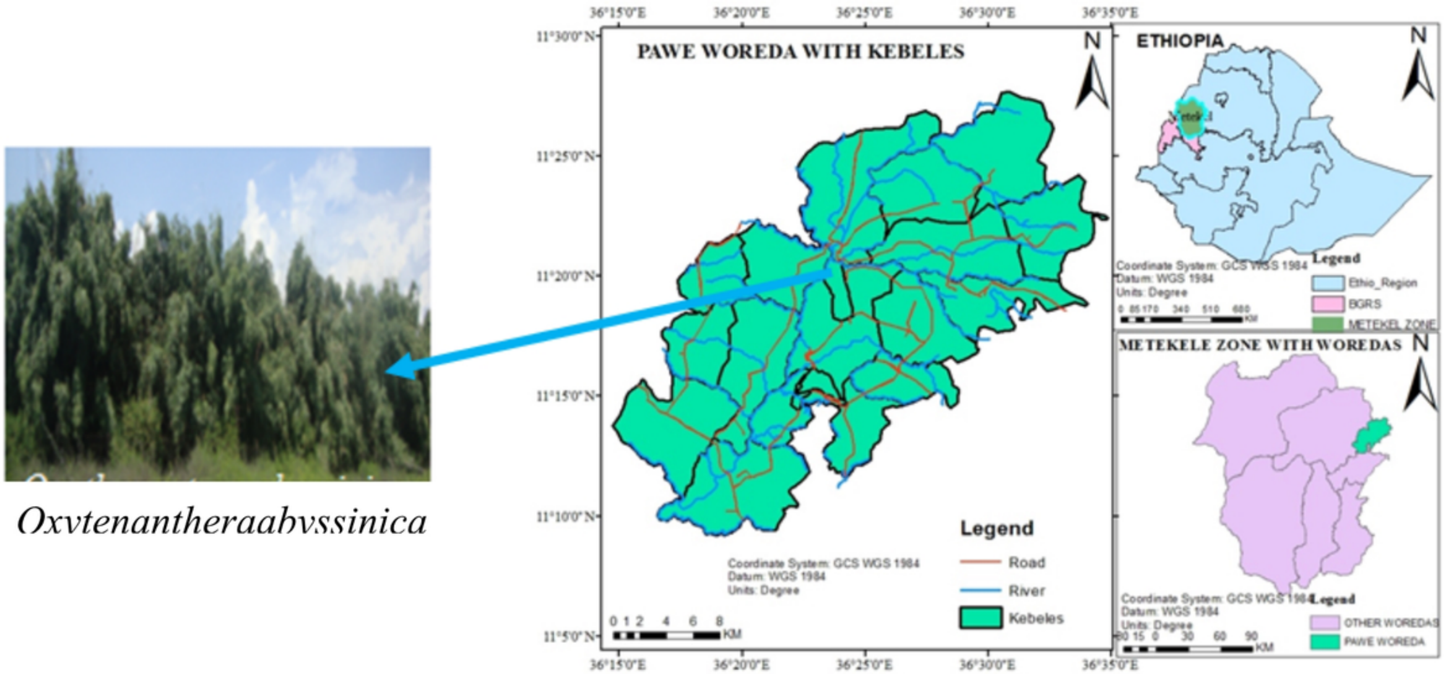

Figure 1

A region in Ethiopiawhere *Oxytenanthera abyssinica* was collected

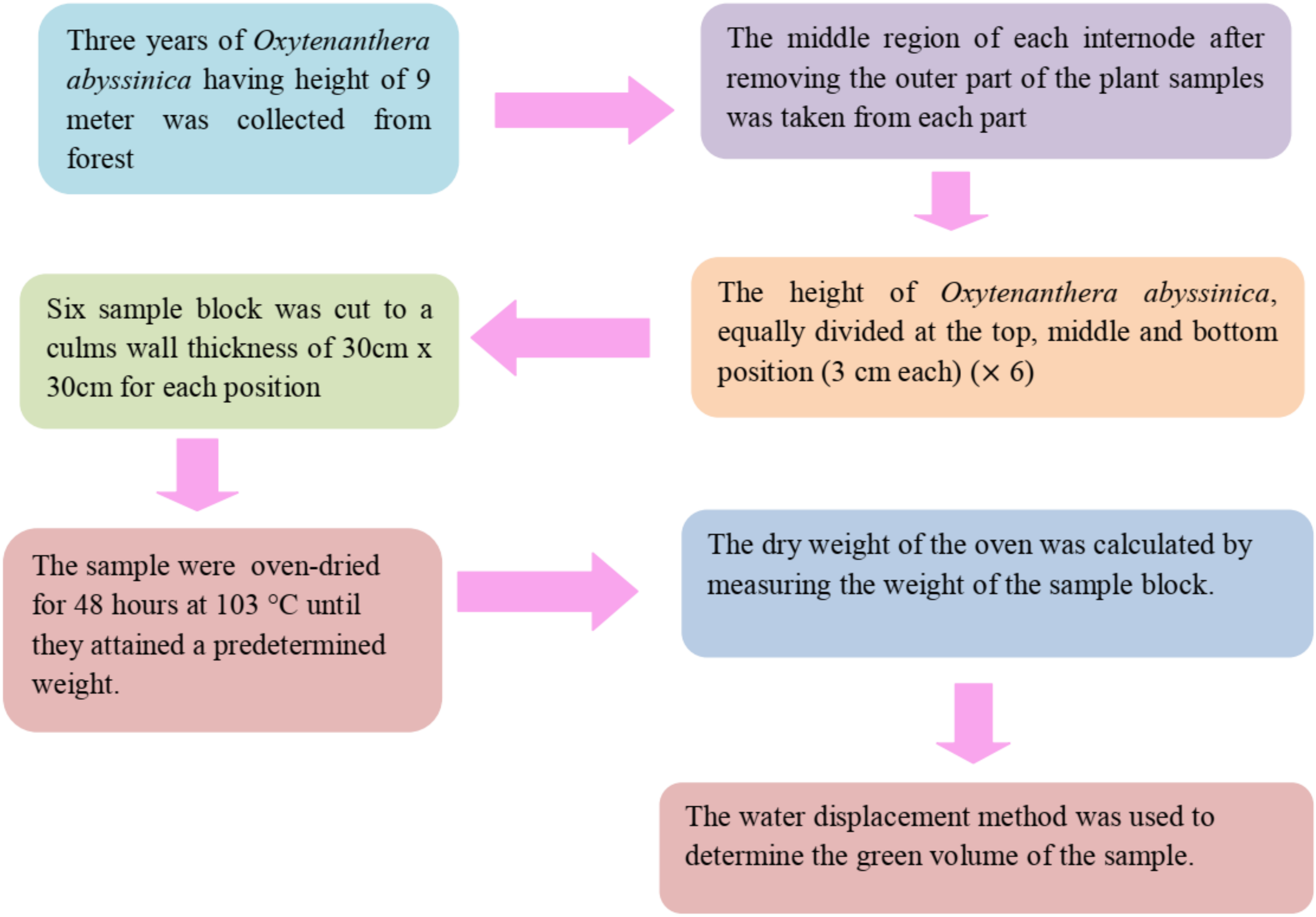

Figure 2

Procedures used to measure the basic density of *Oxytenanthera abyssinica*

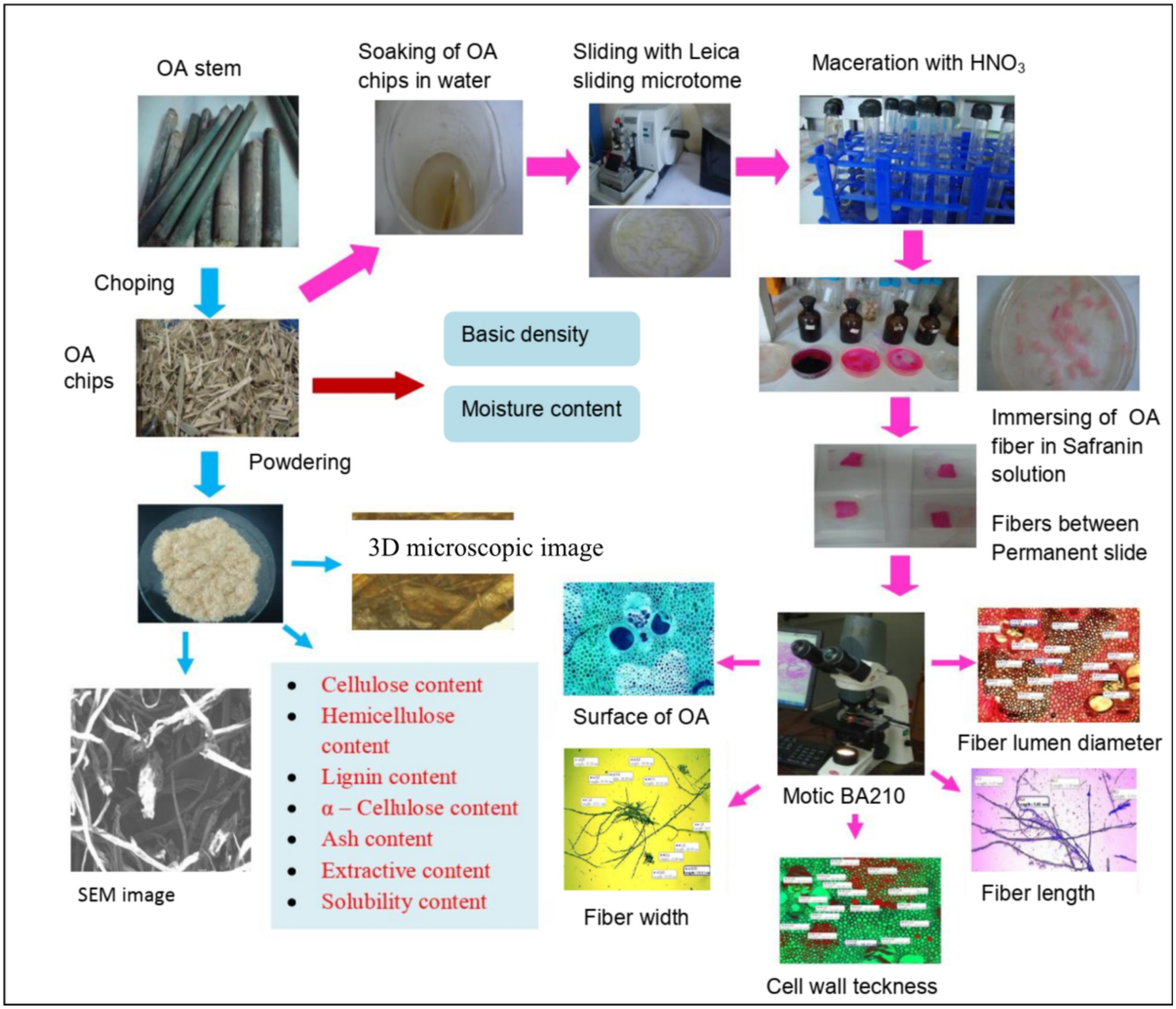

Figure 3

Oxytenanthera abyssinica (OA) fiber morphological characterization procedures

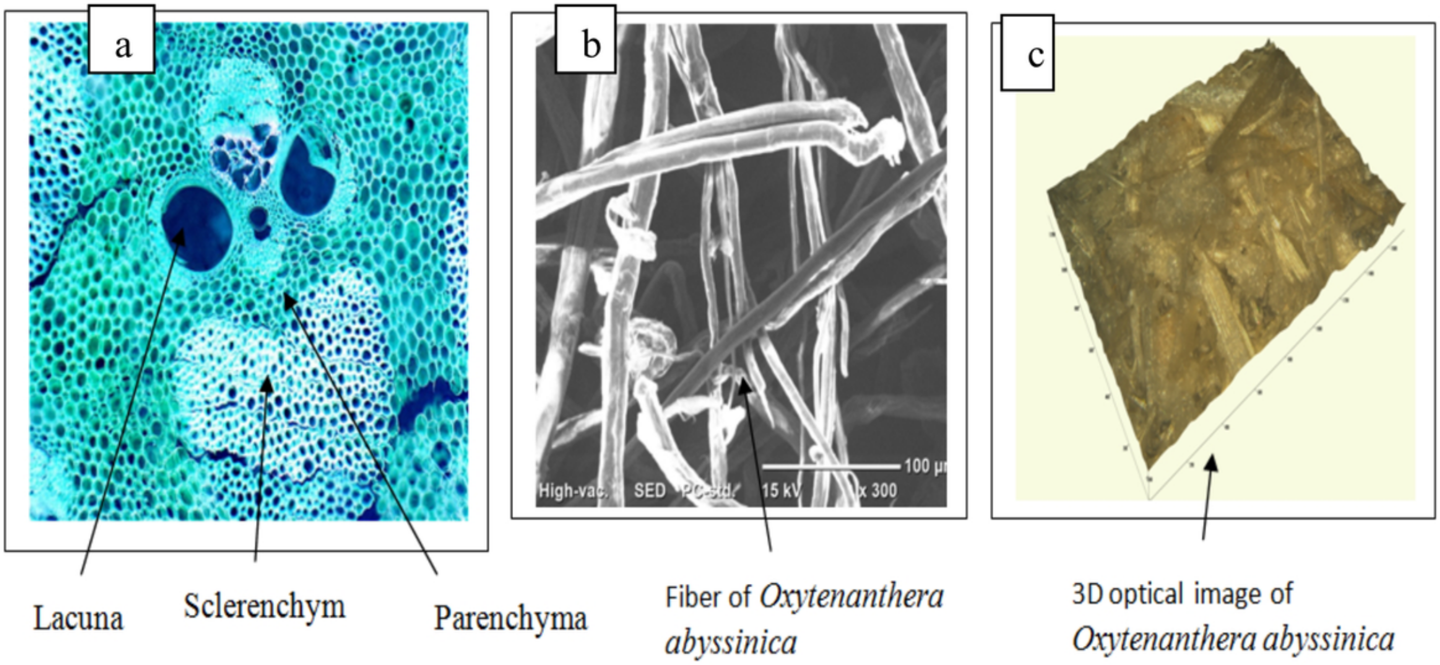

Figure 4

The surface of *Oxytenanthera abyssinica* fiber under an optical microscope (a and c), scanning electron microscope (b)

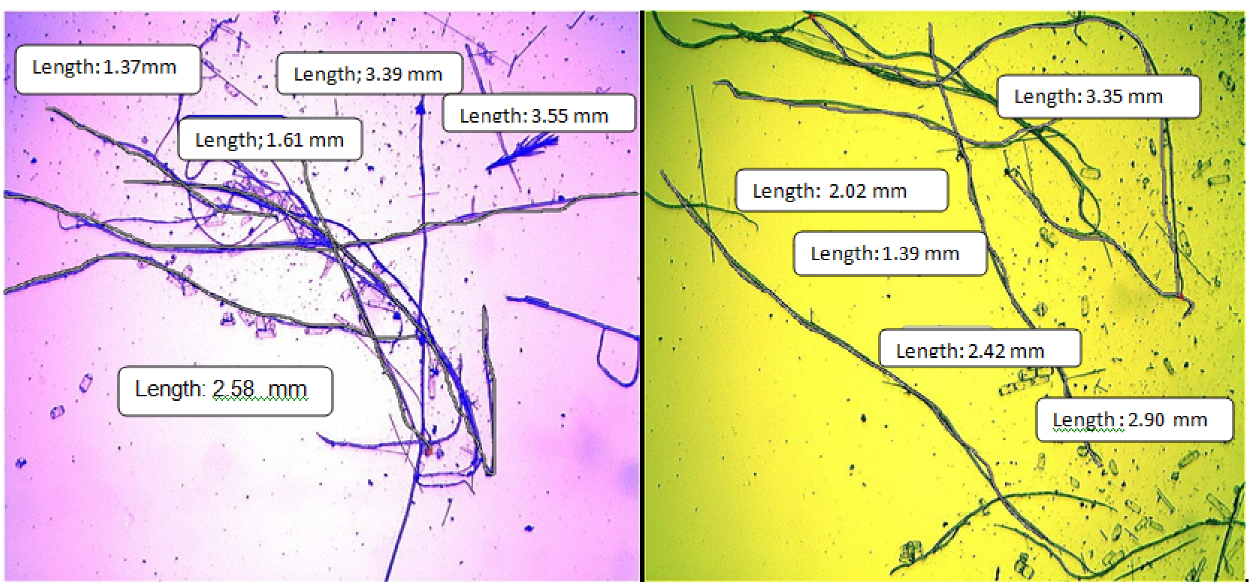

Figure 5

Fiber length of *Oxythenantera abyssinica*

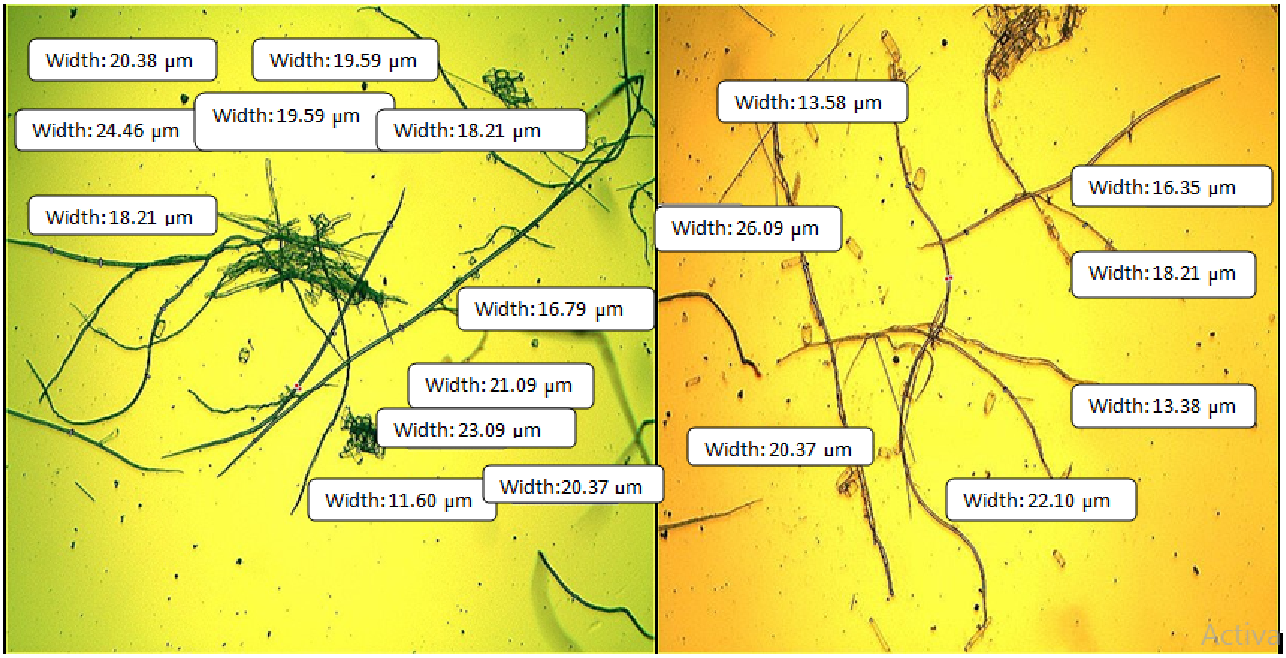

Figure 6

Fiber width of *Oxytenanthera abyssinica*

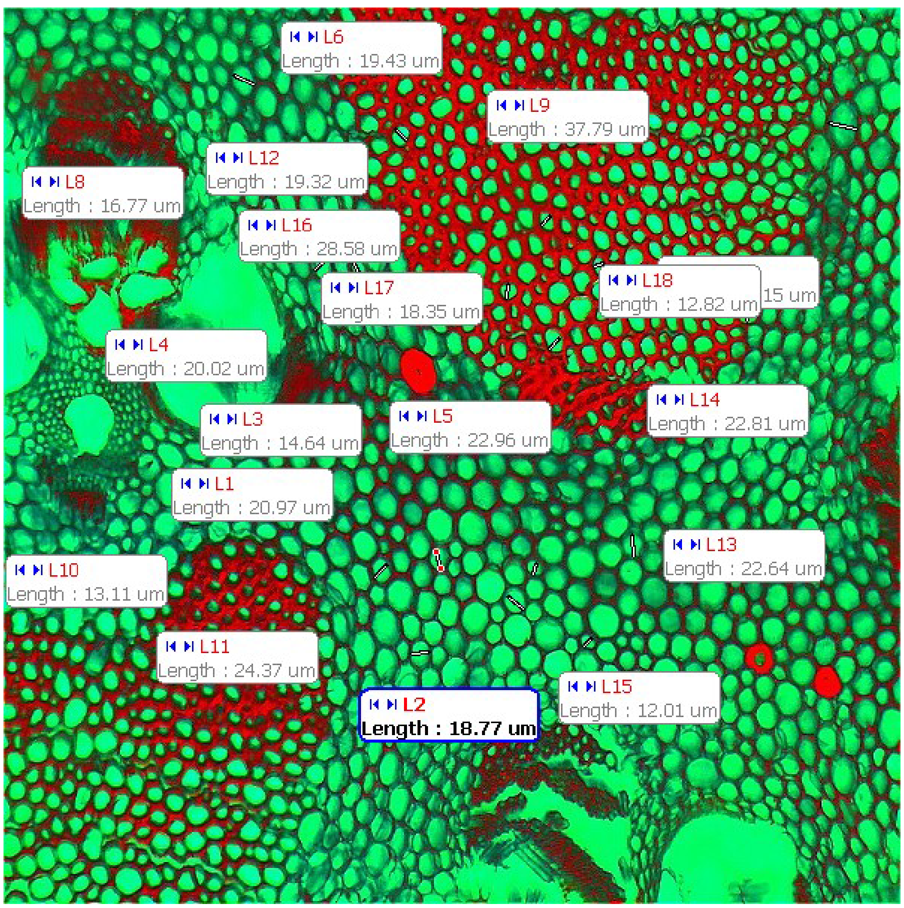

Figure 7

Cell wall thickness of *Oxytenanthera abyssinica*

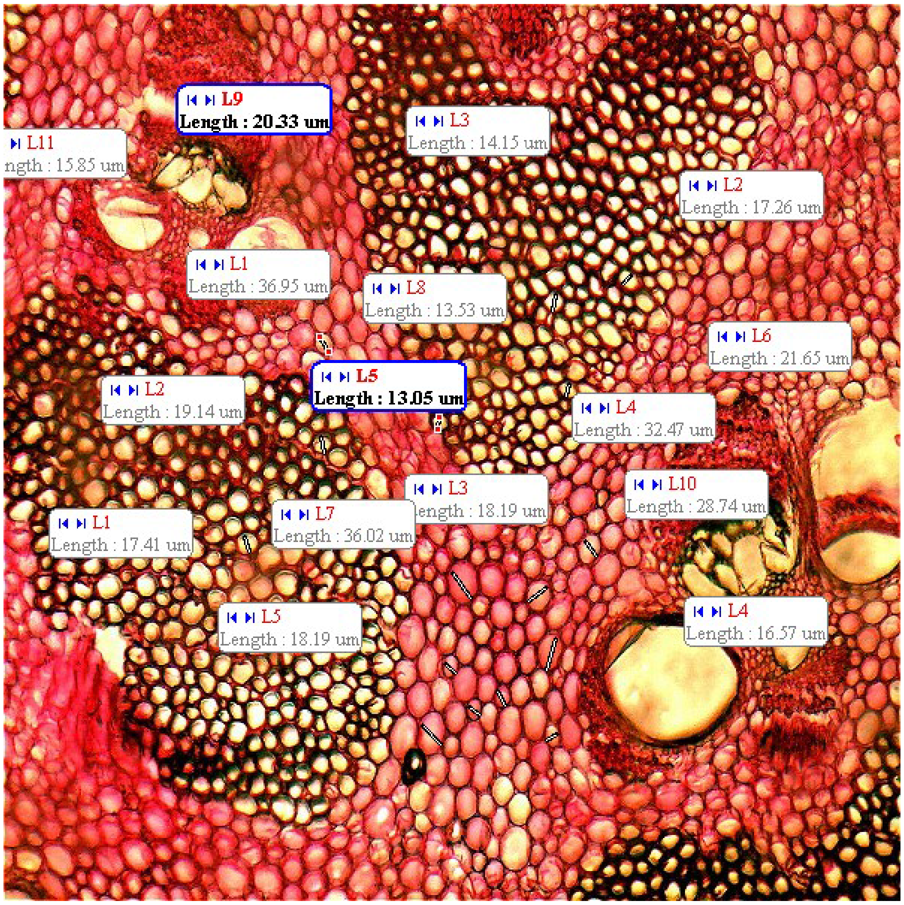

Figure 8

Fiber lumen diameter of *Oxytenanthera abyssinica*

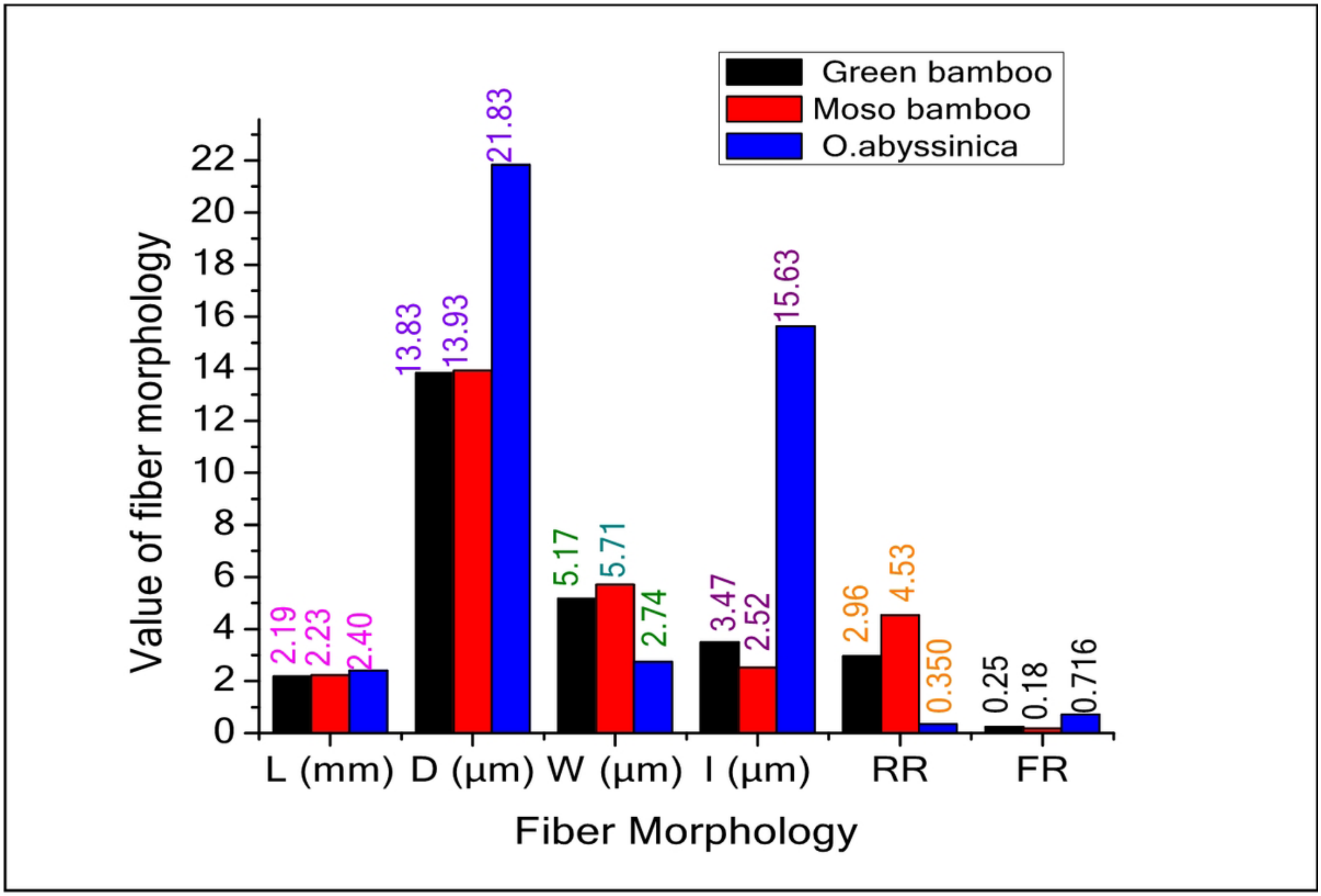

Figure 9

Fiber morphological comparison between *Oxytenanthera abyssinica*, green bamboo, Moso bamboo. Where L: fiber length; D: fiber diameter; W: cell wall thickness; l: fiber lumen diameter; RR: Runkel ratio and FR: flexibility ratio.