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Properties of East African Bamboo

The Physical, Mechanical, Chemical and Fibre Test Results of Three East African Bamboo Species

Wang Hankun, Chen Hong, Zhang Rong, Liu Xing'e and Jayaraman Durai

International Bamboo and Rattan Organisation

The International Bamboo and Rattan Organisation, INBAR, is an intergovernmental organisation dedicated to the promotion of bamboo and rattan for sustainable development.

International Bamboo and Rattan Organisation
PO Box 100102-86, Beijing 100102, China
Tel: +86-10-6470 6161; Fax: +86-10-6470 2166;
Email: info@inbar.int
www.inbar.int

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It has been a great challenge to undertake this study due to the complexities associated with shipping the bamboo samples to China and due to difficulties associated with timely approvals to undertake this study. However, a sincere effort was made to undertake the scientific study and to prepare this document. We hope that this study and publication will be an important tool for bamboo sector development in East Africa.

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Jayaraman Durai

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Acronyms/Abbreviations

AIL	Acid Insoluble Lignin
AMSL	Above Mean Sea Level
ASL	Acid Soluble Lignin
C	Celsius
CFR	Central Forest Reserve
Cm	Centimetre
DBH	Diameter at Breast Height
GB/T	Guobiao Standards (Chinese National Standards)
g/cm^3	grams per cubic centimetre
Ha	Hectares
HPLC	High-Performance Liquid Chromatography
ICBR	International Centre for Bamboo and Rattan
INBAR	International Bamboo and Rattan Organisation
JGT	Chinese National Standards for building and construction
KEFRI	Kenya Forestry Research Institute
KFS	Kenya Forestry Service
M	metres
Mg	milligram
mL	millilitre
Min	minutes
Mm	millimetre
MPa	Mega Pascal
MT	Metric tons
N/mm^2	Newton per square millimetre
NFA	National Forestry Authority
NREL	National Renewable Energy Laboratory
RBG	Royal Botanical Garden
SFA	State Forestry Administration
SRS	Sugar Recovery Standard
STD	Standard Deviation
Syn.	Synonyms
UIRI	Uganda Industrial Research Institute
UN	United Nations
UNIDO	United Nations Industrial Development Organisation
USD	United States Dollar
UV	Ultraviolet
µL	Microliter
µm	Micrometre
%	Per cent

Executive Summary

Ethiopia, Kenya and Uganda hosts about 1.47 million ha, 133, 272 ha, and 54, 533 ha of bamboo resources respectively belonging to two indigenous bamboo species, namely *Oldeania alpina (syn. Yushania alpina / Arundinaria alpina*) and *Oxytenanthera abyssinica.* In addition to this two indigenous species, Ethiopia, Kenya and Uganda has introduced a number of bamboo species from Asia. *Dendrocalamus asper* is a one of the key species growing in Kenya and Uganda. Therefore, the study undertook property tests of these three key species in East Africa.

Under the Dutch-Sino-East Africa Bamboo Development Programme, bamboo resource assessment using remote sensing technology and market and value-chain studies were undertaken in Ethiopia, Kenya and Uganda. This study on physical, mechanical, chemical and fibre properties of bamboo is aimed at providing the scientific data and knowledge on the properties of bamboo, and suitable value chain possibilities. The entire set of knowledge generated on bamboo resource availability, market possibilities and properties of bamboo and its suitability for value-addition will aid industries, enterprises, development and government agencies in decision making.

Bamboo samples belonging to three bamboo species were collected from Kenya and Uganda. Sample of *Oxytenanthera abyssinica* was collected from 1 location (Otze Central Forestry Reserve (CFR), Moyo, Uganda); bamboo samples of high land bamboo (*Oldeania alpina*) were collected from two locations (Echuya CFR (Uganda) and Aberdares range (Kenya)). *Dendrocalamus asper* samples were collected from Kakamega / Siaya county (Kenya).

The bamboo samples were collected and prepared according to the Chinese national standard GB/T 15780-1995 (Testing methods for physical and mechanical properties of bamboos) and Chinese industry standards for building and construction (JGT 199-2007).

Bamboo properties such as (a) physical properties: density (basic and oven dried), and shrinkage (radial, tangential and volumetric); (b) mechanical properties (compressive strength parallel to grain, shear strength parallel to grain, bending strength, tensile strength parallel to grain); (c)

chemical composition (glucan, xylan, arabia xylan, acid soluble lignin, acid insoluble lignin) and (d) morphology and dimension of individual fibre (length and diameter) was studied.

Among the three bamboo species (four samples) studied, *Oldeania alpina (*highland bamboo from Kenya) and *Oldeania alpina* (highland bamboo from Uganda) possess properties suitable for structural applications (building materials) because of their high density, good mechanical properties and dimension stability as well as high lignin content. Please note, *Oldeania alpina* is widely used by industries in Ethiopia for production of parquet floor, laminated lumber, stick based products. It has comparable properties to Moso bamboo, so it could be easily introduced to the Moso bamboo-based product line for industrialisation. *Oldeania alpina* or *Yushania alpina* shows great utilization potential for production of timber substitute products.

Dendrocalamus asper, giant clumping bamboo from Kenya has relatively low density and dimension stability, but has high mechanical properties, especially high bending strength. It is a suitable material to make glued laminated bamboo or bamboo parallel strand lumber for use in structural applications.

Dendrocalamus asper and *Oxytenanthera abyssinica* has high overall content of glucose, xylan and arabia glycan. This quality makes them a suitable species for use in producing bio-fuels and other bio-based materials / composites.

The fibre length of the four samples are in the mid-range of value reported for a typical bamboo species (1.5 -3.2mm) and thus ideal for use in paper and textile industry. Particularly, *Oxytenanthera abyssinica* can be used to produce high quality paper due to its long fibre length and high ratio of length to width. Besides, considering the solid nature of bamboo poles and and high tensile properties, it is also suitable for production of furniture and can be used as a construction material.

1. Introduction

Bamboo, a woody grass, is a fast-growing, renewable and versatile natural resource. There are over 1600 species of bamboo growing across tropical and sub-tropical regions of the world (Vorontsova et al, 2016). It is interlinked with the lives and livelihoods of numerous communities. It is well accepted that bamboo development has the potential to contribute directly to at least seven of the UN's Sustainable Development Goals, including poverty alleviation, affordable and clean energy, affordable and resilient housing, sustainable consumption, climate change mitigation and terrestrial ecosystem protection.

As climate change and global timber and energy shortages intensify, bamboo is growing in importance as a green material. Recent research and technological development have facilitated the production of high-quality durable materials in the form of wood substitutes, fibre and textile products, energy products, composite materials, food and beverages and handicrafts. In fact, bamboo can be used to produce thousands of documented products and utilities. Global internal production and consumption of bamboo products is valued at USD 60 billion, and it is an important globally traded commodity, contributing to approximately USD 2.5 billion in imports and exports (INBAR, 2016).

East Africa, particularly Ethiopia, Kenya and Uganda, hosts rich bamboo resources (Lobovikov et al, 2007). Bamboo is a key part of the forest ecosystem in these countries. Ethiopia, Kenya and Uganda host about 1.47 million ha, 133, 272 ha, and 54, 533 ha of bamboo resources, respectively (INBAR, 2018). Currently, East Africa's bamboo sector remains largely untapped, and the industry is still in its infancy. Bamboo is used in the production of low-quality products, such as fences, firewood, traditional houses, rudimentary furniture, mats and household utensils, such as baskets, winnowing trays, and other subsistence-related products. The sector provides low economic return to farmers and other actors along the bamboo industry's value chains. However, there are few industries in Ethiopia that produce industrial products such as flooring boards, laminated lumber, and bamboo energy products.

Understanding the properties of bamboo (physical, mechanical, chemical and morphological fibre characteristics) is necessary to determine its appropriate application and value-addition. Highland (*Oldeania alpina (syn. Yushania alpina/Arundinaria alpina*) and lowland bamboo (*Oxytenanthera abyssinica*) are the two indigenous species to East Africa. Both these species are proliferating in Ethiopia and Uganda. However, Kenya has only one indigenous species (*Oldeania alpina*). In addition to these two indigenous species, Ethiopia, Kenya and Uganda have introduced several bamboo species from Asia. *Dendrocalamus asper* is now one of the key species growing in Kenya and Uganda. Therefore, this study undertook property testing of three key species in East Africa.

2. Species Description and Characteristics

Oxytenanthera abyssinica, commonly known as “lowland bamboo”, is a tufted, sympodial bamboo, which grows to heights ranging from 3 to 13 metres and ranges from 4 to 10 cm in diameter (UNIDO, 2009; RBG, 2018; ICRAF, UD). It is mainly found in Africa’s deciduous savanna woodlands landscapes. It grows in an altitudinal range between 15 and 2000 M AMSL, where the annual rainfall ranges from 700 to 1000 mm per annum (RBG, 2018). This species is a pan-African species that grows in Angola, Benin, Burkina, Burundi, Cameroon, Central African Republic, Chad, the Republic of Congo (hereinafter referred to as Congo), the Democratic Republic of the Congo (hereinafter referred to as DR Congo), Equatorial Guinea, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Gulf of Guinea Is., Ivory Coast, Kenya, Malawi, Mali, Mozambique, Niger, Nigeria, Senegal, Sierra Leone, Sudan, Tanzania, Togo, Uganda, Zambia and Zimbabwe (RBG, 2018).

Oldeania alpina (Syn. Yushania alpina / Arundinaria alpina), commonly known as “highland bamboo” is a tufted, sympodial bamboo (it has a long rhizome neck) with erect green culms growing to a height of 10–20 metres (UNIDO, 2009a). The diameter of the culm ranges from 5 to 12.5 cm. It commonly grows at altitudes ranging from 2000 to 4000 M AMSL where there is high rainfall ranging from 1500 to 2000 mm (LUSO, 1997; Kelbessa et al, 2000; UNIDO, 2009a; Mulatu et al, 2016). It requires well-drained, deep and humus-rich soil that allows rhizome spread and growth. *Oldeania alpina* is commonly grown in African rift valleys in Burundi, Cameroon, Congo, DR Congo, Ethiopia, Kenya, Malawi, Rwanda, Sudan, Tanzania, Uganda and Zambia (UTPD, 2018).

Dendrocalamus asper is a large bamboo with culms reaching up to 20–30 m in height, with a diameter of 8–20 cm and a wall thickness of 2 cm. It is commonly grown in Bangladesh, southern China, northeastern India, Indonesia, Malaysia, Myanmar, Nepal, the Philippines, Thailand and Vietnam (IPGRI and INBAR, 1998). This species has also been introduced to Benin, DR Congo, Ghana, DR Congo, Kenya and Madagascar (PROTA, 2018).

Samples from three bamboo species were collected from Kenya and Uganda. A sample of *Oxytenanthera abyssinica* was collected from one location (Otze Central Forestry Reserve (CFR), Moyo, Uganda); samples of highland bamboo (*Oldeania alpina*) were collected from two locations (Echuya CFR (Uganda) and Aberdares Range (Kenya)). *Dendrocalamus asper* samples were collected from Kakamega and Siaya Counties (Kenya). Details of the locations and number of samples sent for testing are presented in **Table 1**.

Table 1: Bamboo species and location of sample collection

S. No	Code	Bamboo species	Location of Sample collection	No of Samples
1	D	*Dendrocalamus asper*	Kakamega Forest and Siaya, Kenya	36 samples (18 culms split longitudinally)
2	Y	*Oldeania alpina (Syn. Yushania alpina / Arundinaria alpina)*	Kamae Forest and Ragia Forest (Aberdares Ranges), Kenya	36 samples (18 culms split longitudinally)
2A	N	*Oldeania alpina (Syn. Yushania alpina / Arundinaria alpina)*	Echuya CFR, Kisoro and Kabale, Uganda	36 samples (18 culms split longitudinally)
3	S	*Oxytenanthera abyssinica*	Otze CFR, Moyo, Uganda	36 samples (18 culms split longitudinally)

Dendrocalamus asper samples were collected from Kakamega and Siaya Counties, located in the Nyanza region, Western Kenya. Kakamega County's mean annual temperature ranges from 21 to 23°C, with an annual average rainfall ranging between 1250 and 1750 mm. The rains are evenly distributed all year round (CIAT, 2018). In comparison, Siaya is relatively hot, with a mean annual temperature ranging from 21 to 25°C and an annual rainfall of 1000–1750 mm (CIAT, 2018a).

Samples of *Oldeania alpina* were collected from the Ragia and Kamae forests in Kenya's Aberdares Range. The natural bamboo forest zone lies in an altitudinal range of 2400–4000 m AMSL, and the average rainfall ranges from 1400 to 2200 mm per year (GBM, 2009).

Oldeania alpina samples were also collected from Echuya CFR located in the Kabale and Kisoro Districts, South Western Uganda. Uganda's bamboo growing zone lies in an altitudinal range of

2270–2570 m AMSL. The climate is tropical with two rainfall peaks from March to May and September to November. Annual mean temperatures range from a minimum of 7–15°C and a maximum of 20–26°C. Annual rainfall ranges from 1400–1900 mm (Nature Uganda, 2014).

Samples of *Oxytenanthera abyssinica* were obtained from Otze CFR, Moyo, North Eastern Uganda. Moyo District is located in the northwestern corner of Uganda. Moyo district receives approximately 1200 mm of rainfall annually, distributed across two seasons (April (the shorter rainy season); and between August and October (the main rainy season)). High temperatures are recorded during the months of Jan and Feb, reaching 45°C, and lowest from Aug to Oct, at about 29 °C (World Bank, 2018). The bamboo forest lies in an altitudinal range of 900–1500 m AMSL.

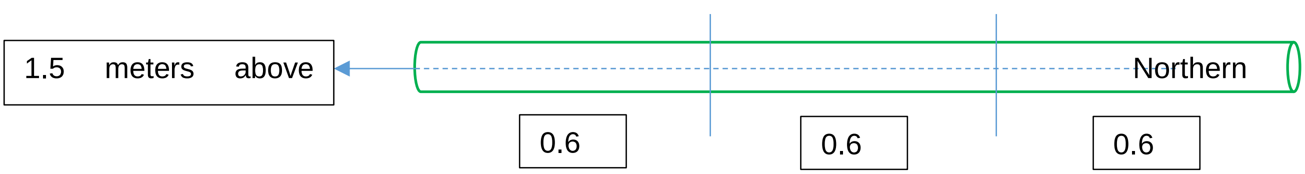
3. Material and methods

3.1 Bamboo collection and preparation protocol

The bamboo samples were collected and prepared according to the Chinese national standard GB/T 15780-1995 (Testing methods for physical and mechanical properties of bamboos) and Chinese industry standards for building and construction: JGT 199-2007 (Testing methods for physical and mechanical properties of bamboo used in building).

Details of the sample collection and preparation protocol are presented below:

1. For each species, the samples collected were those deemed most representative of the bamboo in each area of production, with ages ranging from two to four years.
2. The DBH (1.5 metres in height) of each bamboo culm selected was measured and recorded. The selected culms were at least 50 mm in diameter.
3. Each of the selected bamboo culms/poles were felled or cut at 1.5 metres' height from the ground. Before felling, the north-facing side was marked on the bamboo culms.
4. For each species, 20 bamboo culms were cut and 6 of the 20 were randomly selected for sample preparation.
5. Each chosen culm was cut into three segments from the bottom up as shown in **Scheme 1**, with each segment measuring 0.6 metres, and each segment was carefully marked and numbered sequentially. In addition, the northern facing side was marked on each culm.



Scheme 1: The chosen culms prepared for testing

6. The sample segments were split in half and then oven-dried at about 60°C, until they reached a moisture content of about 7–12% and were then stored in a dry area.
7. All samples collected were healthy, with no defects and/or deformities.

Figures 1-7 below illustrate the bamboo sample collection and preparation process.

Figure 1: Measuring 1.5 m from the ground and measuring the diameter

Figure 2: Marking at 1.5 metres and marking the north facing side

Figure 3: Cutting three samples from the representative bamboo pole and measuring the total length of the selected culm

Figure 4: Preparing three samples of each representative sample and cutting the culm in 0.6-m segments

Figure 5: Samples cut to 0.6 m and splitting the 0.6-m samples into two pieces

Figure 6: Measuring the sample's weight and oven-drying to 7-12% moisture content

Figure 7： Testing moisture content and labelled split samples

Coding: All bamboo samples prepared were coded and sent to the ICBR laboratory by air courier.

3.2 Sample preparation for physical and mechanical properties testing:

All samples for physical and mechanical testing were prepared according to the Chinese National Standard: Testing methods for physical and mechanical properties of bamboos (GB/T 15780-1995).

Air-drying and oven-drying: Each bamboo sample was cut to the specific size required for the test before drying. For the air-drying, the specimens were stored for two weeks at a controlled temperature and in a humidity environment of 20°C ± 2°C and 65% ± 5% humidity. For the oven-drying, the specimen was placed in the oven at 103 °C ± 2 °C for eight hours, and then taken out and weighed every two hours until a constant weight had been reached.

Density: Air-dried and oven-dried bamboo samples (ten per species) of dimensions 10 mm L × 10 mm W × culm wall thickness were prepared for each species. The samples' thicknesses were determined by the culm wall thicknesses. The samples were divided into three segments (outer, middle and inner). Each specimen was weighed, and the radial, chord and longitudinal dimensions were measured before and after oven-drying. The density was calculated according to the weight and volume of each specimen.

Shrinkage: Ten bamboo specimens of 10 mm L × 10 mm W × culm wall thickness were prepared for each species. Each specimen was weighed and its lengths was measured against green, air-dried and oven-dried samples. The green specimens were stored in the humidity chamber at room temperature with a uniform moisture content of approximately 12%. Shrinkage along width/diameter, wall thickness and length were calculated by the following formula for green to air-dried moisture content and green to oven-dried moisture content, where $\beta_{V_{max}}$ and β_{V_s} are the volume shrinkage ratios for green to oven-dried and green to air-dried moisture content; β_{max} and β_s are the radial or tangential shrinkage ratios for green to oven-dried and green to air-dried moisture content, respectively; V_{max}, V_0 and V_s are the volumes of green, oven-dried and air-dried specimens; and l_{max}, l_0 and l_s are the radial or tangential dimensions of green, oven-dried and air-dried specimens, respectively.

$$\beta_{V_{max}} = \frac{V_{max}-V_0}{V_{max}} \times 100\% \; \beta_{V_s} = \frac{V_{max}-V_s}{V_{max}} \times 100\%$$

$$\beta_{max} = \frac{l_{max}-l_0}{l_{max}} \times 100\% \; \beta_s = \frac{l_{max}-l_s}{l_{max}} \times 100\%$$

Compressive strength: Twenty specimens from each bamboo species from the internodal segment, with dimensions 20 mm L × 20 mm W × wall thickness, were prepared to test the bamboo's compressive strength along the grain. The width and thickness of the compressed surface at the centre of the specimens' lengths were measured. The specimens were placed in the central position of the test machine's spherical support, at a loading speed of 80 N/mm^2 per minute until the destruction of the specimen. The compressive strength was calculated by the following formula, where f_c is the compressive strength along the grain, P_{max} is the failure load, b is the width and t is the thickness of the specimen.

$$f_c = \frac{P_{max}}{b\,t}$$

Bending strength: To test the three-point bending modulus, 30 specimens from each bamboo species, with the dimensions 160 mm L × 10 mm W × wall thickness, were prepared. Using centre loading and a span length of 120 mm, the samples were placed on the two supports of the universal testing machine; the load was applied in the chord direction with a uniform speed, the sample was destroyed within 1 ± 0.5 min and the failure load was recorded. The bending strength of the sample was calculated using the following formula, where σ_b is the bending strength of the sample, P_{max} is the failure load, L is the span length (120 mm), t is the thickness and h is the width of the sample.

$$\sigma_b = \frac{3P_{max}L}{2th^2}$$

Shear strength parallel to grain: Twenty specimens from each bamboo species were prepared from the internodal segment of the bamboo. The samples was prepared to specific shapes and sizes in accordance with the Chinese national standard (GB/T 15780-1995). The load was applied parallel to grain at a uniform speed, the sample was destroyed within 1 ± 0.5 min and the failure load was recorded. The shear strength was calculated using the following formula, where τ is the shear strength parallel to grain, P_{max} is the failure load, t is the thickness and L is the shear length.

$$\tau = \frac{P_{max}}{tL}$$

Tensile strength parallel to grain: Twenty specimens from each bamboo species were prepared from the internodal segment of the bamboo. The samples were prepared to specific shapes and sizes in accordance with the Chinese national standard (GB/T 15780-1995). The bamboo nodes were only allowed to occur at the clamping positions at both ends of the samples. The load was applied parallel to grain at a uniform speed, the sample was destroyed within 1 ± 0.5 min and the failure load was recorded. If the fractured part did not appear in the effective middle part, the results were discarded. The tensile strength parallel to grain (σ) was calculated using the following formula, where P_{max} is the failure load, b is the width of the effective part, and t is the thickness of the effective part:

$$\sigma = \frac{P_{max}}{bt}$$

3.3 Sample preparation for chemical composition

Samples for the measurement of chemical composition were prepared according to the National Renewable Energy Laboratory (NREL) analytical procedure (Determination of structural carbohydrates and lignin in biomass). The moisture content of each specimen was controlled at lower than 10%. For each bamboo species, the sample was ground to 20–80 mesh. In the ensuing test, each species sample was analysed in duplicate.

3.3.1 Chemical composition determination method

Two G_3 filtering crucibles were placed in the oven until the constant weight and the weight of the crucibles were measured to the nearest 0.1 mg; 300.0 ± 10.0 mg of the sample were weighed into a tare pressure tube, and the weight was recorded to the nearest 0.1 mg (G). Then, 3.00± 0.01 mL of 72% sulfuric acid was added to each pressure tube. A Teflon stir rod was used to mix for one minute or until the samples were thoroughly mixed. The pressure tube was placed in a water bath set at 30 ± 3 °C and the sample was incubated for 60 ± 5 minutes with stirring. Upon completion of the 60-minute hydrolysis, the tubes were removed from the water bath. The acid was diluted to a 4% concentration through the addition of 84.00 ± 0.04 mL deionised water using an automatic burette. The Teflon caps were screwed on securely, and the sample was mixed by inverting the tube several times to eliminate phase separation between the high and low concentration acid layers.

A set of sugar recovery standards (SRS) was prepared, which included D- (+)glucose, D-(+)xylose, D-(+)galactose, L-(+)arabinose, and D-(+)mannose. The required amounts of each sugar were weighed to the nearest 0.1 mg, and then 10.0 mL deionised water and 348 µL of 72% sulfuric acid were added. The SRS was transferred to a pressure tube and capped tightly. The sealed samples and SRS were autoclaved for one hour at 121°C. After completion of the autoclave cycle, the hydrolysates were slowly cooled to near room temperature before the caps were removed.

For acid insoluble lignin (AIL), the autoclaved hydrolysis solution was vacuum filtered through one of the previously weighed filtering crucibles. The filtrate was captured in a filtering flask. An aliquot of approximately 50 mL was transferred into a sample storage bottle. The solids were rinsed with a minimum of 50 mL fresh deionised water. The crucible and acid insoluble residue were dried at 105 ± 3 °C until they reached constant weight. The weight of the crucible and dry residue were recorded to the nearest 0.1 mg (G2). The crucibles and residue were placed in the muffle furnace at 575 ± 25 °C for 24 ± 6 hours. The crucibles and ash were weighed to the nearest 0.1 mg and the weights recorded (G1). The AIL content was calculated as follows:

$$\mathrm{AIL\%} = \frac{G2 - G1}{G} \times 100\%$$

For acid soluble lignin (ASL) content, determination was completed within 6 hours of hydrolysis. Using the liquor aliquot obtained from the hydrolysis, the sample was diluted as necessary to bring the absorbance into the range of 0.7–1.0, and the dilution (D) was recorded. The absorbance of the sample was measured at an appropriate wavelength on a UV-visible spectrophotometer, with a background of deionised water or 4% sulfuric acid. The absorbance at 205 nm of each sample (A) was recorded, and the reproducibility should be ±0.05 absorbance units. The ASL content was calculated as follows, where V is the total volume of the hydrolysis liquor aliquot, 110 is the absorption coefficient and G is the mass of the sample.

$$\mathrm{ASL\%} = \frac{D \times A \times V}{110 \times G} \times 100\%$$

For structural carbohydrates, the liquor obtained from the hydrolysis was used. An approximately 20-mL aliquot of each liquor was transferred to a 50 mL Erlenmeyer flask. Calcium carbonate was used to neutralise each sample to pH 5–6. The sample for HPLC analysis was prepared by passing the decanted liquid through a 0.2 µm filter into an autosampler vial. The samples and the SRS were analysed by HPLC. The test sample chromatograms were checked to ascertain the sugar content. For more information, please refer to *National Renewable Energy Laboratory (NREL) analytical procedure*: *Determination of structural carbohydrates and lignin in biomass* (Sluiter et al, 2008).

3.4 Sample preparation for morphological properties of individual fibre testing

The following process was used for bamboo fibre maceration: bamboo samples from different species were cut into 0.25×0.25×5 cm bars (i.e., toothpick-sized pieces). Glacial acidic acid, 30% hydrogen peroxide and distilled water were used as the maceration solution at a ratio of 5:1:4.

The samples were macerated at 60°C for 4–6 hours in an ultrasonic cleaning machine. After maceration, the fibres were further separated with a stir rod, and were then washed thoroughly with distilled water until neutral. The distilled water was drained using a vacuum. A small amount of phenol was added as preservative and distilled water was also added to immerse the fibres. The fibres were stored in a jar in a refrigerator for the later determination of fibre length and strength. The diluted mixture was then spread evenly on a transparent glass sheet of 20×20 cm and another piece of glass was placed on top. The glasses with the fibres were then dried in an oven at 50°C for 24 hours so that the water would evaporate. The fibres were observed with microscope and the images were obtained. The length and diameter were measured by the Image-Pro Plus software from the images. Typically, three to four hundred fibres were selected and measured for each group.

4. Results and Discussion

4.1 Physical properties

4.1.1 Density

The bamboo’s density influences its other physical and mechanical properties. According to previous studies, the density or specific gravity of woody bamboos ranges broadly between 0.4 and 0.8 (Li, 2004; Anokye et al, 2016). Data on density are an important parameter in determining its suitability for value addition, including its product lines, machine and/or tool specification, glue composition and adjustments in pressing time, heat and pressure for the production of various engineered products.

The basic, oven-dried and air-dried densities of the three different bamboo species (four samples) were tested. **Figure 8** shows the treatment and drying process of the samples. The oven-dry density and basic density of four samples are as summarised in **Table 2**.

(a) Samples immersed in water | (b) Samples air-dried | (c) Samples dried in oven

Figure 8: Samples for measuring density and shrinkage

Table 2: Oven-dry density and basic density of bamboo

Samples	Oven-dry density (STD*) g/cm^3	Basic density (STD) g/cm^3
D	0.6774 (0.04)	0.5084 (0.02)
Y	0.9055 (0.03)	0.7843 (0.007)
N	0.7941 (0.003)	0.6194 (0.01)
S	1.001(0.045)	0.8053 (0.05)

*STD: standard deviation

The results indicate that both oven-dried density and basic density are S>Y>N>D. The sample S (*Oxytenanthera abyssinica*) showed the highest oven-dried density at 1.001 g/cm^3, and sample D (*Dendrocalamus asper*) showed the lowest oven-dried density at 0.6774 g/cm^3. *Oldeania alpina* from Kenya has a higher oven-dried density compared to the same species samples from Uganda.

The samples' air-dried densities are shown in Tables 3 and 3A. They followed the same trend in that sample S showed the highest air-dry density while sample D showed the lowest. The result also indicated that the air-dry density varies in response to different moisture contents.

Table 3: Air-dry density of bamboo

Samples	Y1	Y2	Y3	S1	S2	S3
Moisture content (%)	7.14	7.31	7.07	5.77	5.83	5.50
Air-dry density (g/cm^3)	0.9515	0.9506	0.9531	1.077	0.9845	0.9787

Table 3A: Air-dried density of bamboo

Samples	N1	N2	N3	D1	D2	D3
Moisture content (%)	7.03	7.62	6.95	7.69	7.84	7.44
Air-dry density (g/cm^3)	0.8106	0.8245	0.8285	0.6498	0.689	0.7118

Higher density indicates higher strength. Different bamboo species have different densities, and the density varies within the same bamboo species, across different age-groups, depending on the position of the culm (i.e., bottom, middle or top) and the cross-section of the culm (i.e., the outer, middle or inner layer) (Sattar, 1995; Li, 2004; Kamruzzaman et al, 2008; Narasimhamurthy et al., 2013). Test results of economically important bamboo species, such as *Bambusa balcooa, Bambusa blumeana, Bambusa nutans, Bambusa tulda Dendrocalamus strictus* and *Phyllostachys pubescens*, indicate densities of 0.65, 0.50, 0.68, 0.71, and 0.72 g/cm^3, respectively (Sattar, 1995 and Li, 2004). However, a study by Falayi et al (2014) on the physical and mechanical properties of *Phyllostachys pubescens* indicated that the densities at different culm positions range from 0.6413 to 0.6733 g/cm^3. Yu et al (2008) studied the physical and mechanical properties of Moso bamboo at various vertical and horizontal positions: the results indicated a density ranging from 0.553 to 1.0006 g/cm^3. Sattar (1995) also indicated that teak (*Tectona grandis*) and sal (*Shorea robusta*) in India have densities of 0.60 g/cm^3 and 0.71 g/cm^3, respectively.

Phyllostachys pubescens, or Moso bamboo, is the most extensively used product for high-end value addition in China. The analysis results of the three bamboo species indicate that *Oxytenanthera abyssinica* and *Oldeania alpina* have densities that are comparable to that of Moso bamboo.

4.1.2 Shrinkage

The size and volume of bamboo shrink and expand in all directions due to the evaporation and/or absorption of moisture, and this mainly occurs in cross-sections of bamboo (Zhaohua and Wei, 2018). The amount of shrinkage is proportional to the water evaporation below the saturation point. Shrinkage of bamboo is different along radial, and tangential direction and its volume. The shrinkage of bamboo from green to oven-dry and from green to air-dry were investigated and the results are shown in **Table 4**.

For each of the four samples, the shrinkage from green to oven-dried was much higher than that from green to air-dried. The shrinkage along the radial direction was highest in sample D, followed by samples Y, S and N, both in green to oven-dried and air-dried specimens. Tangential shrinkage in the case of green to oven-dried was highest for sample Y, followed by samples S, D and N. However, for the green to air-dried samples, the tangential shrinkage was highest for sample S, followed by D, N and Y. Volumetric shrinkage was highest in sample D, followed by S, Y and N for the green to oven-dried samples. However, for the green to air-dried specimens, sample D had the highest shrinkage, followed by N, S and Y.

Table 4: Shrinkage values of bamboo

Samples	Shrinkage (STD*), %					
	Shrinkage from green to oven-dry			Shrinkage from green to air-dry		
	Radial	Tangential	Volumetric	Radial	Tangential	Volumetric
D	9.27 (0.64)	7.03 (0.27)	16.18 (0.83)	5.88 (0.44)	4.20 (1.13)	9.67 (1.13)
Y	6.78 (0.33)	8.80 (3.10)	15.93 (3.16)	3.43 (0.22)	3.57 (0.50)	7.24 (0.88)
N	7.42 (0.23)	6.52 (0.59)	14.42 (1.20)	4.90 (0.13)	3.99 (0.58)	9.24 (0.46)
S	7.59 (0.26)	8.63 (0.30)	15.96 (0.35)	4.31 (0.31)	5.05 (0.27)	9.11 (0.33)

***** STD: standard deviation

Of all the samples, Y had the lowest radial, tangential and volumetric shrinkage in the green to air-dried tests; and sample N had the lowest shrinkage in the green to oven-dried tests. This indicates that *Oldeania alpina* from Kenya has the highest dimensional stability, followed by *Oldeania alpina* from Uganda. *Dendrocalamus asper* has the lowest dimensional stability among the three species.

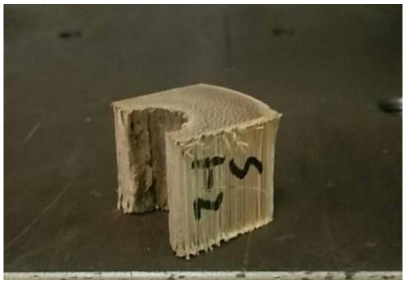
Schroeder (1971), studying volumetric shrinking and swelling differences between hard and softwoods reported average shrinkages of 12.4 – 16.4% and 9.6 – 12.5%, respectively. Increase in the density of the wood indicate increase in shrinkage and swelling, and a higher percentage of lignin acts as a restraint for dimensional change.

The tangential, radial and volumetric expansion of bamboo from different tropical and temperate regions ranges from 2.5 to 11.6 %, 4.1 to 24.8% and 7.8 to 36.54% (Zhaohua and Wei, 2018; Wahab et al, 2012). Specifically, Moso bamboo (*Phyllostachys pubescens*), which is the most widely used bamboo in industrial applications in China has a tangential, radial and volumetric expansion of 5.77, 9.87 and 19.31%. A study by Thuc and Tuong (2017) showed that radial, tangential and volumetric shrinkages of *Dendrocalamus giganteus* bamboo culm from fibre saturation point to 12% were in the range of 4.8–6.6%, 4.3–5.7% and 9.2–12.1% respectively, and radial, tangential and volumetric shrinkages from fibre saturation point to 0% were 6.2–8.7%, 6.0–7.4% and 12.2–15.8% respectively. *Phyllostachys pubescens* and *Dendrocalamus giganteus* are the two most widely used species in the production of engineered bamboo products. The test results of this study are comparable for both species.

4.2 Mechanical properties

The mechanical properties of bamboo are a key parameter for the processing and value-addition of bamboo. Bamboo is thought to be one of the best functionally gradient composite materials available. As a natural biomaterial, its mechanical properties vary according to species, age, place of origin, and even its different parts. In industry, raw materials must be tested to meet the performance requirements of products such as flooring, furniture, or decorative materials. The compressive, shear, bending and tensile strengths of the four bamboo specimens (from the three species) were investigated. **Figure 9** shows images of the samples before and after testing. The compressive strength represents the most important parameter as a structural load-bearing material. Shear strength is crucial in the design of building both joint and bending and tensile strength reflect the elasticity and toughness of bamboo and bamboo-based panels (Gao et al, 2010).

(a) Samples before compressive testing



(b) Samples after compressive testing

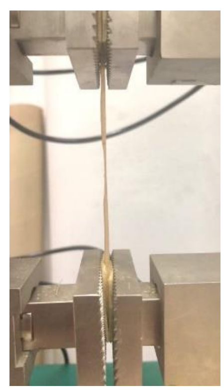
(c) Samples before shear testing

(d) Samples after shear testing

(e) Samples before bending testing

(f) Samples after bending testing

(g) Samples before tensile testing



(h) Samples after tensile testing

Figure 9: Different samples before and after mechanical property testing

The various bamboo samples exhibit different mechanical properties, as shown in Table 5. The compressive strength of the tested samples, parallel to grain, ranges from 58 to 87 MPa. Sample Y has the highest compressive strength, followed by D>N>S. This is comparable to and even higher than some high-strength woods, such as pine (40~65MPa) (Yang, 2001) and *Quercus acutissima* (50~70MPa) (Yang et al, 2001).

The highest shear strength parallel to grain of the samples are ranging from 8.5 to 13MPa. Sample D has the highest value, followed by Y>N>S. In typical soft and hardwoods, shear strength parallel to grain tends to increase with the wood's density (Gibson and Ashby, 1998). However, no similar trend was observed in this study. This may be because the structures of typical woods and bamboo are quite different (Grosser and Liese, 1971; Gibson and Ashby, 1998). Compared to structural woods and bamboo products, the shear strength parallel to grain for the four bamboo samples is greater than that of Douglas fir (8 MPa) (Kretschmann, 2010) and lower than those of teak, laminated bamboo lumber and bamboo scrimber or strand woven bamboo, which are over 15 MPa (Srivaro, 2017; Sharma et al., 2015). This property, for Y and D, was comparable to Scots pine (13 MPa) (Domone and Illston, 2010).

Modulus of rupture (MOR), a main bending property of the samples, were tested. Sample Y has the highest MOR, at 253 MPa, followed by D and N, while sample S has the lowest MOR at 146 MPa. This property is much greater than that of structural woods, such as teak, Scots pine (Srivaro, 2017; Domone and Illston, 2010) and Douglas fir (Kretschmann, 2010), as well as bamboo products (Sharma et al., 2015).

Sample D had the highest tensile strength at 287 MPa, followed by Y and S, while sample N had the lowest tensile strength at 206 MPa. Compared with structural woods, the tensile strengths of the bamboo samples examined here were much higher than those of Scots pine (92 MPa) (Domone and Illston 2010) and Douglas fir (66 MPa) (Langum et al, 2009).

Of the four samples, *Oldeania alpina* from Kenya has the highest compressive and bending strength; *Dendrocalamus asper* from Kenya has the highest shear and tensile strengths; *Oxytenanthera abyssinica* has the lowest compressive and shear strength; and *Oldeania alpina* from Uganda has the lowest bending and tensile strength. Overall, *Oldeania alpina* (samples from Kenya) and *Dendrocalamus asper* have mechanical properties that are superior to those of the other two specimens.

Moso bamboo (*Phyllostachys pubescens*) is the main species used for producing timber substitute products in China, and has been used in house and bridge construction, furniture, handicraft and papermaking. (Jinhe, 2001). According to previous research on Moso bamboo

(Zhang et al, 2012; Yanhui et al, 2011), its compressive strength parallel to grain is 59.46 MPa, its shear strength parallel to grain is 12.86 MPa, its bending strength is 132.46 and its tensile strength varies from 136.05 to 297.21 MPa. As a reference, the mechanical properties of Moso bamboo are lower than those of *Dendrocalamus asper* and *Oldeania alpina*, but slightly higher than *Oxytenanthera abyssinica*. *Oldeania alpina*, in particular, has a similar diameter at breast height, culm-wall thickness and culm taper compared to those of Moso bamboo, and relatively good mechanical properties. As such, it could be easily introduced to the Moso bamboo-based product line for industrialisation.

Table 5: Mechanical properties of bamboo strips

Sample	Compressive strength parallel to grain (STD*) MPa	Shear strength parallel to grain (STD) MPa	Bending strength (STD) MPa	Tensile strength parallel to grain (STD) MPa
D	75.7(1.3)	13(2.0)	206.8(29.0)	287.6（8.8）
Y	87.3(7.7)	12.5(2.0)	253.1(38.9)	280.1（12.9）
N	61.5(7.8)	9.1(2.0)	146.3(28.6)	206.7（24.8）
S	58.6(15.5)	8.5(1.7)	156.3(25.1)	270.6（29.3）

*STD: standard deviation

4.3 Chemical composition

Chemical composition analysis is a crucial step in appreciating bamboo's potential as a bio-fuel, fibre and for pulp production. It is well established that bamboo's chemical composition is similar to that of wood, with cellulose, hemicellulose and lignin accounting for more than 90% of its biomass (Zhouhua and Wei, 2018).

The chemical composition of bamboo species was analysed, and the results are presented in **Table 6**. The overall lignin content of the four samples ranges from 21 to 24%, which is in the upper range of the normal value of the 11–27% reported for non-woody biomass, at the lower end of the value for softwoods (24–37%) and within the same range as the normal value reported for hardwoods (17–30%) (Fengel et al, 1984; Dence, 1992). This indicates that the three bamboo species can be used not only as biomass energy but can also be value-added to applications similar to those of soft and hardwoods. Similarly, the glucan content is 44–48%, similar to the reported cellulose content of soft (40–52%) and hardwoods (38–56%). The samples' xylan contents were at the upper end, or even higher than that of softwood (10–15%) and within the range of the normal value reported for hardwoods (10-35%) (Panshin, 1980).

Considering that the cellulosic content in the range of 44–48 % makes all three bamboo species suitable for pulp and the paper industry (Li, 2004). *Dendrocalamus asper* has the highest proportion of glucan (48%), followed by *Oxytenanthera abyssinica* (46.02 %), making them highly suitable for pulp production compared to *Oldeania alpina.*

Table 6: Chemical composition of bamboo

Sample	Glucan (%)	Xylan (%)	Arabia glucan (%)	Acid soluble lignin (%)	Acid insoluble lignin (%)
D	48.00	15.05	0.32	0.14	21.10
Y	44.90	15.47	0.32	0.13	24.36
N	44.72	16.77	0.35	0.18	21.53
S	46.02	14.85	0.97	0.11	23.93

Lignin in bamboo changes with the elongation of the culm, and the age and position of the culm (Li, 2004). The study on *Phyllostachys pubescens* indicates that lignin is higher in three-year-old bamboo compared to that in one and five-year-old culms, with a lignin content ranging from 21.26 to 24.30%. *Dendrocalamus asper* (D) has the lowest lignin content (21.10%), followed by *Oldeania alpina* from Uganda (21.53%) and *Oxytenanthera abyssinica* (23.93%), while the highest lignin is found in *Oldeania alpina* (24.36%) from Kenya. The lignin contents of the four samples tested (from three species) are similar to that of *Phyllostachys pubescens.* Comparatively higher lignin values indicate the high heating value of the biomass, making it suitable for biomass applications, while higher lignin also indicates higher structural rigidity (Scurlock, 2000), making the material suitable for structural applications, such as construction and furniture-making. *Oldeania alpina* from Uganda and *Oxytenanthera abyssinica* are relatively suitable for bio-energy and structural applications.

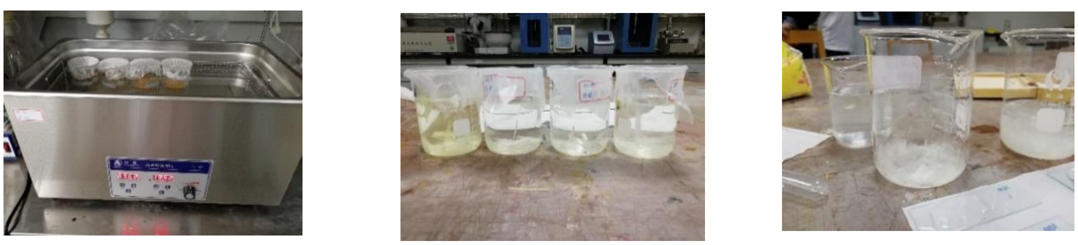
4.4 Morphology and dimension of individual bamboo fibre

Bamboo is a key source of raw material for pulp and the paper industry, weaving, textiles and fibre-based composite industries, particularly in South East Asia. The bamboo culm is comprised of around 50% parenchyma, 40% fibres and 10% vessels and sieve tubes (Liese and Hamburg, 1987). The fibres contribute 60–70% of the culm tissue's total weight. Bamboo fibre is of good quality and suitable for large-scale fibre-based product development. China produces more than 2 million MT of bamboo pulp and over 100, 000 tons of fibre products annually (Zhaohua and Wei, 2018). Analysis of the lengths and diameters of individual fibres is key in appreciating the splitting properties of bamboo and its products and its suitability for fibre products and applications, such as pulp and paper production, weaving and textiles, as well as composite products. In this study, individual bamboo fibres were isolated from the three different species and their morphologies were characterised. **Figure 10** illustrates the samples during the fibre isolation process.

(a) Bamboo (removal of outer and inner parts)

(b) Cut into small strips

(c) Immersed in the chemical solution



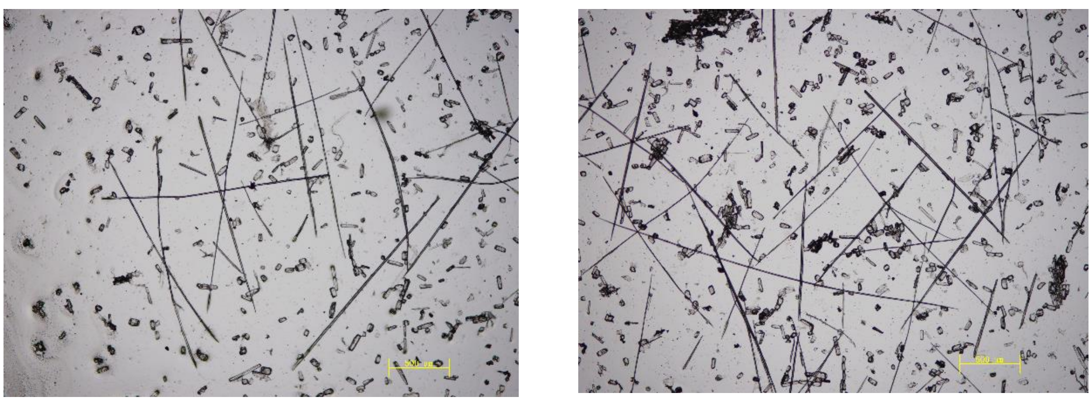
(d) Heated for 4 h at 65℃ with ultrasonic treatment

(e) De-colourised bamboo strips using glacial acidic acid and hydrogen peroxide

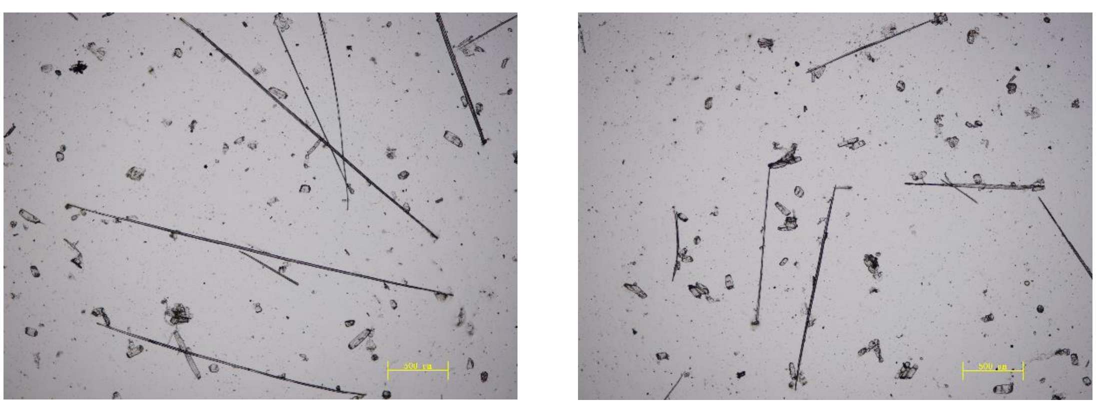
(f) Washed with deionised water to neutrality

Figure 10: Process of isolating individual fibre using a chemical method.

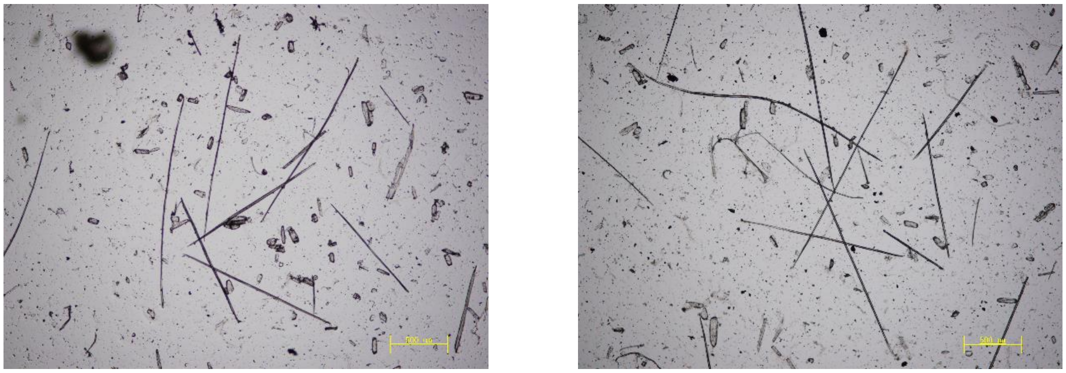
The morphologies of the bamboo fibres from the different species were observed by optical microscopy and the images are shown in **Figure 11**. The length and diameter of the individual bamboo fibres were measured and are summarised in **Table 7**. Long fibres were successfully isolated from the bamboo to a length of 1.7–2.1 mm, which is within the mid-range of the normal value reported for bamboos (1.5–3.2 mm) (Bassam, 1998). The length of the bamboo fibres varies considerably among the different species. The length of the fibre from sample S (*Oxytenanthera abyssinica*) was 2.14 mm, making it the longest among the four samples, while sample S has the lowest length at 1.68 mm. These bamboo fibres are longer than those of hardwoods (1–1.5 mm) (Liese, 1995), and shorter than the long fibres of softwoods. For example, among the softwoods, the fibre lengths of black spruce*, P. radiata* and southern pine were 3.5, 3.0, and 4.6 mm, respectively (Smook, 1997). A study by Li (2004) indicated that the mean fibre length of other bamboo species, such as *Guadua angustifolia, Phyllostachys edulis, Bambusa tulda, B. vulgaris* and *Dendrocalamus giganteus*, were 1.6 mm, 1.5 mm, 3 mm, 2.3 mm and 3.2 mm, respectively. Li's study (2004) indicates that the fibre length varies in each internode, that the fibre increases from bottom to top, and fibre content is greater on the outer one-third of the wall; The fibre length of Moso bamboo ranged from 1.6 –3.1 mm.



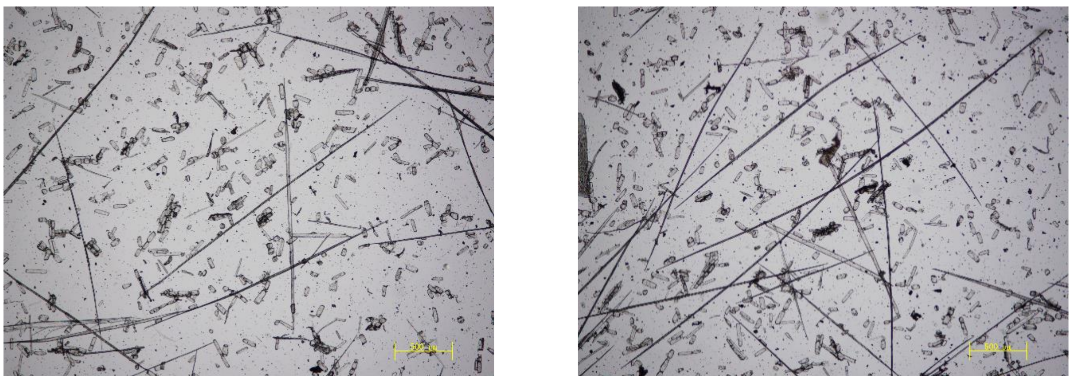
(a) bamboo fibre isolated from *Dendrocalamus asper*



(b) bamboo fibre isolated from *Oldeania alpina* (Uganda)



(c) bamboo fibre isolated from *Oleania alpina* (Kenya)



(d) bamboo fibre isolated from *Oxytenanthera abyssinica*

Figure 11: Individual bamboo fibres of different species

The diameter of the bamboo fibres from the four samples ranges from 10.42 to 13.53 µm. Sample N has the highest diameter and sample D has the lowest. Furthermore, the length-to-diameter ratios of the bamboo fibres were 178 for sample D, 126 for sample N, 134 for sample Y and 190 for sample S. Typically, the length-to-width ratio varies between 150:1 and 250:1, and the larger, the better (Wang et al., 2008, Yang et al., 2008).

Table 7: Length and diameter of individual bamboo fibre

Sample	D		N		Y		S	
	length (mm)	diameter (µm)	length (mm)	diameter (µm)	length (mm)	diameter (µm)	length (mm)	diameter (µm)
Mean	1.85	10.42	1.70	13.53	1.68	12.50	2.14	11.28
STD	0.51	2.78	0.47	3.94	0.34	3.52	0.62	3.54
CV	0.28	0.27	0.28	0.29	0.20	0.28	0.29	0.31

STD: standard deviation; CV: coefficient of variation.

Conclusion

As a sustainable natural resource, bamboo has significant potential as an alternative source of raw materials, as a timber substitute, in bio-energy applications, crafts, furniture, construction, composites, pulp and paper production, among others. The vast underutilised bamboo resources in East Africa present a major opportunity for the development of different value chains contributing to livelihoods, economy and the environment.

Bamboo with good structural rigidity and high lignin content is a valuable building material (Scurlock et al, 2000). Among the three bamboo species (four samples) studied, samples Y (*Oldeania alpina*, a highland bamboo from Kenya) and N (*Oldeania alpina,* a highland bamboo from Uganda) possessed these qualities and the potential to be a suitable material for structural purposes (i.e., building materials) due to its high density, good mechanical properties and dimension stability, as well as its high lignin content.

Both samples Y and N are *Oldeania alpina (Syn. Yushania alpina/Arundinaria alpina*). This bamboo is widely used in Ethiopian industries for the production of parquet flooring, laminated lumber and stick-based products. As mentioned previously, it has similar DBH, culm wall thickness and culm taper to those of Moso bamboo, and comparably good mechanical properties; thus, it could be easily introduced to the Moso bamboo-based product line for industrialisation. Since Moso has been the most commonly utilised bamboo in industrial bamboo-based manufacturing worldwide, *Oldeania alpina* shows great utilisation potential as a timber substitute.

Sample D (*Dendrocalamus asper*, giant clumping bamboo from Kenya) has relatively low density and dimension stability, but has high mechanical properties, in particular high bending strength. It is suitable for the production of glued laminated bamboo or bamboo parallel-strand lumber for use in structural applications (Sinha et al., 2013; Ahmed and Kamke., 2011). Sample S (*Oxytenanthera abyssinica*, a lowland bamboo from Uganda) not only has good bending strength but also high tensile strength, so it is also suitable for the production of glued laminated boards. Furthermore, the high overall contents of glucose, xylan and arabia glycan in sample D and S also make this species suitable for use in the production of bio-fuels and other bio-based materials. For example, it is reported that bamboo can be used as a fuel for power generation, since its lower moisture content at harvest obviates the need for drying (Molini and Irizarry, 1982). It has also been demonstrated that de-lignified bamboo pulp can be used as a substrate for ethanol fermentation. In addition, other work has verified the preparation of a bio-ethanol from bamboo culms (Ram and Seenayya, 1991).

Moreover, the fibre lengths of the four samples are in the mid-range of the values typically reported for bamboo species (1.5 -3.2mm), and are thus ideal for use in the paper and textile industries. In particular, sample S can be used to produce high-quality paper due to its long fibre length and high length-to-width ratio. Besides, considering that the bamboo is relatively solid and has high tensile properties, it is also suitable for use in furniture or construction.

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