

Technical Paper

Age-specific properties, machine and product compatibility of east African highland (*Oldeania alpina*) and lowland (*Oxytenanthera abyssinica*) bamboo

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The International Bamboo and Rattan Organization (INBAR) is an intergovernmental organization dedicated to the promotion of bamboo and rattan for sustainable development. For more information, please visit www.inbar.int.

About this Working Paper

This work is an INBAR publication produced as part of the Dutch-Sino East Africa Bamboo Development Programme—Phase II, funded by the Kingdom of the Netherlands and the Chinese government. The Dutch-Sino East Africa Bamboo Development Programme II is a triangular South-South cooperation to support livelihood development, food security, and better environmental management by developing robust bamboo value chains and a sustainable bamboo industry in Ethiopia, Kenya, and Uganda.

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Foreword

INBAR has encouraged initiatives worldwide to utilize bamboo's potential to transform member states' economies. Bamboo is a fast, renewable, and sustainable alternative to conventional woody biomass, with applications ranging from construction to biofuel. Since 2017, the Dutch-Sino East Africa Bamboo Development Programme has been working to develop value chains and support livelihoods in Ethiopia, Kenya, and Uganda. The programme aims to apply the experience gained in other parts of the world to promote the role of bamboo plantations in forest landscape restoration, soil erosion control, water conservation, and climate change mitigation and adaptation.

This report presents the results of a joint collaborative effort between the International Centre for Bamboo and Rattan (ICBR) and the Dutch-Sino East Africa Bamboo Development Programme (Phase-II) on testing the age-wise properties, machine, and product compatibility of Ethiopian highland (*Oldeania alpina*) and lowland (*Oxytenanthera abyssinica*) bamboo species. Although the report focuses on Ethiopian bamboo species, but it has significant value and potential for replication in other African countries where similar species grow in different agro-climatic zones. The outcomes of the report can assist upcoming bamboo industries in making informed decisions regarding the establishment of high-end bamboo products.

The research provides data on age-wise properties testing and compatibility with high-end manufactured products of two significant bamboo species in Ethiopia. The goal is to assist investors, policymakers, and researchers in making decisions and participate in the value chains of bamboo to maximize economic and environmental advantages.

Ali Mchumo
Director General
International Bamboo and Rattan Organization

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Acronyms/Abbreviations

| | |
|-------------------------------|---|
| BLVL | Bundle Laminated Veneer Lumber |
| CBAE | Content of Benzene Alcohol Extract |
| CCWE | Content of Cold Water Extract |
| CHWE | Content of Hot Water Extract |
| COV | Coefficient of Variation |
| EFCCC | Ethiopian Environment, Forestry and Climate Change Commission |
| GB/T | Guobiao Standards (Chinese National Standards) |
| GPa | Giga Pascal |
| H ₂ O ₂ | Hydrogen peroxide |
| ICBR | International Centre for Bamboo and Rattan |
| INBAR | International Bamboo and Rattan Organization |
| KN | Kilonewton |
| mL | Milliliter |
| mm | Millimeter |
| MPa | Mega Pascal |
| NaOH | Sodium hydroxide |
| PF | Phenolic resin |
| µm | Micrometer |
| °C | Degree Celsius |

Executive Summary:

Ethiopia's bamboo resources consist of two native species and several exotic species introduced by the national government agencies for testing and trials. The Ethiopian Forestry Development, formerly known as the Ethiopian Environment, Forestry and Climate Change Commission (EFCCC)¹, has developed a ten-year bamboo strategy and action plan (2019-2030) to promote the growth and development of the sector. Recently, the Ethiopian Investment Commission has included bamboo as a priority sector in their investment guidebook² to encourage new investors in bamboo development. A conducive business ecosystem has been developed for the sector to augment the vast potential of bamboo as an industrial raw material for modern applications, such as engineered bamboo and biofuel, in addition to its traditional uses for handicrafts and household implements.

The research is a collaboration between INBAR-Dutch-Sino East Africa Bamboo Development Programme (Phase-II) and International Centre for Bamboo and Rattan (ICBR). Testing the properties, machines, and product compatibility of age-wise Ethiopian highland (*Oldeania alpina*) and lowland (*Oxytenanthera abyssinica*) bamboo species will provide a fresh perspective to make informed decisions in particularly the investors.

Under the research, the bamboo samples were collected and prepared in accordance with the Chinese national standard GB/T 15780-1995, which outlines testing methods for the physical and mechanical properties of bamboos and product compatibility. The sample collection and preparation protocol is presented below:

- Collected the representative bamboo samples from the bamboo growing areas in Ethiopia, with ages of 2, 3, and 4 respectively.
- Measure and record the diameter at breast height (1.5 meters) of each selected bamboo culm. The culms were harvested~ 50 mm in diameter (for lowland bamboo).
- The bamboo culms were selected by felling or cutting at a height of 1.5 meters from the ground, and then cut into two sections, each with a length of 2 meters.
- For sample preparation, 20 bamboo culms per age of the selected species were harvested.
- The collected samples were healthy and free from defects or deformities.

¹ https://www.inbar.int/resources/inbar_publications/2019-2030-ethiopian-bamboo-development-strategy-and-action-plan/

² <https://www.unido.or.jp/files/EIC-Investment-Guide-FINAL-IP-Updated-Feb.-2023.pdf>

- The samples were labelled with a code consisting of the age, sample number, and section number. For example, “S-2-1-1” represents section 1 of the first two-year-old lowland bamboo (*Oxytenanthera abyssinica*). The section next to 1.5 m is labelled as S-2-1-1, then sequentially labelled as S-2-1-2. Another bamboo is labelled as S-2-2-1 and S-2-2-2. The summary includes the bamboo species, sample location, age, and number.
- The bamboo samples were oven-dry at approximately 60°C until they reached a moisture content of 7-12% and stored in a dry area.
- The samples collected from Ethiopia were shipped to the International Centre for Bamboo and Rattan (ICBR) lab for physical and mechanical testing, following the Chinese National Standard for testing the physical and mechanical properties of bamboo (GB/T 15780-1995).

The following are the main findings regarding the age-wise property, machine and product compatibility of the Ethiopian highland (*Oldeania alpina*) and lowland (*Oxytenanthera abyssinica*) bamboos:

I. Highland Bamboo (*Oldeania alpina*)

Chemical testing was conducted to determine the suitability of highland bamboo for various applications. The study observed the effect of age and height position on the chemical composition varies in different section and ages. It was found that content of cold water extract (CCWE), and content of hot water extract(CHWE) increased with age, while content of Benzene Alcohol Extract(CBAE), ash content, and holocellulose decreased slightly with age. The highest holocellulose content was observed at the top portion, and the lowest at the bottom portion. There was only a slight decrease in holocellulose content between the 2-year-old and 3-year-old highland bamboo. Therefore, it is a promising source of bioethanol due to its high holocellulose content. Specifically, the top portion of 2-3-year-old highland bamboo can be used for bioethanol production.

The ash content of bamboo is a key factor in its carbonization, representing the inorganic residue that remains after ignition at high temperatures. The ash content of highland bamboo showed only a slight decrease from 2-year-old to 3-year-old, ranging from 0.96% to 1.31%. This makes it suitable for producing carbon/activated carbon for water adsorption and electrochemistry.

Mechanical testing is crucial in determining the processing and value-addition of bamboo due to its mechanical properties. As a natural biomaterial, bamboo's mechanical properties vary depending on factors such as species, age, and origin. This study investigated the compressive, bending and tensile strength properties of highland bamboo at different ages and heights.

The highest values for compressive strength and modulus were observed at the top part of the 3-year-old section, with values of 88.50 MPa and 33.41 GPa, respectively. The same section also exhibited the highest bending strength, tensile strength and bending modulus, measuring 265.06 MPa, 243.38 Mpa and 35.14 GPa respectively. In contrast, the shear strength decreased from bottom to top, contradict the results of several further research (Deng et al, 2016), but consistent with the several Indonesia bamboo species (Hartono et al, 2022). Similar to the compressive and tensile strength, the shear strength in bamboo is likewise affected by the increasing proportion of vascular bundle from the bottom to the top of the bamboo stem.

The study found that tissue proportion varies with age and height. Fiber proportion ranged from 41.5% to 48%, basic parenchyma from 37.67% to 45%, vessel at 12%, and sieve tube at 1.5% to 2.34%. The highest fiber proportion was found in the top portion of 3-year-old highland bamboo, at 55%, which explains why this portion had the highest mechanical properties.

The physical testing of the study also considered the basic density to be an important factor in determining the suitability of bamboo for various application. The air-dry density varied between 0.80-0.85 g/cm³, the oven-dry density varied between 0.78-0.82 g/cm³, and the basic density varied between 0.51-0.58 g/cm³. The highest air-dry density, oven dry density and basic density were found in the middle part of 3-year. Generally, the density at both ages increased as the height of bamboo increase.

II. Lowland Bamboo (*Oxytenanthera abyssinica*)

Chemical testing showed that the chemical composition of lowland bamboo (*Oxytenanthera abyssinica*) changes with age. Specifically, the content of the cold water extract(CCWE), content of hot water extract (CHWE), and ash content increase as the bamboo gets older. On the other hand, the content of Benzene Alcohol Extract(CBAE) decreases from 1-year-old to 2-year-old, then increases from 2-year-old to 3-year-old. The holocellulose content follows the opposite trend, increasing initially and then decreasing. It is worth noting that the holocellulose

content of lowland bamboo is slightly higher than that of highland bamboo. This bamboo can be used for pulp and paper production. Specially, lowland bamboo that is 2 years old contains the highest amount of holocellulose and is a potential source of raw material for the pulp and paper industry.

Mechanical testing showed that the compressive strength parallel to the grain of lowland bamboo decreased from 122.32 MPa to 92.20 MPa as the age increased from 1 to 3 years old. Similarly, the compressive modulus decreased from 34.33 GPa to 25.77 GPa in 2 to 3 years' age. The compressive strength and modulus of 1-year-old lowland bamboo were the highest, measuring 122.32 MPa and 34.33 GPa, respectively. The bending strength and modulus of 2-year-old lowland bamboo were the highest, measuring 163.55 MPa and 14.20 GPa, respectively. The bending properties increased from 1-year-old to 2-year-old, but decreased from 2-year-old to 3-year-old. Likewise, the 2-year-old lowland bamboo had the highest shear strength (11.66 MPa), and the change rule was similar to the bending properties. Anatomical testing showed that the 1-year-old lowland bamboo had the highest fiber proportion (68%) and the lowest basic parenchyma proportion (17%). Fiber mainly provides support to bamboo and enables it to bear more force when pressed, which is consistent with the results of compressive properties. Additionally, the fiber proportion decreased as the age increased, with a decrease of up to 30%. The results show that lowland bamboo has long fibers, with a mean length ranging from 1681.96 μm to 2221.86 μm . These long fibers contribute to the higher tearing resistance of paper produced from lowland bamboo.

With respect to physical testing, the test showed the density of lowland bamboo at different age. The air-dry density changed from 0.87 g/cm^3 to 0.95 g/cm^3 , the oven-dry density changed from 0.83 to 0.91 g/cm^3 , and the basic density changed from 0.57 g/cm^3 to 0.64 g/cm^3 . The three different densities all increased with age from 1-year-old to 2-year-old, then decreased from 2-year-old to 3-year-old.

Product Compatibility Testing:

The research also focused on two high-end engineered bamboo products through machine compatibility testing. The findings are as follows:

I. Bamboo Laminated Boards

The test results indicate that bamboo laminations made from Ethiopian highland bamboo possess favorable physical and mechanical properties. These laminated bamboo products can be utilized in various applications, similar to those of Moso bamboo, including bamboo flooring, furniture, and large-scale laminated bamboo

II. Bundle Laminated Veneer Lumber (BLVL)

The Ethiopian highland bamboo (*Oldeania alpina*) is hollow and has a large diameter, which allows it to be processed into strips using a splitting machine in the factory before further processing. However, the Ethiopian lowland bamboo (*Oxytenanthera abyssinica*) has a small diameter and is solid, making it unsuitable for processing using a crushing machine to produce the desired product.

The BLVL made from highland bamboo (*Oldeania alpina*) has a coarser and more irregular fiber texture, but it is stronger. The elastic modulus of the BLVL flooring made from Ethiopia highland bamboo is $E=13270$ MPa, with a static bending strength of $X_{\text{mean}}=150.9$ MPa and $X_{\text{min}}=146.4$ MPa. These qualities meet the national standard of Chinese standards of GB/T 30364-2013 for manufacturing the 'Bamboo Scrimber Flooring'. Although the horizontal shear strength index falls slightly below the standard, it can be improved by optimizing the hot-pressing parameters for the boards during production.

In nutshell, the study recommends using 2-year-old lowland bamboo for its high holocellulose content, long fibers, and good mechanical properties. The species performs better than *Dendrocalamus farinosus* and can be used for pulp and paper production. Similarly, highland bamboo (*Oldeania alpina*) has many applications similar to the Chinese Moso bamboo species, including bamboo flooring, furniture, and large laminated bamboo products.

1. Introduction

Bamboo is a non-wood forest resource that has great potential as a substitute for wood due to its high productivity, rapid growth, and ease of reproduction (Zhan et al., 2015). It grows fast in tropical and subtropical regions and is often referred to as “green gold” due to its diversity (Fang et al., 2018). Bamboo is widely distributed, occurring naturally in a range between 40 degrees southern and northern latitude on all continents except Europe. Bamboo is widely distributed in tropical and subtropical zones, covering approximately 31.5 million hectares between 46°N and 47°S latitude. In 2010, it accounted for about 0.8% of the world's total forested area (Song et al., 2011). There are over 1600 species of bamboo worldwide (Vorontsova et al., 2016).

Bamboo is a superior wood substitute that is cost-effective, efficient, and has high potential for environmental protection (Ebissa et al., 2022). Bamboo is a versatile material that has been used in over 1500 applications and its usage is rapidly increasing. Its sustainability makes it an important resource for building a sustainable future. It is commonly used in construction, flooring, handicrafts, charcoal, pulp production (Fastriasari et al., 2023; Shang et al., 2023), nanofiber extraction (Asada et al., 2021), composite materials (Ochi, 2022; Rudi et al., 2022), and biofuel production (Song et al., 2022).

Sub-Saharan Africa is home to approximately 3 million hectares of bamboo forest, primarily consisting of *Oldeania alpina* (also known as *Yushania alpina* / *Arundinaria alpina*), a highland bamboo, and *Oxytenanthera abyssinica*, a lowland bamboo, which grow on drier and very poor soils. Ethiopia has the largest area of natural bamboo in Africa, with about 1 million hectares of bamboo, of which 850,000 hectares are lowland and 350,000 hectares are highland bamboo (Kassahun et al., 2000, Tsinghua University and INBAR, 2018). Ethiopia has committed to restoring one-sixth of its land into productivity by 2025, with bamboo playing a crucial role in this effort (Tsegaye et al., 2020). The bamboo sector in East Africa is currently largely untapped, and the industry is still in its infancy.

The properties of the plant depend on its age and height position (Majumdar et al., 2015), and vary with species, environmental conditions, age, and location, as well as culm height (Liese and Weiner, 1996). Understanding the variation in bamboo properties with age and height is crucial for its potential utilization. Therefore, this study conducts a detailed analysis of properties at different ages and heights of *Oldeania alpina* and *Oxytenanthera abyssinica*.

2. Description of Bamboo Species

2.1. *Oldeania alpina*

Oldeania alpina, also known as 'highland bamboo', is a species of significant conservation value in Afromontane ecosystems across Africa. It is limited to elevations of 2000-4000m and is mainly distributed in Burundi, Cameroon (Mt. Cameroon), and mountains of Democratic Republic of Congo (Kivu), Ethiopia, Kenya, Malawi, Rwanda, Sudan and Tanzania (UTPD, 2018; Yebeyen et al., 2022). In Ethiopia, the highland bamboo grows naturally and in smallholder plantations, covering a large area from the Bale Mountains, Bonga, and Metu in the south to the north-western part of the country, up to Dangla in the north (Kidane et al., 2023). The culm diameter of the rapidly growing highland bamboo ranges from 5 to 12.5 cm, with a bamboo height of 2 to 20 m and internode length of 12 to 65 cm (Stapleton, 2013). This

ecologically and economically important indigenous species is used in seven main categories: fuelwood (22.5%), construction (22%), handicrafts (17%), agriculture (14.5%), pharmacopoeia (14%), worship (8%), and food (2%) (Ndavaro et al., 2023).

2.2 *Oxytenanthera abyssinica*

Oxytenanthera abyssinica, also known as 'lowland bamboo', is a plant native to Ethiopia and tropical Africa that holds significant socio-economic and ecological importance (Kristina and Juan, 2013). It is a tufted, sympodial bamboo with semi-solid and solid culms that have a maximum diameter of 10 cm (ranging from 5-10 cm) and a maximum height of 13 m (ranging from 3-13 m) (Mulatu et al., 2016). *Oxytenanthera abyssinica* is a species that thrives in lowland areas with poor soils, even rocky ones, and can tolerate high temperatures (averaging 20-35°C) and low rainfall (down to about 600mm). In Ethiopia, it covers approximately 85% of the country's total bamboo area, which amounts to around 850,000 hectares in the central, southwest, and southern regions (Oumer et al., 2020; Worku et al., 2022, 2023). This fast-growing and high-yielding resource is renewable (Anjulo et al., 2022).

PART-ONE: Age-wise Property Testing

3.1 Research Methods

3.1.1 Desk Review

Bamboo's basic characteristics are crucial for precise purposes, such as composite raw materials. Anatomical, physical, mechanical, and chemical properties all play a fundamental role. Structural changes due to ageing can affect the properties and utilization of bamboo (Liese and Weiner, 1996). The mechanical properties of bamboo generally increase as the plant ages, reaching a peak at 3-6 years before decreasing (Low and Che, 2006). Moso bamboo's flexural and parallel-to-grain compressive strengths were positively correlated with its age, and its mechanical strength increased as it aged (Han G. et al., 2021).

3.1.2 Sample Collection Tools and Protocol Development

In China, bamboo is mostly collected by hand, with the help of auxiliary tools such as hand saws and chain saws (Figure 1), despite the fact that it grows abundantly on hillsides. Recently, there have been studies on using UAV technology to harvest bamboo.

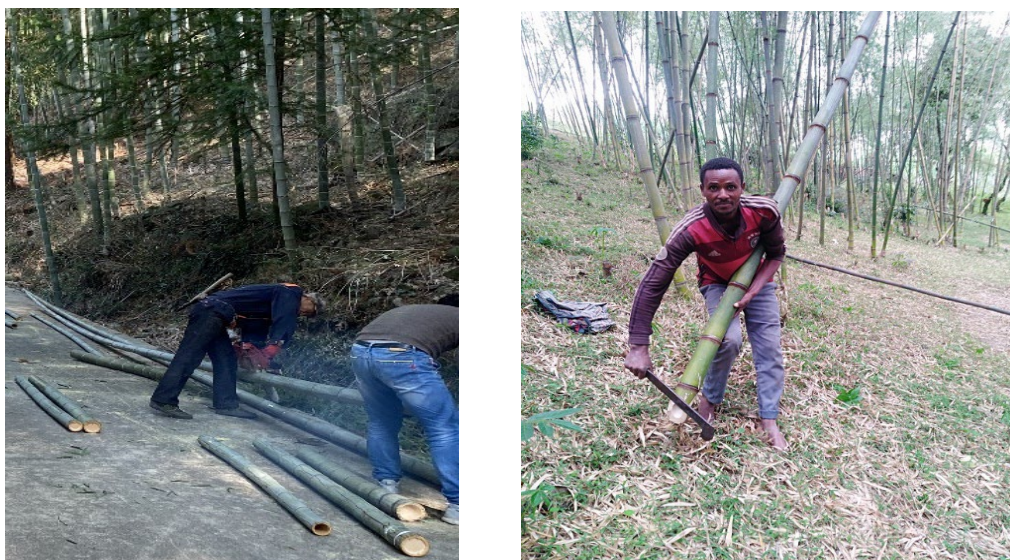


Figure 1: Cut the bamboo with a Chainsaw in China (L) and Special knife locally made for bamboo harvesting at Sidama Region, Ethiopia (R).

The bamboo samples were collected and prepared following the Chinese national standard GB/T 15780-1995, which outlines testing methods for physical and mechanical properties of bamboos.

Details of the sample collection and preparation protocol are presented below (also refer annex 1 and 2):

- To ensure representativeness, samples were collected from each species at ages 2, 3, and 4.
- Measure and record the diameter at breast height (1.5 meters) of each selected bamboo culm. Culms must be at least 50 mm in diameter (40 mm for lowland bamboo).
- Cut each selected culm at 1.5 meters from the ground, then cut two 2-meter sections upward from the cut end to use as test material, as shown in Figure 2. Mark the north-facing side of the culms before felling.

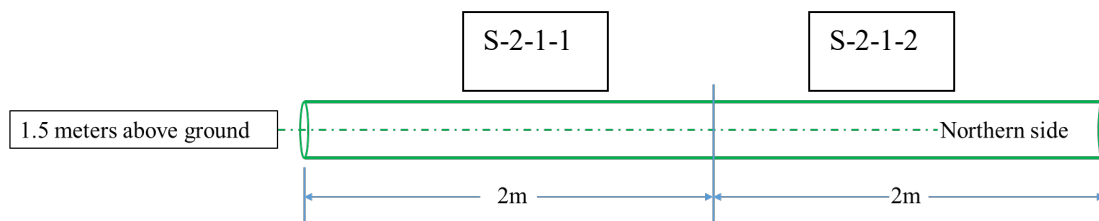


Figure 2: Scheme of bamboo samples selected, cut, and marked.

For each species, cut 20 bamboo culms per age for sample preparation. Try to maintain consistent diameter levels.

- Ensure all collected samples are healthy and free from defects or deformities. Number each sample as 'code-age-sample number-section number', for example, 'S-2-1-1' represents section 1 of the first two-year-old *Oxytenanthera abyssinica* bamboo.
- The section adjacent to the 1.5-meter mark is numbered as S-2-1-1, and then sequentially numbered as S-2-1-2. Another bamboo is numbered as S-2-2-1 and S-2-2-2, and so on, as shown in Figure 1. Table 1 presents the section number (S. No.), code, and a summary of the bamboo species, location of the sample, age, and the number that to be collected.

Table 1: The code and the summary of bamboo species, location of sample, age, number that need to be collected

| Code | Bamboo Species | Location of Sample collection | Age | Number of samples | Total samples |
|------|--|-------------------------------|------------|---------------------|---------------|
| S | <i>Oxytenanthera abyssinica</i> | Ethiopia | 2a, 3a, 4a | 20 samples each age | 60 |
| A | <i>Oldeania alpina</i> (Syn <i>Yushania alpina</i> / <i>Arundinaria alpina</i>) | Ethiopia | 2a, 3a, 4a | 20 samples each age | 60 |

- Store them in a dry area.
- After cutting, split the bamboo culm samples in half and oven dry them at approximately 60°C until they reach a moisture content of 7-12%.

3.1.3 Sample Testing Process and Techniques

Samples were collected from two bamboo species, *Oxytenanthera abyssinica* and *Oldeania alpina*, in Ethiopia. The number of samples collected from EY and ES were 77 and 57, respectively. Please refer to Table 2 for further details on the number of samples sent for testing.

Table 2: The information of bamboo species received for age-wise property testing.

| Code | Bamboo species | Age | Number of Segments | No of Samples | Sample ID |
|------|---|-----|--------------------|---------------|-----------|
| EY | <i>Oldeania alpina</i> (Syn. <i>Yushania alpina</i> / <i>Arundinaria alpina</i>) | 2a | 1 (bottom) | 10 | EY CII-1 |
| | | | 2 (middle) | 11 | EY CII-2 |
| | | 3a | 1 (bottom) | 21 | EY CIII-1 |
| | | | 2 (middle) | 26 | EY CIII-2 |
| | | | 3 (top) | 9 | EY CIII-3 |
| ES | <i>Oxytenanthera abyssinica</i> | 1a | 2 (middle) | 22 | ES-1 |
| | | 2a | 2 (middle) | 25 | ES-2 |
| | | 3a | 1 (bottom) | 10 | ES-3 |

The physical and mechanical testing samples were prepared in accordance with the Chinese National Standard GB/T 15780-1995: Testing methods for physical and mechanical properties of bamboo.

3.1.3.1 Physical testing method

The bamboo samples were cut to the required size before drying. Air-drying involved storing the specimens for one month in a controlled environment at $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and $65\% \pm 5\%$ humidity. Oven-drying involved placing the specimens in an oven at $103^{\circ}\text{C} \pm 2^{\circ}\text{C}$ for eight hours, and then weighing them every two hours until a constant weight was achieved.

Density: For each species, we prepared air-dry and oven-dry bamboo samples measuring 10mm in length, 10mm in width, and the same thickness as the culm wall. We determined the thickness of each sample based on the culm wall thickness. We weighed each specimen and measured its radial, tangential, and longitudinal dimensions before and after oven-drying, ensuring adherence to strict metrics and units. The density of the material was calculated using two different methods: air-dry density and oven-dry density. The air-dry density (g/cm^3) was calculated using formula (1) and the oven-dry density was calculated using formula (2).

The variables used in the formulas are: w for moisture content, m for quantity (g), and V for volume (cm³). It is important to note that the values for w , m , and V differ between the air-dry and oven-dry methods.

$$\rho_w = \frac{m_w}{V_w} \quad (1)$$

$$\rho_0 = \frac{m_0}{V_0} \quad (2)$$

Shrinkage: including line shrinkage and volume shrinkage on air-dry and oven-dry. The sample was made of wet material with saturated moisture and the size was 10mm (length)× 10mm (width)× t (the culm wall thickness). In the center of any diameter direction of the sample, draw a straight line perpendicular to the bamboo green and bamboo yellow surfaces, and then draw a dot near the two ends of the straight line. After that draw a dot in the center of the bamboo yellow surface. The radial and tangential dimensions were respectively measured at the dot points on the sample with a dial indicator measuring device. The specimens were dried for 10 days in a controlled environment at 20°C ± 2°C and 65% ± 5% humidity. 2-3 samples were used to test the tangential size, and then measured every 2 days, until the difference between the two consecutive test results was not greater than 0.02mm, that is, air drying was considered to have been achieved. Then repeat the above measurement process. Next placing the specimens in an oven at 103°C ± 2°C, and then weighing them every two hours until a constant weight was achieved. Repeating the above measurement process once a more and weighting the oven-dry mass. The oven-dry shrinkage and the air-dry shrinkage of radial or tangential were calculated using formula (3). The variables used in the formulas were: B for oven-dry or air-dry shrinkage of radial or tangential (%), L_{\max} for the mean size of the wet material sample in radial or tangential direction against the bamboo green and bamboo yellow (mm), and L , for the mean size of the oven-dry or air-dry material sample in radial or tangential direction against the bamboo green and bamboo yellow (mm).

$$B = \frac{L_{\max} - L}{L_{\max}} \times 100 \quad (3)$$

According to the size measured in the above process, the sample volume of saturated moisture, air-dry, oven-dry were calculated. The oven-dry shrinkage or air-dry shrinkage of

volume was calculated using formula (4). The variables used in the formulas were: β_v for oven-dry or air-dry shrinkage of radial or tangential (%), V_{\max} for volume of saturated moisture (mm³), and V for volume of the oven-dry or air-dry (mm³).

$$\beta_v = \frac{V_{\max} - V}{V_{\max}} \times 100 \quad (4)$$

3.1.3.2 Chemical testing method

The chemical composition of the samples was prepared following the Chinese National Standard for fibrous raw material (GB/T 2677). Each bamboo species was ground to 40-60 mesh and analyzed in duplicate.

To determine holocellulose content, 2g of the sample (accurate to 0.0001g) was wrapped in qualitative filter paper, tied with a wire, and placed into a Soxhlet extractor with a benzol mixture. To determine holocellulose content, 2g of the sample (accurate to 0.0001g) was wrapped in qualitative filter paper, tied with a wire, and placed into a Soxhlet extractor with a benzol mixture. To determine holocellulose content, 2g of the sample (accurate to 0.0001g) was wrapped in qualitative filter paper, tied with a wire, and placed into a Soxhlet extractor with a benzol mixture. The extractor was then placed in a boiling water bath for 6 hours of extraction.

The sample was air-dry before being carefully brushed into a 250 mL conical bottle. Then, 65 mL of distilled water, 0.5 mL of glacial acetic acid, and 0.75 g of sodium chlorite (80% purity) were added. A 25 mL conical bottle was inverted at the mouth of the conical bottle, and the mixture was heated in a 75 °C water bath for 1 hour. The conical flask was rotated and shaken frequently during the heating process. After one hour, add 0.5 mL of glacial acetic acid and 0.75g of sodium chlorite. Shake well and heat in a 75°C water bath for another hour. Repeat this process twice until the sample turns white.

Finally, remove the conical bottle from the water bath and allow it to cool. Filter the solution using a G2 filter with a constant weight. Wash the filter with distilled water until it is no longer acidic. Then, wash the filter with acetone three times. Drain the lotion and remove the filter. Wash the outside of the filter with distilled water. Move the filter to an oven and dry it at 105±3°C until it reaches a constant weight. Burn the obtained holocellulose in a high-temperature electric furnace until it reaches a constant weight. Record the ash content of the holocellulose. The holocellulose content was calculated using the following formula (3): $m_1 - m_2 - m_0$, where

m_1 is the mass of the dried holocellulose (g), m_2 is the mass of ash in the holocellulose (g), and m_0 is the initial dried mass (g).

$$\text{Holocellulose} = \frac{m_1 - m_2}{m_0} \times 100 \quad (5)$$

Ash: The sample was weighed accurately at 2-3g (with an accuracy of 0.0001g) and placed in a pre-burned magnetic crucible. It was then carefully burned on an electric furnace to carbonize it, and finally put in a Mafuo furnace at $575^\circ\text{C} \pm 25^\circ\text{C}$ until all black carbon was removed from the ash. After cooling the crucible in the air for 5-10 minutes, it was placed in a dryer, cooled for half an hour, and weighed again. Place the crucible into the high-temperature furnace and repeat the above steps until a constant weight is achieved. Calculate the ash using the following formula (6): m_1 is the mass of the crucible after burning (in grams), m_2 is the mass of the burned crucible containing ash (in grams), and m is the dried mass.

$$\text{Ash} = \frac{m_2 - m_1}{m} \times 100 \quad (6)$$

Benzene Alcohol Extract: The Benzene Alcohol Extract contains the crushed sample, which was weighed accurately at 3 ± 0.2 g (accurate to 0.0001g). It was then wrapped with qualitative filter paper and tied with wire before being placed into a Soxhlet extractor. A benzol mixture was added and the extractor was put into a water bath for extraction. The heater was adjusted to ensure the boiling rate of the organic solvent in the Soxhlet extractor was no less than 4 times per hour. The extraction process lasted for 6 hours. After extracting the contents, transfer them to a weighing bottle with a constant weight. Rinse the bottom of the bottle with a benzol mixture 3-4 times before pouring in the lotion. Place the weighing bottle in a water bath to heat and evaporate any excess solution. Finally, wipe the outside of the weighing bottle and dry it in an oven at $105 \pm 3^\circ\text{C}$ until the weight is constant. The formula (7) was used to calculate the content of benzene alcohol extract. This formula uses the mass of the dried benzenol extract (m_1), the mass of the air-dry samples (m_2), the mass of the empty bottle (m_0), and the moisture content of the sample (w).

$$\text{CBAE} = \frac{(m_1 - m_0)100}{m_2(100 - w)} \times 100 \quad (7)$$

Hot Water Extract: To extract the sample, accurately weigh 1.9-2.1g (to 0.0001g) and transfer it to a 300mL conical flask. Add 200mL of distilled water heated to $95-100^\circ\text{C}$ and fill the flask with a reflux or air condenser. Boil the sample in a water bath for 3 hours, shaking it regularly.

Decant the mixture through a 1G2 glass filter, washing the residue and conical bottle with hot distilled water and transferring all residue to the filter. Continue washing until the liquid is colourless, then wash the filtrate 2-3 more times. Dry the filtrate and wash the outside of the filter with distilled water before placing it in an oven at $105\pm 3^{\circ}\text{C}$ to dry. The formula (8) was used to calculate the content of hot water extract. The formula uses the oven-dry mass before extract (m_1) and the oven-dry mass after extract (m_2) as variables.

$$CHWE = \frac{m_1 - m_2}{m_1} \times 100 \quad (8)$$

Klason Ligin: Accurately weigh a sample of 1g (accurate to 0.0001g) (while also weighing the sample to determine moisture). Wrap with qualitative filter paper, tie with thread, put into Soxhlet extractor, add benzol mixture, and put in water bath for 6h extraction. Take the sample out and air dry, unpack the filter paper package, brush it carefully with a clean brush into a 250mL conical bottle with a ground plug, add 15mL of 72% sulfuric acid, which is chilled to $12-15^{\circ}\text{C}$ in advance, plug the bottle tightly, and shake for 1min, so that the sample is completely impregnated with acid. Then the conical bottle is placed in a constant temperature water bath with a pre-adjusted temperature of $18 \sim 20^{\circ}\text{C}$, and kept at this temperature for 2.5 hours, shaking the contents of the bottle every 10min, after reaching the specified time, all the contents of the conical bottle are moved into the conical bottle with a capacity of 1000mL, rinsing the conical bottle with distilled water, and all the residue and lotion are poured into the conical bottle. Then dilute with water until the acid concentration is 3%, so that the total volume reaches 560mL. Heat and boil for 4 hours, and add water to maintain volume. Filter the acid insoluble lignin with the constant weight filter paper already in the weighing bottle, and wash with hot distilled water until the liquid is no longer cloudy with a few drops of 10% barium chloride, and check the edge of the filter paper with pH test paper. Then, the filter paper is transferred to the original constant reuse weighing device and placed in the oven at $105\pm 2^{\circ}\text{C}$ to dry to constant weight. Calculate the Klason ligin using the following formula (9): m_1 is the mass of acid-insoluble after drying, m_2 is the mass of ash (in grams), and m_0 is the dried mass.

$$Klasonligin = \frac{m_1 - m_2}{m_0} \times 100 \quad (9)$$

α -cellulose: Accurately weigh 2g of the prepared sample (weighing to 0.0001g) in a 100-150mL beaker (at the same time weigh the sample separately to determine moisture), and

add 30mL of 175g•L⁻¹ NaOH solution to impregnate the sample. Add the alkali according to the following procedure, first add 15mL, stir carefully with a flat-headed glass rod for 2-3min to make a uniform paste, and then add the remaining alkali, while stirring evenly and carefully for 1min, and avoid violent mixing. Then cover the beaker with a glass dish and place it in a constant temperature water bath at 20±0.5°C for mercerization. After 45min (including the time of alkaline immersion), add 30mL (20±0.5°C) of distilled water into the beaker, stir it carefully for 1-2min, and then transfer the slurry in the beaker into a glass filter with constant weight. Then vacuum pump slowly suction filter.

Under weak vacuum filtration, wash with 25mL 95g•L⁻¹ NaOH for 3 times (25mL each time), and maintain the washing time at 2-3min each time. When all filtrate filtered out, with 400mL 18-20°C distilled water fully washed, in the case of not using vacuum filtration, add 18-20°C 2mol•L⁻¹ acetic acid solution, continue to wash with distilled water until not acidic. After washing, rinse around the filter and place it in the oven at 105±3°C to dry to constant weight. Calculate the Klason lignin using the following formula (10): m₁ is the mass of cellulose after drying, m₂ is the mass of ash (in grams), and m₀ is the dried mass.

$$\alpha - cellulose = \frac{m_1 - m_2}{m_0} \times 100 \quad (10)$$

3.1.3.3 Mechanical testing method

Tensile strength parallel to grain: 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 (11), where P_{\max} was the failure load, b was the width of the effective part, and t was the thickness of the effective part.

$$\sigma = \frac{P_{\max}}{bt} \quad (11)$$

Compressive Strength: To test the compressive strength of each bamboo species, specimens were prepared from the internodal segment with dimensions of 20mm length, 20mm width, and wall thickness. The width and thickness of the compressed surface at the

center of the specimen's length were measured. The specimens were then placed in the central position of the test machine's spherical support and loaded at a speed of 1mm/min until destruction. The formula (12) was used to calculate the compressive strength along the grain at the given moisture content. The failure load, width (b), and thickness (t) of the specimen were taken into account.

$$\sigma_w = \frac{P_{\max}}{bt} \quad (12)$$

Bending Properties: To test the three-point bending modulus, prepare specimens from each bamboo species with dimensions of 160 mm in length, 10 mm in width, and wall thickness. Place the samples on the two supports of the universal testing machine and apply a center load in the tangential direction at a uniform speed of 8 mm/min with a span length of 120 mm. Record the failure load when the sample is destroyed within 1 ± 0.5 min. The formula (13) was used to calculate the bending strength of the sample. The bending strength is represented by, while represents the failure load, L represents the span length (120 mm), t represents the thickness, and h represents the width of the sample.

$$\sigma_b = \frac{3P_{\max}L}{2bh^2} \quad (13)$$

The formula (9) was used to calculate the elasticity modulus at a given moisture content (w). The difference between the 20% and 40% load (P) and the difference between the deformation values corresponding to 20% and 40% (f) were also taken into account.

$$E_w = \frac{PL^3}{4bh^3f} \quad (14)$$

Shear strength parallel to grain: 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 (15), where τ was the shear strength parallel to grain, P_{\max} was the failure load, t was the thickness and L was the shear length.

$$\tau = \frac{P_{\max}}{tL} \quad (15)$$

The mechanical properties samples were stored for one month at a controlled temperature of $20^\circ\text{C} \pm 2^\circ\text{C}$ and $65\% \pm 5\%$ humidity, as shown in Table 3.

Table 3: The sample quantity for mechanical properties.

| Sample ID | Tensile | Compressive | Bending | Shear |
|-----------|---------|-------------|---------|-------|
| EY CII-1 | 21 | 38 | 39 | 40 |
| EY CII-2 | 28 | 39 | 34 | 36 |
| EY CIII-1 | 44 | 39 | 35 | 30 |
| EY CIII-2 | 40 | 34 | 38 | 27 |
| EY CIII-3 | 26 | 31 | 30 | 32 |
| ES-1 | / | 69 | 71 | 82 |
| ES-2 | / | 76 | 71 | 97 |
| ES-3 | / | 19 | 23 | 41 |

3.1.3.4 Anatomical testing method

Tissue proportion: Cubic blocks measuring 1 × 1 × 1 cm were cut from each specie and sanded to create a smooth surface. The surface was then scanned using an HP Precision scanner at a 9600-dpi resolution. The tissue proportion of each specie was measured using a self-developed plant surface analyzer.

Fiber size: The fiber size of the bamboo samples was measured by cutting them into toothpick-sized pieces measuring 0.25 × 0.25 × 5 cm. The fibers were macerated in a soft solution consisting of one part 30% H₂O₂, four parts distilled water, and five parts glacial acetic acid for 4-6 hours at 60°C in an ultrasonic cleaning machine. Afterward, the fibers were separated further with a stir rod and washed thoroughly with distilled water until neutral. The distilled water was drained using a vacuum. Finally, a small amount of phenol was added as a preservative, and distilled water was used to immerse the fibers. The fibers were stored in a jar in a refrigerator for later determination of their length and strength. The diluted mixture was spread evenly on a transparent 20x20 cm glass sheet, covered with another piece of glass, and dried in an oven at 50°C for 24 hours to evaporate the water. The fibers were then observed and measured using a trinocular microscope (Leica DM LB2, Germany). 50 fibers were randomly selected and measured for each group.

3.2 Results and Discussion

3.2.1 *Oldeania alpina* (highland bamboo)

3.2.1.1 Chemical testing

Accurate chemical characterization of bamboo is crucial in determining its suitability for various applications. This analysis enables the evaluation of potential conversion yields and process economics (Sluiter et al., 2010). Bamboo's chemical characteristics, such as α -cellulose and hemicellulose, are closely associated with the pulp and paper industry (Sadiku et al., 2016).

Table 4 presents the effect of age and height position on the chemical composition results of highland bamboo. Generally, 1% NaOH extract, Content of Cold Water Extract (CCWE) and Content of Hot Water Extract (CHWE) increased with age, while Content Benzene Alcohol Extract (CBAE), ash, α -cellulose, klason lignin, pentosane and holocellulose decreased slightly with age. CCWE, CHWE and α -cellulose increased from bottom to middle, and then decreased from middle to top at the same age, while the ash and klason lignin changes were opposite. The CBAE and 1% NaOH extract decreased from bottom to top, while the holocellulose and pentosan increased from bottom to top at the same age.

Table 4: Chemical composition of highland bamboo in different ages and heights

| Test index | EY CII-1 | EY CII-2 | EY CIII-1 | EY CIII-2 | EY CIII-3 |
|-------------------------|-----------------------------|-----------------|-----------------|-----------------|-----------------|
| Moisture content (%) | 4.88 (0.53) ^a | 4.37 (0.07) | 4.76 (0.40) | 4.34 (0.07) | 3.98 (0.28) |
| CCWE (%) ^b | 10.02 (3.31) | 10.26 (1.84) | 10.58 (1.92) | 12.81 (3.21) | 9.49 (1.60) |
| CHWE (%) | 11.43 (3.35) | 11.91 (1.76) | 13.19 (2.03) | 13.92 (2.21) | 11.31 (1.89) |
| CBAE (%) | 3.11 (0.15) | 3.17 (0.15) | 3.29 (0.85) | 3.01 (0.47) | 2.20 (0.53) |
| 1% NaOH Extract (%) | 30.09 (5.17) | 31.57 (4.06) | 31.76 (3.99) | 31.61 (4.57) | 29.34 (3.65) |
| Ash (%) | 1.13 (0.44) | 1.23 (0.41) | 1.17 (0.18) | 0.96 (0.23) | 1.31 (0.47) |
| Holocellulose (%) | 70.42 (1.39) | 71.41 (1.07) | 69.34 (0.98) | 70.04(1.87) | 71.14 (0.96) |
| α -cellulose (%) | 48.06 (2.38) | 48.44 (2.22) | 45.73 (1.49) | 47.01 (1.68) | 48.36 (0.73) |

| | | | | | |
|-------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Klason lignin (%) | 20.16 (1.98) | 20.61 (1.80) | 19.49 (1.81) | 18.86 (2.02) | 19.34 (1.36) |
| Pentosan (%) | 16.48 (0.40) | 16.54 (0.10) | 14.57 (0.48) | 15.10 (0.19) | 16.42 (0.87) |
| α -cellulose (%) | 48.06 (2.38) | 48.44 (2.22) | 45.73 (1.49) | 47.01 (1.68) | 48.36 (0.73) |

Note: a, standard deviation, similarly hereinafter; b, CCWE, content of cold water extract, similarly hereinafter.

Bamboo is a promising source for bioethanol production due to its high holocellulose content (Tsegaye et al., 2020). Figure 2a shows the effect of age and height position on main chemical content, with an increase in holocellulose observed at higher height positions. The top portion of the bamboo had the highest holocellulose content, while the bottom portion had the lowest. The holocellulose content is enhanced by the presence of a higher vascular bundle at the top (Wang et al., 2011). However, the decrease in holocellulose content between 2-year-old and 3-year-old highland bamboo was minimal, which is inconsistent with the effect of age on *Phyllostachy pubescens* (Li et al., 2007) and *Melocanna baccifera* (Hossain et al., 2022). According to Bao et al. (2001), bamboo contains approximately 62-79% holocellulose, which is within the range found in wood species.

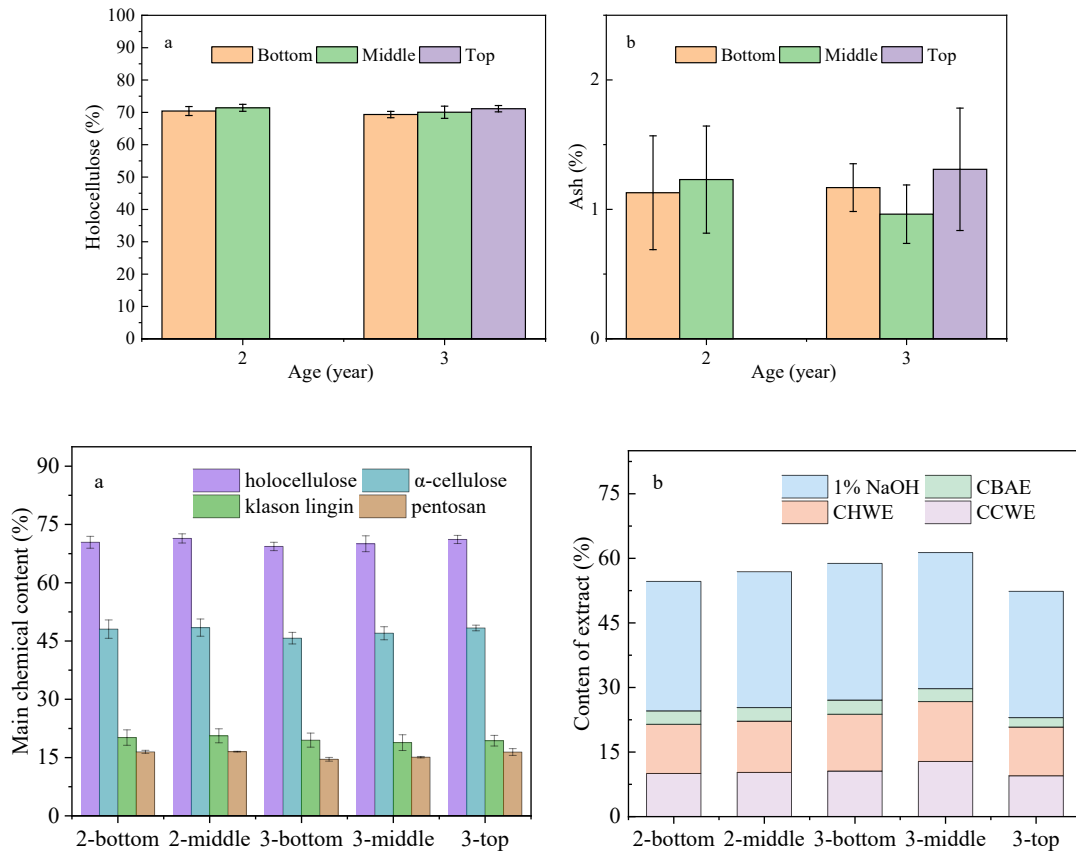


Figure 3: Main Chemical (a) and different extract (b) content at different ages and heights.

The ash content of bamboo is a key factor in its carbonization process. It refers to the inorganic residue that remains after being ignited at high temperatures. Figure 2b presents the impact of age and height position on ash content. The ash content of highland bamboo showed little decrease between the 2-year-old and 3-year-old plants, ranging from 0.96-1.31%. This is lower than the ash content reported by other researchers for the same species (Kapu and Trajano, 2014; Tsegaye et al., 2020), as well as lower than the ash content of Moso bamboo, which ranges from 4-5.3%. Typically, wood from temperate zones has an ash content of less than 1%, while that from tropical climates is slightly higher (Song et al., 2008). This bamboo can be used to prepare carbon or activated carbon for water adsorption and electrochemistry.

3.2.1.2 Mechanical testing

Bamboo exemplifies the concept of functionally graded materials, where properties are continuously graded based on spatially varying microstructure resulting from non-uniform distribution of different constituents (Silva et al., 2006). Understanding the mechanical properties of bamboo is crucial for processing and value-addition. As a natural biomaterial, its mechanical properties vary depending on species, age, place of origin, and even different parts.

The compressive strength is the most important parameter for bamboo as a load-bearing material, while bending and tensile strength reflect its elasticity and toughness (Gao et al., 2010). This study investigated the compressive and bending properties of highland bamboo at different ages and heights. Figure 3 shows images of the samples before and after testing.

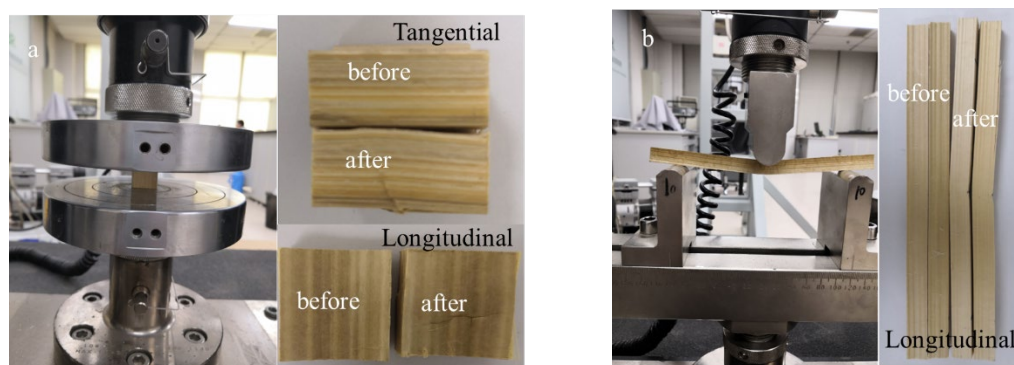


Figure 4: Samples in compressive (a) and bending (b) test.

Table 5 shows the mechanical properties of highland bamboo at different ages and heights. The compressive strength parallel to the grain ranged from 79.03 to 88.50 MPa, while the compressive modulus ranged from 26.72 to 33.41 GPa. The bending strength ranged from 159.36 to 265.06 MPa, and the bending modulus ranged from 14.69 to 35.14 GPa. The tensile strength parallel to grain ranged from 221.37 to 243.38 MPa, while the tensile modulus ranged from 18.11 to 20.22 GPa. The shear strength parallel to grain ranged from 6.15 to 8.48 MPa.

The highest values for compressive strength and modulus were found at the top part of the 3-year-old section, with values of 88.50 MPa and 33.41 GPa, respectively. The same section also exhibited the highest bending strength, tensile strength and bending modulus, measuring 265.06 MPa, 243.38 Mpa and 35.14 GPa respectively. Bamboo is primarily composed of vascular bundles and parenchyma, and the presence of vascular bundles affects the density and moisture content of the bamboo. The density of bamboo, which is influenced by the proportion of parenchyma and vascular bundles, impacts several mechanical properties, including compressive and bending strength (Correal and Arbeláez, 2010). Hang et al. (2018) found that the highest density of the bamboo stem is located at the top, which affects its compressive and bending properties at that point.

Table 5: Mechanical properties of highland bamboo in different ages and heights.

| Test index | | EY CII-1 | EY CII-2 | EY CIII-1 | EY CIII-2 | EY CIII-3 |
|-------------|-----------|----------|----------|-------------|-----------|-----------|
| Compressive | Max | 14.43 | 11.96 | 15.46(2.68) | 13.91 | 12.52 |
| | Load (KN) | (2.34) | (2.63) | | (1.86) | (2.34) |

| | | | | | | |
|------------------------------|----------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| properties parallel to grain | Strength (MPa) | 82.54 (5.48) | 79.03 (6.64) | 81.74 (10.66) | 86.07 (8.46) | 88.50 (7.93) |
| | Modulus (GPa) | 28.11 (4.20) | 28.71 (4.25) | 26.72 (3.57) | 31.49 (3.13) | 33.41 (4.25) |
| Bending properties | Max Load (N) | 819.75 (105.44) | 705.79 (93.33) | 791.38 (161.39) | 837.95 (174.52) | 640.97 (98.16) |
| | Strength (MPa) | 222.57 (14.05) | 224.40 (22.23) | 159.36 (24.22) | 216.22 (19.99) | 265.06 (38.45) |
| | Modulus (GPa) | 23.56 (3.62) | 25.78 (3.91) | 14.69 (3.46) | 22.26 (3.47) | 35.14 (6.66) |
| Tensile properties | Max Load (N) | 4405.20 (789.34) | 4394.17 (593.32) | 4826.16 (697.49) | 4843.76 (619.15) | 4579.37 (719.20) |
| | Strength (MPa) | 221.37 (26.29) | 241.03 (32.79) | 223.20 (35.90) | 237.93 (33.73) | 243.38 (24.67) |
| | Modulus (GPa) | 19.71 (2.79) | 19.20 (2.97) | 20.22 (3.10) | 18.11 (2.78) | 20.16 (3.06) |
| Shear properties | Max Load (N) | 1342.45 (212.14) | 1024.78 (152.83) | 1226.59 (185.86) | 1177.77 (165.10) | 950.60 (130.59) |
| | Strength (MPa) | 8.48 (1.22) | 6.74 (0.97) | 8.16 (1.16) | 7.57 (1.02) | 6.15 (0.87) |

Figure 4 show how the different mechanical strength and modulus vary with the length of the culm. Generally, the mechanical properties increase from bottom to top except the shear strength, which is consistent with previous studies (Tomak et al., 2012; Oka et al., 2014). This difference is attributed to the presence of large vascular bundles in bamboos. The sclerenchyma fibers are more closely packed at the top section of the bamboo, which is smaller than the bottom section (Lo et al., 2004). The compressive strength and modulus values were 9% and 25% higher, respectively, in the top portion compared to the bottom portion for 3-year-old highland bamboo. The bending strength and modulus increased by 67% and 140%, respectively, from bottom to top for 3-year-old highland bamboo. The compressive and bending properties of highland bamboo increase with age, but there are differences

between the changes in compressive and bending properties. The average compressive strength for 2 and 3-year-old highland bamboo was 80.79 MPa and 85.44 MPa, respectively. The compressive modulus values were 28.41 GPa and 30.54 GPa, respectively. The bending modulus and strength values of 2 and 3-year-old highland bamboo were found to be similar, with an average bending modulus of 24.67 GPa and 24.03 GPa, and bending strength values of 223.49 MPa and 213.55 MPa respectively. In contrast, the shear strength decreased from bottom to top, contradict the results of several further research (Deng et al, 2016), but consistent with the several Indonesia bamboo species (Hartono et al, 2022). Similar to the compressive and tensile strength, the shear strength in bamboo is likewise affected by the increasing proportion of vascular bundle from the bottom to the top of the bamboo stem.

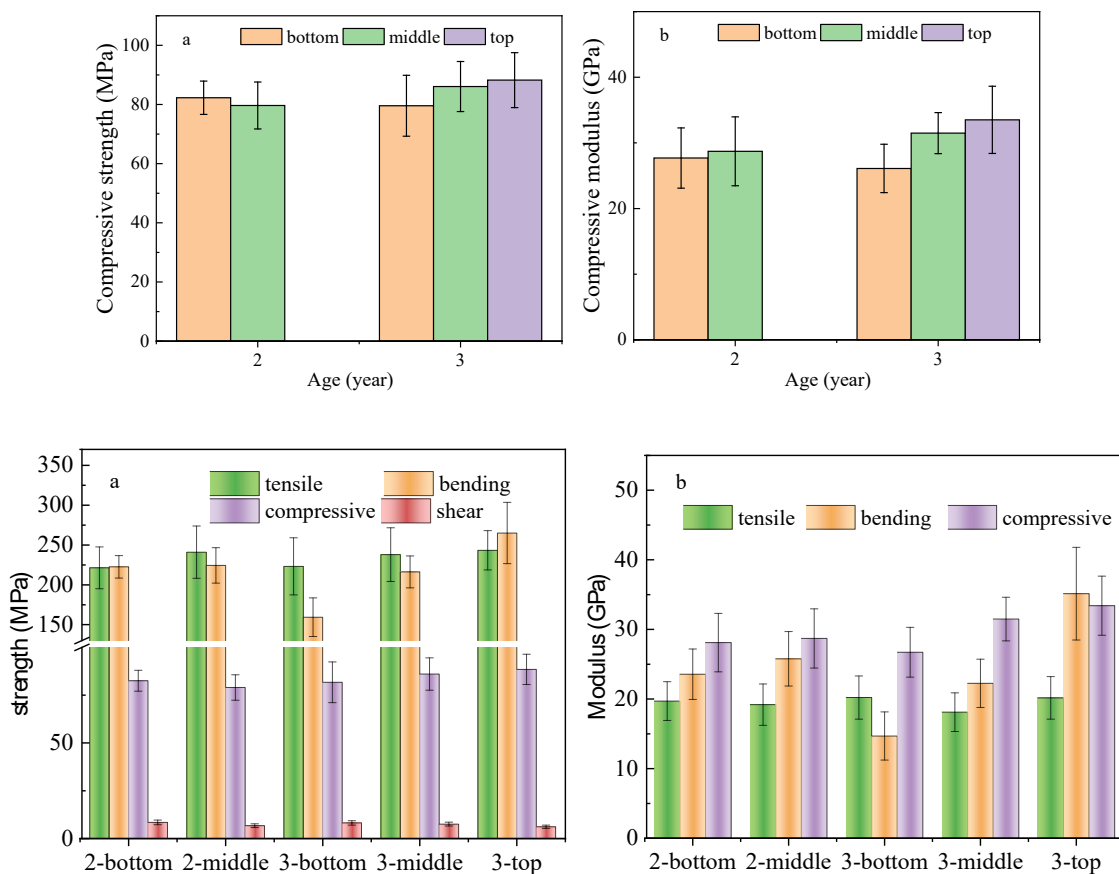


Figure 5: Mechanical strength (a) and modulus (b) of highland bamboo in different heights and ages.

3.2.1.3 Anatomical Testing

Bamboo identification can be facilitated by examining its anatomical features (Nordahlia et al., 2023). Additionally, the mechanical properties, preservative absorption, and properties of end products, particularly pulp and paper, are influenced by bamboo's anatomical properties (Razak et al., 2010; Wang et al., 2016). Anatomical properties can affect the durability,

toughness, workability, and strength of bamboo (Liese, 1985; Razak et al., 2010). This paper investigates variations in anatomical characteristics, such as tissue proportion, fiber length, fiber size, and fiber wall thickness at different ages and heights.

Figure 6 displays images of the samples used for tissue proportion measurement, and the results are presented in Table 6. The study found that tissue proportion varies with age and height. Fiber proportion ranged from 41.5% to 48%, basic parenchyma from 37.67% to 45%, vessel at 12%, and sieve tube at 1.5% to 2.34%. The highest fiber proportion was found in the top portion of 3-year-old highland bamboo, at 55%, which explains why this portion had the highest mechanical properties.

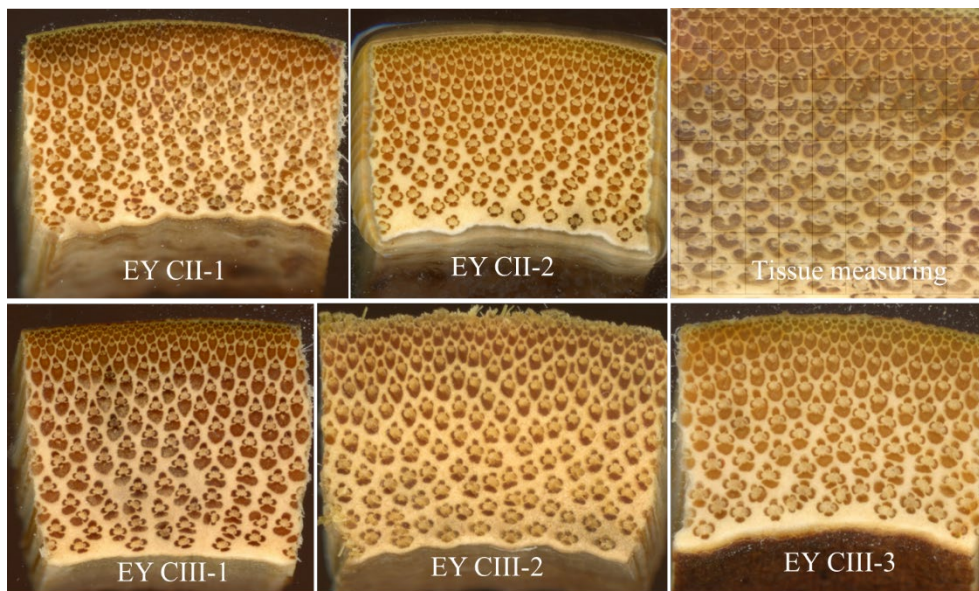


Figure 6: Tissue proportion measuring of highland bamboo.

Table 6: The tissue proportion of highland bamboo in different ages and heights.

| Tissue (%) | EY CII-1 | EY CII-2 | EY CIII-1 | EY CIII-2 | EY CIII-3 |
|------------------|----------|----------|-----------|-----------|-----------|
| Fiber | 46 | 37 | 48 | 41 | 55 |
| Basic parenchyma | 42 | 48 | 38 | 44 | 31 |
| Vessel | 10 | 14 | 12 | 13 | 11 |
| Sieve tube | 2 | 1 | 2 | 2 | 3 |

The sclerenchymatous tissue of bamboo consists of vascular bundle caps and isolated strands made of bamboo fibers with tapered ends. These fibers play a crucial role in supporting the weight of the bamboo. Figure 7 presents the morphologies of individual fibers from highland

bamboo of different ages and heights, while Table 7 summarizes their length, diameter, and wall thickness. Long fibers were isolated from highland bamboo successfully, with a length of 1.4-1.8 mm, which falls within the normal range reported for bamboos (1.5-3.2 mm) (Bassam, 1998). Fiber length decreased with age, from 1746.10 μm to 1564.61 μm . From the bottom to the top portion, fiber length first increased and then decreased. This may be attributed to the correlation between fiber length and internode length (Liese, 1998).

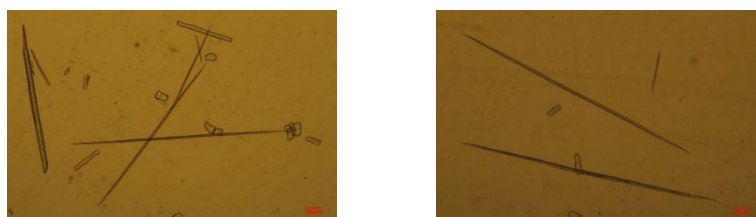


Figure 7: Individual bamboo fibers of highland bamboo.

Table 7: The fiber size of highland bamboo in different ages and heights.

| Index (μm) | EY CII-1 | EY CII-2 | EY CIII-1 | EY CIII-2 | EY CIII-3 |
|-------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Fiber length | 1824.35 (522.20) | 1667.85 (385.95) | 1455.34 (429.96) | 1681.42 (236.37) | 1557.06 (396.32) |
| Fiber diameter | 21.53 (5.72) | 19.16 (5.99) | 19.53 (7.67) | 19.15 (6.68) | 17.67 (6.55) |
| Fiber wall thickness | 10.02 (3.00) | 10.10 (2.83) | 10.57 (3.89) | 9.97 (3.40) | 8.88 (2.72) |

The thickness of the fiber cell wall decreased slightly in highland bamboo from 2 to 3 years old. The thickness of the fiber cell wall decreased from the bottom to the top portion. Variations in the fiber cell wall exist in different species, which may be due to the individual characteristics of bamboo (Liese, 1985). As the bamboo grows taller, the fiber elongation will cease, but the thickness of the fiber cell wall will continue to increase until maturation (Gan and Ding, 2006).

3.2.1.4 Physical Testing

The basic physical properties are very important to assess its suitability for various end products and usage. Basic density is considered to be important factor in determining the suitability of bamboo for various application and chemical treatment. Shrinkage is an important factor affecting dimensional stability.

The density of highland bamboo was presented in Figure 8. The air-dry density varied between 0.80-0.85 g/cm³, the oven-dry density varied between 0.78-0.82 g/cm³, and the basic density varied between 0.51-0.58 g/cm³. The highest air-dry density, oven dry density and basic density were found in the middle part of 3-year. Generally, the density at both ages increased as the height of bamboo increase.

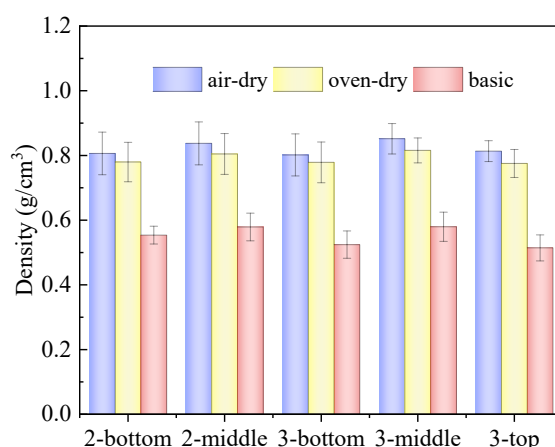


Figure 8: Density of highland bamboo.

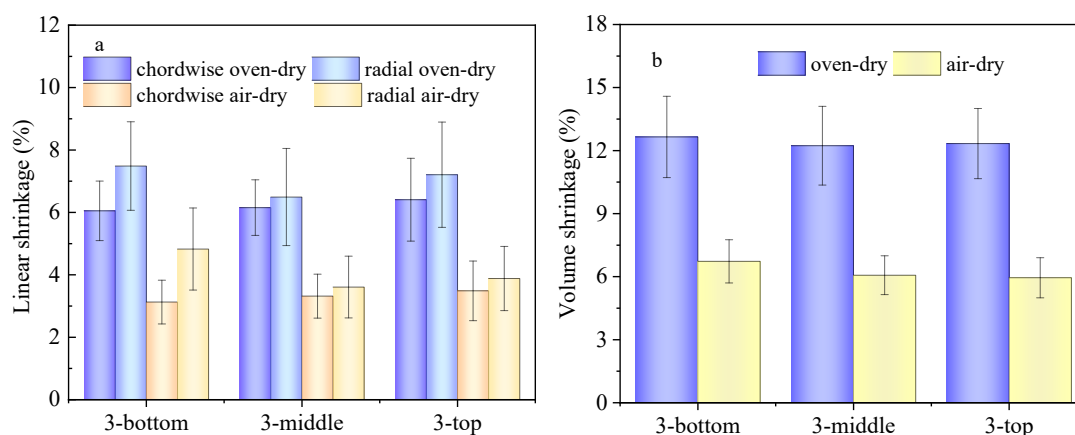


Figure 9: Linear and volume shrinkage of highland bamboo at different height.

The percentage of bamboo's dimensional stability is based on how much it shrinks radially and chordwise. The oven-dry shrinkage in chordwise varied between 5.68-6.41%, the oven-dry shrinkage in radial varied between 6.27-7.49%. While the air-dry shrinkage in chordwise varied between 2.88-3.49%, the air-dry shrinkage in radial varied between 3.60-4.83%. In general, the shrinkage in radial was higher than the chordwise. The oven-dry volume shrinkage was changed from 11.42% to 11.65%, and the air-dry volume shrinkage was changed from 5.95% to 6.73%. Figure 9 showed the linear and volume shrinkage of 3-year highland bamboo at different height. The oven-dry and air-dry shrinkage in chordwise increased with the height increase, while the air-dry volume shrinkage had the opposite regular,

which decreased with the height increase. The oven-dry and air-dry shrinkage in radial, oven-dry volume shrinkage decreased from bottom to middle, then increased from middle to the top.

3.2.2 *Oxytenanthera abyssinica* (Lowland Bamboo)

3.2.2.1 Chemical testing

Table 8 presents the effect of age on the chemical composition results of lowland bamboo. Generally, the CCWE, CHWE, and ash increased with age, while the CBAE decreased from 1-year-old to 2-year-old, then increased from 2-year-old to 3-year-old. Generally, the CCWE, CHWE, and ash increased with age, while the CBAE decreased from 1-year-old to 2-year-old, then increased from 2-year-old to 3-year-old. Generally, the CCWE, CHWE, and ash increased with age, while the CBAE decreased from 1-year-old to 2-year-old, then increased from 2-year-old to 3-year-old. The holocellulose content showed the opposite trend, increasing initially and then decreasing.

Table 8: Chemical composition of lowland bamboo in different ages.

| Test index | ES-1 | ES-2 | ES-3 |
|-------------------------|--------------|--------------|--------------|
| Moisture content (%) | 5.34 (0.94) | 5.13 (0.51) | 4.61 (0.29) |
| CCWE (%) | 8.17 (3.04) | 8.89 (2.23) | 11.44 (3.71) |
| CHWE (%) | 8.70 (2.45) | 9.29 (1.99) | 12.48 (3.45) |
| CBAE (%) | 2.88 (0.98) | 1.53 (0.21) | 2.55 (0.76) |
| 1% NaOH Extract (%) | 23.29 (4.70) | 24.52 (3.97) | 28.54 (6.35) |
| Ash (%) | 1.44 (0.93) | 0.77 (1.48) | 1.28 (1.41) |
| Holocellulose (%) | 75.16 (2.25) | 75.88 (1.79) | 72.35 (1.82) |
| α -cellulose (%) | 51.73 (2.96) | 54.19 (1.44) | 51.07 (2.80) |
| Klason lignin (%) | 18.06 (1.37) | 18.33 (1.26) | 19.18 (2.30) |
| Pentosan (%) | 16.41 (0.25) | 16.27 (0.89) | 15.71 (0.24) |

Figure 10 presents the effect of age on the mechanical content of lowland bamboo. The highest holocellulose content and α -cellulose were 75.88% and 54.19% for the 2-year-old lowland bamboo, while the highest ash content and pentosan were 1.44% and 16.41% for the 3-year-old lowland bamboo. These values were lower than those reported for *Oxytenanthera abyssinica* by Amsalu et al. (2017). The holocellulose contents and α -cellulose of lowland

bamboo were both higher than those of highland bamboo but the ash content was lower than that. *Dendrocalamus farinosus* and *Neosinocalamus Affinis* are the main pulp and paper raw materials in China, with holocellulose contents of 72.7% (Yao et al., 2016) and 72.93% (Liang et al., 2019), respectively. The holocellulose content of lowland bamboo was slightly higher than that of *D. farinosus*, indicating its potential use in pulp and paper production. A 2-year-old bamboo can be a potential source of raw material as it contains the highest amount of holocellulose, which is consistent with the *D. farinosus*. It is recommended to use 2-year-old bamboo for pulping with *D. farinosus* (Yang et al., 2015a). Meanwhile, the lowland bamboo has low ash content, which can be used as a raw material for carbon materials, and the optimal age for use was 3-year, as it had low ash content and highest klason lignin.

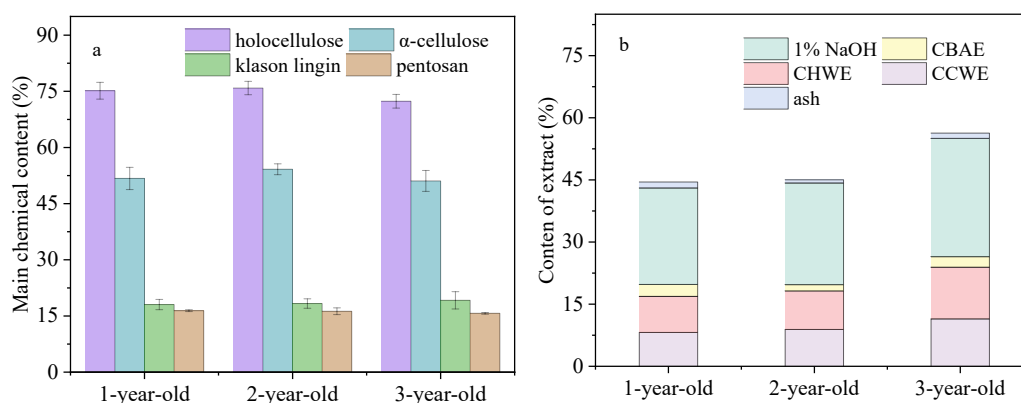


Figure 10: Chemical content of lowland bamboo at different ages

3.2.2.2 Mechanical Testing

Table 9 and Figure 11 present the effect of age on the mechanical properties of lowland bamboo. The compressive strength parallel to grain decreased from 122.32 MPa to 92.20 MPa as the bamboo aged from 1 to 3 years old. Similarly, the compressive modulus decreased from 34.33 GPa to 25.77 GPa. The highest compressive strength and modulus were observed in 1-year-old lowland bamboo.

Table 9: Mechanical properties of lowland bamboo in different ages.

| Test index | | ES-1 | ES-2 | ES-3 |
|--|----------------|----------------|----------------|--------------|
| Compressive properties parallel to grain | Max Load (KN) | 24.66 (4.59) | 21.45 (3.07) | 25.27 (3.30) |
| | Strength (MPa) | 122.32 (14.23) | 105.64 (13.26) | 92.20 (8.64) |

| | | | | |
|--------------------|----------------|------------------|------------------|------------------|
| | Modulus (GPa) | 34.33 (4.61) | 33.31 (4.48) | 25.77 (2.28) |
| Bending properties | Max Load (N) | 924.37 (178.07) | 995.36 (126.46) | 1226.11 (217.54) |
| | Strength (MPa) | 150.09 (16.12) | 163.65 (14.33) | 119.77 (11.09) |
| | Modulus (GPa) | 13.56 (2.10) | 14.20 (2.17) | 8.67 (1.23) |
| Shear properties | Max Load (N) | 1353.78 (188.31) | 1813.78 (279.41) | 1411.04 (197.89) |
| | Strength (MPa) | 8.67 (1.21) | 11.66 (1.69) | 9.12 (1.30) |

The bending strength and modulus of the 2-year-old lowland bamboo were the highest at 163.65 MPa and 14.33 GPa, respectively. These properties increased from 1-year-old to 2-year-old, but decreased from 2-year-old to 3-year-old. Also, the 2-year-old lowland bamboo had the highest shear strength (11.66 MPa), and the change rule was similar to the bending properties. These results are superior to those of *Dendrocalamus farinosus*, the main species used in pulp and paper production in China. Previous research on *D. farinosus* (Yang, 2014) has shown that its compressive strength parallel to grain is 61.40 MPa, with a compressive modulus of 17.52 GPa. Its bending strength and modulus are 183.99 MPa and 14.02 GPa respectively. It is worth noting that the mechanical properties of 2-year-old lowland bamboo are higher than or equal to those of *D. farinosus*, particularly in terms of bending modulus. Therefore, lowland bamboo could be a suitable alternative for pulp production, especially when it is 2 years old.

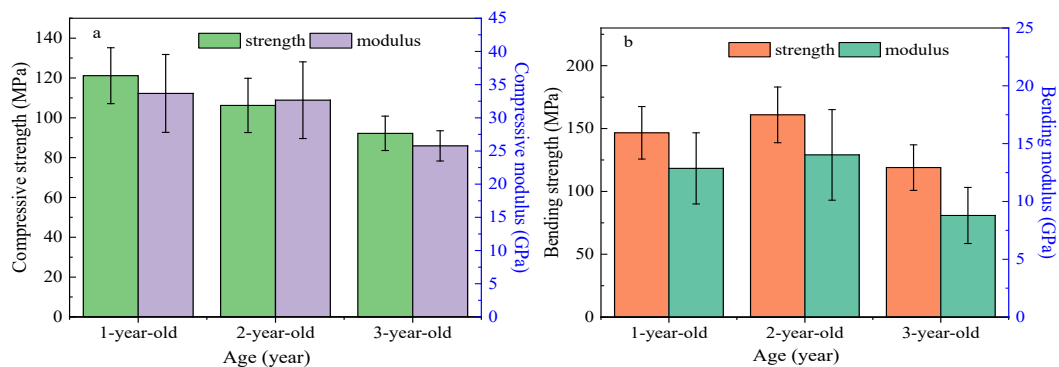


Figure 11: Compressive properties (a) and bending properties (b) in different age.

3.2.2.3 Anatomical Testing

The anatomical structure of bamboo is basic knowledge for understanding the physical and mechanical properties as well as the utilizations of the bamboo (Xing et al., 2015). Figure 12 displays images of tissue samples used to measure proportions, and the results are presented in Table 10. The results show that the fiber proportion was highest in 1-year-old lowland bamboo, at 68%, while the basic parenchyma proportion was lowest, at 17%. In bamboo, the fiber primarily serves a supportive function and can withstand greater force when compressed. This aligns with the findings on compressive properties. Additionally, the proportion of fiber decreases as the bamboo ages, with a decrease of up to 30%.

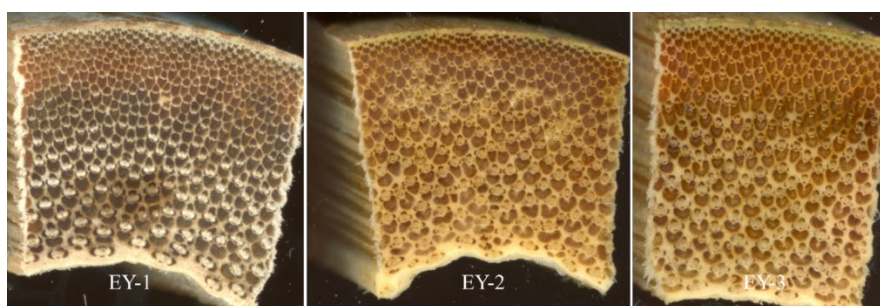


Figure 12: Tissue proportion measuring of lowland bamboo

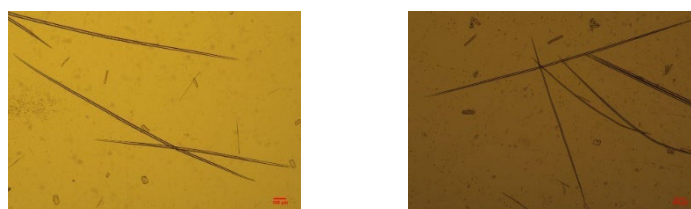


Figure 13: Individual bamboo fibers of lowland bamboo.

Figure 13 and Table 10 present the statistics for fiber morphology and size. The results indicate that fiber morphology varies with age, with fiber length increasing as age increases. The mean value for fiber length of lowland bamboo ranges from 1681.96 μm to 2221.86 μm . The average length of bamboo fiber is longer than *Bambusa pervariabilis* (Xiang et al., 2020), 1750 μm , *D. farinosus*, 870 μm (Yang et al., 2015b) and is equivalent to *Pinus* spp., 2300 μm to 3600 μm (Gulsoy and Ozturk, 2015). Therefore, lowland bamboo fibers are classified as long fibers according to the International Society for Wood Anatomy (Wheeler et al., 1989). Longer fiber length will contribute to the higher tearing resistance of paper (Sharma et al., 2011).

Table 10: Anatomical properties of lowland bamboo in different ages

| Index | | ES-1 | ES-2 | ES-3 |
|--|------------------|---------------------|---------------------|---------------------|
| Tissue Proportion (%) | Fiber | 68 | 62 | 48 |
| | Basic parenchyma | 17 | 26 | 38 |
| | Vessel | 14 | 9 | 11 |
| | Sieve tube | 1 | 3 | 3 |
| Fiber length (μm) | | 1848.31 (572.29) | 1681.96 (670.29) | 2221.86 (769.21) |
| Fiber diameter (μm) | | 18.83 (5.93) | 18.54 (5.90) | 16.60 (5.87) |
| Fiber wall thickness (μm) | | 9.73 (3.30) | 9.46 (2.30) | 8.74 (2.47) |

3.2.2.4 Physical Testing

Density is a unit of relatively constant value that may be used to assess bamboo uses. Figure 14 showed the density of lowland bamboo at different age. The air-dry density changed from 0.87 g/cm^3 to 0.95 g/cm^3 , the oven-dry density changed from 0.83 to 0.91 g/cm^3 , and the basic density changed from 0.57 g/cm^3 to 0.64 g/cm^3 . The three different densities all increased with age from 1-year-old to 2-year-old, then decreased from 2-year-old to 3-year-old. That is all of the maximum of three different densities were in 2-year-old. High-density bamboo must be cooked under more difficult nanocellulose separation conditions (Maulana et al, 2022).

The shrinkage of lowland bamboo at different age was shown to Table 11. The shrinkage decreased with the age increase, that is the 2-year-old bamboo had the higher dimensional stability.

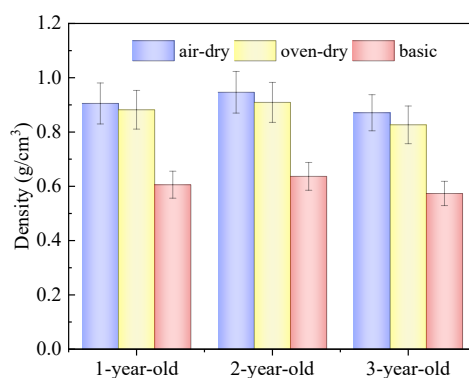


Figure 14: Density of lowland bamboo.

Table 11: Shrinkage of lowland bamboo in different ages

| Index | | ES-1 | ES-2 |
|------------------|--------------------|-----------------|--------------|
| Linear shrinkage | Chordwise oven-dry | 8.68 (1.33) | 8.48 (1.26) |
| | Radial oven-dry | 8.99 (2.09) | 8.48 (2.11) |
| | Chordwise air-dry | 5.83 (1.21) | 5.08 (1.23) |
| | Radial air-dry | 6.56 (1.83) | 5.73 (1.52) |
| Oven-dry volume | | 16.79 (2.69) | 15.62 (2.46) |
| Air-dry volume | | 11.14 (1.80) | 10.09 (1.65) |

3.3 Conclusions

The optimal age for using *Oxytenanthera abyssinica* (lowland bamboo) is two years old, as it has the highest holocellulose content, long fibers, and good mechanical properties. It can be used for pulp and paper production, and its performance is superior to that of *Dendrocalamus farinosus*. Otherwise, the 3-year-old lowland bamboo can be used to the raw material for carbon. It is important to note that all metrics and units must be strictly adhered to. Similarly, highland bamboo has many applications similar to those of the Chinese Moso bamboo species, such as bamboo flooring, furniture, and large laminated bamboo.

PART-TWO: Product Testing

4.0 Product Testing

4.1 Bamboo Laminated Board

The task is to produce laminated bamboo using Ethiopian highland bamboo and provide the physical and mechanical properties of the bamboo laminations. The production process of laminated bamboo is shown in Figure 15.

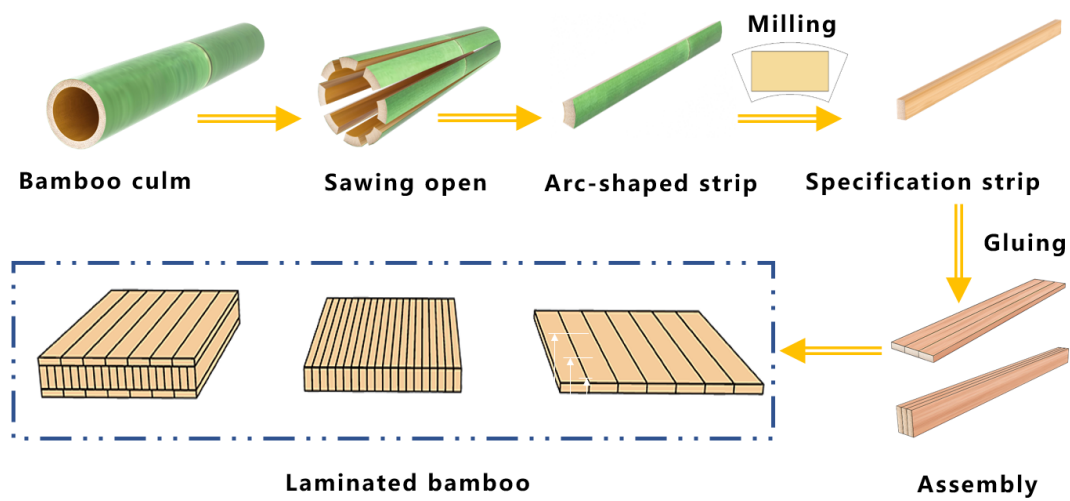


Figure 15: Production process of laminated bamboo

4.1.1 Manufacturing of bamboo strips

The bamboo culms were sliced into pieces and kiln-dried until the moisture content reached 9%-12%. This process resulted in obtaining bamboo strips (refer to Figure 16).



Figure 16: Bamboo culms (left) and Bamboo strips (right)

Figure 16 shows that the diameter of the Ethiopian highland bamboo is small, and the culms are not straight from top to bottom. Obtaining bamboo strips with needed specification during the sawing and milling process was difficult. If thicker bamboo strips were desired, most of them would have an inner layer (see Figure 17 left). Therefore, the thickness of the bamboo strips was limited to 4-5 mm. In Ethiopian highland bamboo, the thickness of the bamboo strips used for production is much lower than that of Moso bamboo. Additionally, many bamboo culms are damaged by worms, resulting in numerous bamboo strips with wormholes (Figure 17 right).



Figure 17: Bamboo strips with inner layers (left) and wormholes (right)

4.1.2 Manufacturing of bamboo lamination

The bamboo strips were sorted by colour, and those with wormholes and inner layers were not used in the production of laminated bamboo. Phenolic resin (PF) was used in the production process, with hot press process parameters set at a side pressure of 2.5MPa, main pressure of 1.5MPa, pressing time of 20 minutes, hot temperature of 140°C, and resin content of 180 g/m². The main production process for bamboo laminations is shown in Figure 18.



Figure 18: The main produce process for bamboo laminations

4.1.3 Physical and mechanical properties testing

4.1.3.1 Test standard

The physical and mechanical testing samples were prepared in accordance with the Chinese National Standard: Test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels (GB/T17657-2013). The test samples are illustrated in figures 19, 20, and 21.

4.1.3.2 Physical properties test preparation

Density: Measure and weigh each sample separately to determine its geometric dimensions. Then, calculate the density based on the weight and volume of each sample, using the appropriate metrics and units.

$$\rho = \frac{m}{l \times b \times t} \times 1000 \quad (1)$$

Among them:

ρ —density of the sample, g/cm³;

l —length of the sample, mm;

b —width of the sample, mm;

t —thickness of the sample, mm.

Moisture content (MC): Weigh the specimen immediately after sawing and dry it at (103±2) °C until the mass is constant. Cool the dried specimen in a desiccator to prevent moisture absorption. Weigh the specimen after it has cooled to room temperature. The mass difference between the two weighing, taken 6 hours apart, should be less than 0.1% of the sample mass, indicating a constant sample mass.

$$H = \frac{m_2 - m_1}{m_1} \times 100\% \quad (2)$$

Among them:

H—water absorption rate of test piece, %

m_1 —the mass of the specimen before drying, g,

m_2 —the mass of the specimen after drying, g.

Thickness swelling ratio: To measure the thickness of the center point of the sample, immerse it in a water tank with a pH value of 7 ± 1 and a temperature of $(20 \pm 1)^\circ\text{C}$, ensuring that the temperature remains constant throughout the test. The sample's surface should be perpendicular to the water surface, and the distance between the samples and the bottom and wall of the tank should be at least 15mm. The upper part of the sample should be submerged below the water surface by (25 ± 5) mm. Allow the sample to soak for 24 hours. After soaking, remove the sample, wipe off any water on the surface, and measure its thickness at the original measuring point. The measurement process must be completed within 10 minutes. Ensure that the immersion water is replaced for each test.

$$T = \frac{t_2 - t_1}{t_1} \times 100\% \quad (3)$$

Among them:

T—water absorption thickness expansion rate, %

t_1 —thickness of sample before immersion in water, mm,

t_2 —the thickness of the sample after immersion in water, mm.

Water absorption ratio: To determine the sample's density, measure its mass and immerse it in a water tank with a pH value of 7 ± 1 and a temperature of $(20 \pm 1)^\circ\text{C}$. Keep the temperature constant throughout the test and ensure that the sample surface is perpendicular to the water surface. Maintain a distance of at least 15mm between the samples and between the samples and the bottom and wall of the tank. The upper part of the sample should be (25 ± 5) mm below the water surface. After soaking the sample for 21 hours, remove it from the water and wipe the surface dry. Weigh the sample within 10 minutes.

$$W = \frac{m_2 - m_1}{m_1} \times 100\% \quad (4)$$

Among them:

W—sample water absorption, %

m_1 —sample mass before immersion in water, g,

m_2 - the mass of the sample after immersion in water, g.

Delamination: Immerse the sample completely in hot water at a temperature of $(63 \pm 3)^\circ\text{C}$ for 3 hours. Immerse the sample completely in hot water at a temperature of $(63 \pm 3)^\circ\text{C}$ for 3 hours. After 3 hours, remove the sample from the water and place it in a drying oven at the same temperature for another 3 hours. Immerse the sample completely in hot water at a temperature of $(63 \pm 3)^\circ\text{C}$ for 3 hours.

Formaldehyde emission: To collect formaldehyde, follow these steps: First, place a crystallization dish with a diameter of 240mm at the bottom of a desiccator. Then, add (300 ± 1) ml of distilled water and maintain the water temperature at $(20 \pm 1)^\circ\text{C}$. Next, position the crystallization dish in the center of the bottom of the desiccator and cover it with a wire support net. Insert the test piece into the sample holder and place it in the center of the support net in the desiccator directly above the sample dish. Maintain the temperature at $(20 \pm 0.5)^\circ\text{C}$ for 24 hours \pm 10 minutes to allow distilled water to absorb the formaldehyde released from the test piece. Conduct a blank test simultaneously. The second step is to measure the mass concentration of formaldehyde. Firstly, accurately draw 25ml of the formaldehyde solution into a 100ml Erlenmeyer flask with a stopper. Next, add 25ml of acetylacetone-ammonium acetate solution, stopper the bottle, and shake well. Then, place the bottle into a water tank at $(65 \pm 2)^\circ\text{C}$ and heat it for 10 minutes. Finally, store the solution in a dark place at 20°C for (60 ± 5) minutes. The solution's absorbance was measured at 412 nm using a spectrophotometer. Next, draw a standard curve based on the relationship between the mass concentration of formaldehyde solution and the absorbance. Determine the mass concentration using the iodometric method and check it at least once a month.



Figure 19: Sample preparation for physical properties testing

4.1.3.3 Mechanical properties test preparation

Compressive strength: Measure the width and length of the specimen. Place the sample on the support, apply a load, and completely destroy it within (60 ± 30) seconds. Record the maximum load at the point of destruction.

$$\tau_c = \frac{F_{max}}{b \times l} \quad (5)$$

Among them:

τ_c —the compressive strength of the sample along the grain, MPa;

F_{max} —failure load, N;

b —shear surface width, mm;

l —the length of the shear plane, mm.

Bending strength: To measure the sample, place it at the center of the testing machine bracket and load it at a speed of 15mm/min until it fails. Record the maximum load, as well as the width and thickness of the sample.

$$\sigma = \frac{3 \times F_{max} \times l}{2 \times b \times t^2} \quad (6)$$

Among them:

σ —Static bending strength of the sample, MPa

F_{max} —failure load, N

l —distance between two supports, mm;

b —width of the sample, mm;

t —thickness of the sample, mm.

Shear strength: Begin by measuring the length and width of the shear plane of the specimen. Next, pre-treat the specimens according to the following steps:

(1) Immerse in cold water for 24 hours at a temperature not lower than 17°C, with a recommended test temperature of (20±3) °C.

(2) Immerse in hot water at (63±3) °C for 3 hours, then allow to cool at room temperature for 10 minutes. (3) Perform a

boil-dry-boil treatment. Soak the specimen in boiling water for one hour, then dry it in a blast oven at (60±3) °C for 16 to 20 hours. After that, place it in cold water for at least one hour.

Next, boil it in water for 72 hours by soaking it in boiling water for (72±1) hours, and then place it in cold water at a temperature lower than 30°C for at least one hour.

Finally, clamp both ends of the treated specimen in a pair of movable fixtures of the testing machine. The test pieces should be aligned in a straight line, with their centers passing through the axis of the movable fixtures of the testing machine. The distance between the clamping part and the notch of the test piece should be no more than 5mm. During the final test, apply the load evenly until the specimen is destroyed within (30±10) seconds of loading, and record the maximum load value.

$$\tau = \frac{F_{max}}{b \times l} \quad (7)$$

Among them:

τ —shear strength of adhesive layer, MPa;

F_{max} —the maximum load when the sample is damaged, N;

b —shear surface width, mm;

l—the length of the shear plane, mm.

Tensile strength: To measure the thickness and width of the sample, place it between the two chucks of the tensile testing machine in a vertical position. Ensure that the center of the sample passes the axis of the movable fixture of the testing machine. Load the compound evenly and destroy the specimen within (60 ± 30) s from the beginning of loading. Record the maximum load.

$$\sigma = \frac{F_{max}}{b \times t} \quad (8)$$

Among them:

σ —tensile strength of sample, MPa

F_{max} —failure load, N

b—sample width, mm;

t—thickness of sample, mm.

Nail holding power: To test the holding force of the screw on the board surface, start by drilling a pilot hole at the center of the sample surface using a $\Phi (2.7\pm0.1)$ mm drill. The depth of the pilot hole should be 19mm. Use either GB845-ST4.2×38-CH or GB846-ST4.2×38-CH self-tapping screw with a length of 38mm and an outer diameter of 4.2mm. Screw in the screw until the screwing depth is (15 ± 0.5) mm. Screw in the screw until the screwing depth is (15 ± 0.5) mm. Screw in the screw until the screwing depth is (15 ± 0.5) mm. The screwed thread should be full thread, while the incomplete thread (y in the figure) should have a length of 3.7mm. Ensure that the guide holes and screws are perpendicular to the board surface. Measure the force of holding the screw on the side of the sample plate at the center point of the adjacent two sides of the sample. The guide hole and screw screwing depth should be the same as mentioned above. After tightening the screws, immediately perform the nail pull test. The special metal fixture and the sample should be in contact at a perpendicular angle to the tensile centerline of the testing machine. The screw should also be aligned with the tensile centerline of the machine. When removing the nails, apply an even load and reach the maximum load within (60 ± 30) seconds of loading. Record the maximum load value.

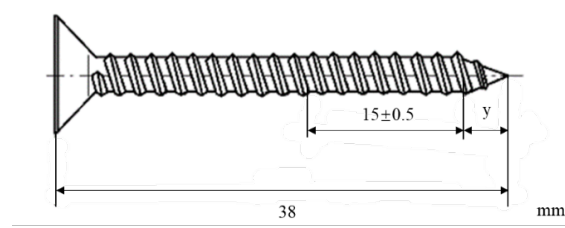


Figure 20: Tapping Screw



Figure 21: Sample preparation for mechanical properties testing

4.1.4 Test process and results

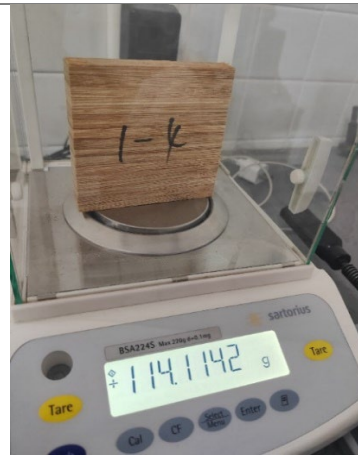
4.1.4.1 Physical properties

4.1.4.2 Test process

The main test process was shown in Figure 22.



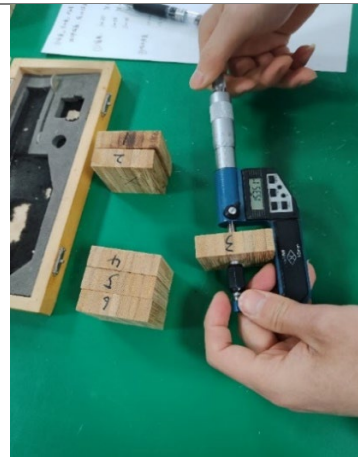
(a) Measure sample size



(b) Measure the weight of the sample



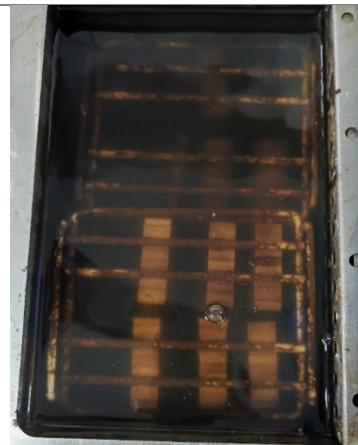
(c) The sample was dried at 103°C



(d) Measure the thickness



(e) The sample was fixed on the rack



(f) Soak the sample in the sink at
20°C



(g) Soak the sample in the sink at 63°C



(h) The sample was dried at 63°C



(i) Sample pre-treatment



(j) Put the sample into the holder



(k) Formaldehyde emission samples



(l) Formaldehyde emission testing

Figure 22: Samples (a-i) for measuring physical properties

4.1.4.3 Test results

The physical properties of bamboo laminations were shown in table 12.

Table 12: Physical properties of bamboo laminations

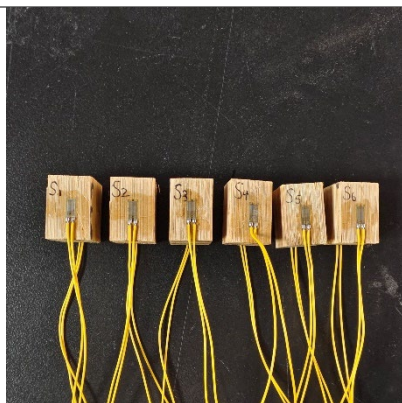
| Physical properties | Value (COV*) |
|--------------------------|--------------------------------|
| Density | 0.76 g/cm ³ (1.86%) |
| Moisture content | 9.1% (1.04%) |
| Thickness swelling ratio | 0.88% (21.22%) |
| Water absorption ratio | 22.9% (10.41%) |
| Delamination | Not found |
| Formaldehyde emission | 0.008 mg/m ³ |

*COV: coefficient of variation

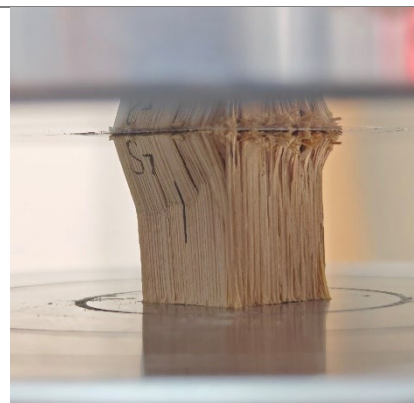
4.1.5 Mechanical properties

4.1.5.1 Test process

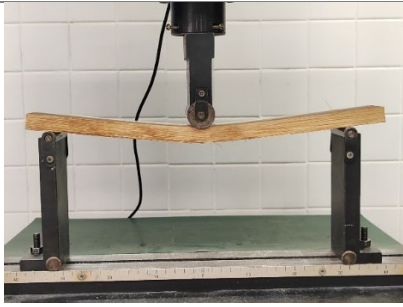
The main test process was shown in Figure 23.



(A-1) Compressive testing



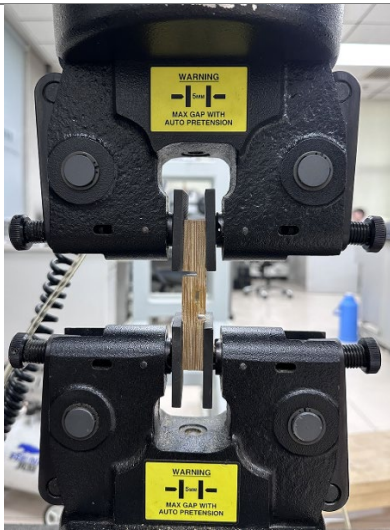
(A-2) Failure model



(B-1) Bending testing



(B-2) Failure mode



(C-1) Shear testing



(C-2) Failure model



(D-1) Tensile testing



(D-2) Failure mode



(E-1) Nail holding power testing



(E-2) Failure mode

Figure 23: Samples (A-E) for measuring mechanical properties

4.1.5.2 Test results

Table 13 presents the mechanical properties of bamboo laminations, while table 14 shows the results of the nail holding power test in different directions (refer to figure 11).

Table 13: Mechanical properties of bamboo laminations

| Mechanical properties | Strength (COV*) MPa | Modulus (COV) GPa |
|-----------------------|---------------------|-------------------|
| Compressive testing | 82.42 (10.61) | 15.25 (14.89%) |
| Shear testing | 4.62 (5.78) | --- |
| Bending testing | 122.85 (8.64%) | 15.20 (5.28%) |
| Tensile testing | 149.26 (28.11%) | 18.71 (10.61%) |

*COV: coefficient of variation

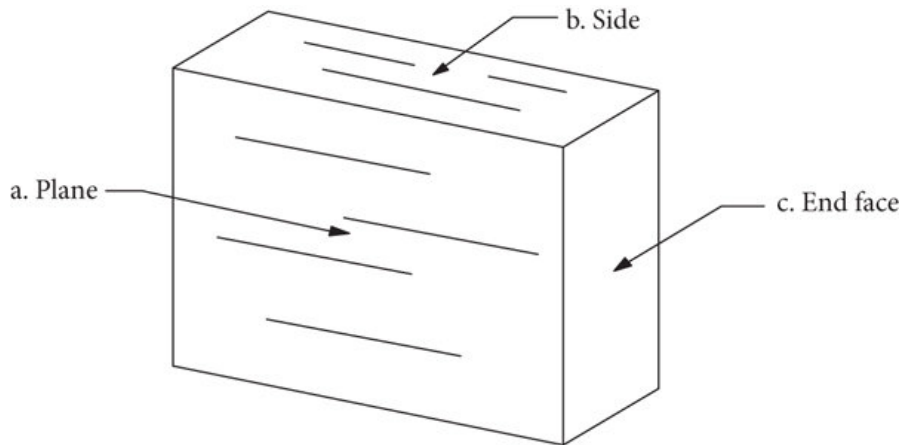


Figure 24: Diagram showing the nail-holding power test of specimens.

Table 14: Nail holding power of cross-laminated bamboo

| Type | Nail holding power (COV*) N |
|-----------|-----------------------------|
| The plane | 2403 (8.95%) |
| The side | 2049 (11.91%) |
| End face | 1059 (426.72%) |

*COV: coefficient of variation

4.1.6 Recommendations

(1) The test results indicate that bamboo laminations made from Ethiopian highland bamboo possess favorable physical and mechanical properties. These laminated bamboo products can be utilized in a variety of applications, similar to those of Moso bamboo, including bamboo flooring, furniture, and large-scale laminated bamboo (see figure 22).



Bamboo flooring



Bamboo furniture



Laminated Bamboo

Figure 25: Bamboo products based on bamboo strips

(2) The diameter of Ethiopian highland bamboo is smaller than that of Moso bamboo, and its culms are not straight from top to bottom. Obtaining bamboo strips of required specification during the sawing and milling process is difficult, with a much lower success rate compared to Moso bamboo. It should be noted that the number of Ethiopian highland bamboo culms is limited. It is unclear whether the culms were selected prior to delivery or if the Ethiopian highland bamboo culms naturally have these properties. Further information on the dimensions and properties of Ethiopian highland bamboo is necessary to determine its suitability for producing bamboo strips. Additionally, it is important to maintain high moisture content when making bamboo strips. In most factories, bamboo is cut and sawn immediately after harvesting.

Due to the limited number of bamboo culms available, there are few bamboo strips left to produce laminated bamboo. Only a few bamboo laminations pass physical and mechanical tests and are used for production, as shown in Figure 26.



(a) Bamboo laminated sheet



(b) Cross laminated Bamboo

Figure 26: Products made from Ethiopian highland bamboo strips

4.2 Bamboo Bundle Laminated Veneer Lumber (BLVL)

The extraction of refined bamboo fiber is carried out based on the material characteristics of bamboo species sampled from Ethiopia. BLVL was innovatively developed by whole-sheeting technology of the bamboo fiber bundle curtain formation to increase its uniformity and reduced density. Samples of outdoor flooring, tea trays, and other products were also prepared.

4.2.1 Process of BLVL Production

Bamboo fiber bundles derived from Ethiopian Highland bamboo were formed by the brooming machine. A whole-sheet bamboo bundle veneer with weaving specifications for curtain production has been fabricated. The preparation of Ethiopian highland bamboo BLVL has resulted in increased evenness and reduced density. Additionally, product samples of outdoor flooring and furniture have been made from Ethiopian highland bamboo BLVL in accordance with the task assignment.

Key accomplishments include improving the process of making bamboo fiber bundles from Ethiopian highland bamboo, creating bamboo fiber bundle curtains with weaving specifications for curtain production in roll form, and developing effective techniques for gluing, laying, hot pressing, and producing furniture and outdoor flooring products. The production and manufacturing process for Ethiopian highland bamboo BLVL and its products has been fully established (refer to Figure 27). Below are the research findings and issues encountered during the development and trial process.

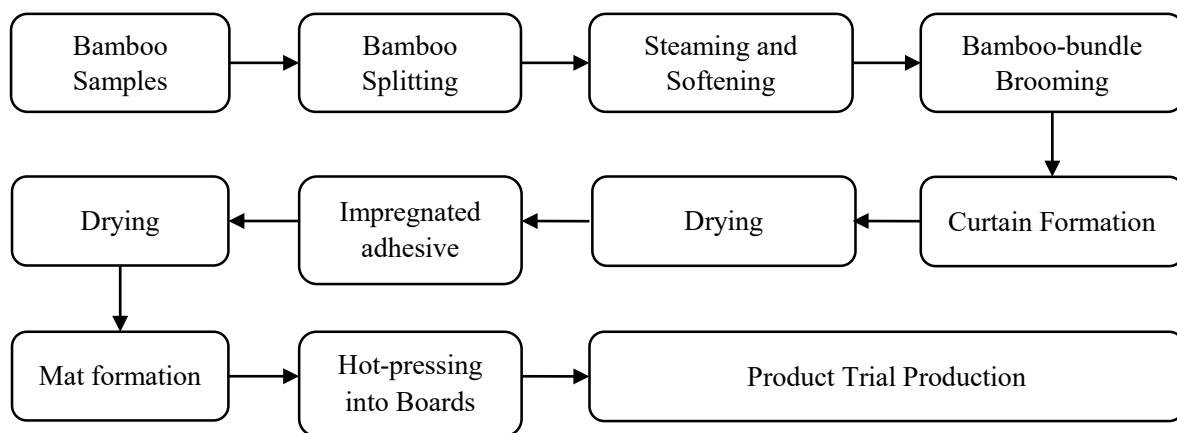


Figure 27: African bamboo BLVL production process and respective African bamboo products

4.2.1.1 Bamboo Splitting Process

The Ethiopian highland bamboo has a large diameter and is hollow (Figure 28). It can be crushed in the factory using a splitting machine (Figure 29) before further processing. On the other hand, the Ethiopian lowland bamboo is solid and has a small diameter, which makes it unsuitable for processing using a splitting machine. Specialized cutters must be developed for this purpose. Only the Ethiopian highland bamboo species were used in the trials of this study, as the Ethiopian lowland bamboo available for experimentation was of insufficient quality.



Figure 28: Highland bamboo (left) and lowland bamboo (right) harvested from Ethiopia



Figure 29: Processing of Ethiopian highland bamboo by splitting machine (left) and highland bamboo strips (right)

4.2.1.2 Steaming and Softening

Domestically sourced fresh Moso bamboo is used for processing bamboo bundle units. However, Ethiopian bamboo takes longer to transport to Chinese processing sites and became dry and brittle by the time it arrived, making it unsuitable for immediate processing. After undergoing carbonization, steaming, and softening procedures (as shown in Figure 30), brooming machine was used to prepare bamboo fiber bundles with relatively high binding rate.



Figure 30: Ethiopian bamboo strips produced by carbonization steaming and softening

4.2.1.3 Bamboo-bundle Brooming

During the brooming process to form fiber bundles, Ethiopian highland bamboo was found to be susceptible to blade sticking and strip jumping (refer to Figure 31). This may be due to the high sugar content of the bamboo, which overflowed during the bundling process and adhered to the blade. Strip jumping may occur due to the thicker walls, higher fiber strength, and toughness of Ethiopian highland bamboo compared to Moso bamboo. This results in a thicker peeled section when using the brooming machines designed for Moso bamboo. It is important to develop appropriate machinery for the specific type of bamboo being processed.



Figure 33: Brooming Ethiopian highland bamboo strips (left) and bamboo fiber bundle strips after brooming (right)

4.2.1.4 Full-sheet Curtain Formation of Bamboo Fiber-Bundles

The production of Ethiopian highland bamboo bundle curtains involved the use of a full-sheet transformation machine to standardize and process the bamboo fiber bundles into a bamboo fiber bundle curtain (see Figure 32). These bamboo fiber bundle curtains were then rolled and packed for easy transportation, storage, and uniform lamination of the sheets.



Figure 34: The full-sheet (left) and rolled (right) bamboo fiber bundle curtains made from Ethiopian highland bamboo

4.2.1.5 Hot-pressing into Boards

After gluing and drying, the bamboo fiber bundle curtains were evenly layered and placed on a pressing machine. It was then hot-pressed to create four 4'x8' BLVL boards with a target thickness of either 18 mm or 30 mm (Figure 33). The process resulted in evenly layered and sturdy BLVL boards. These boards were used to create outdoor reassembled bamboo flooring,



Figure 35: Laying and hot-pressing of African highland bamboo (left) and resulting board (right)

as well as prototypes of tables, chairs, and other products for further development.

4.2.1.6 Product Trial Production

The BLVL made from Ethiopian highland bamboo was used to create a variety of outdoor furniture, including two round tables, two folding tables, three folding chairs, and two tea stools, as well as multiple outdoor floorboards (see Figure 34) and other custom products. These products, including some custom pieces, were previously displayed at the International Centre for Bamboo and Rattan (ICBR). The report shows that the outdoor flooring made from

Ethiopian highland bamboo BLVL had high strength and elastic modulus ($E=13270$ MPa), as well as static bending strength ($X_{\text{mean}}=150.9$ MPa, $X_{\text{min}}=146.4$ MPa). All indicators meet the 'Excellent Product' standard of GB/T 30364-2013, the national standard for 'Bamboo Scrimber Flooring', except for the horizontal shear strength which was slightly below standard.



Figure 36: Sample tables and chairs (left), outdoor reassembled flooring (right) fabricated from layers of African highland bamboo bundle laminated composites.

4.2.2 Measures for improvement and Recommendations

Reasonable Material Selection

The highland bamboo with a large internal hollow diameter is preferred for manufacturing bamboo BLVL and related products, compared to solid lowland bamboo.

Pre-treatment Procedures

Prior to bamboo-bundle brooming, the highland bamboo needs to undergo steam-softening procedures. This is necessary due to its coarseness, high sugar content, and other undesirable characteristics, such as insect boreholes and drying during long-distance transportation, which could negatively impact subsequent processing. The material is also prone to blade sticking and strip jumping during the brooming process. To ensure the bamboo is in good condition, it should be pre-treated by removing any sugar and insect boreholes. Additionally, it should be effectively preserved during transportation to prevent drying and excessive fragility.

Improving Processing Equipment

Chinese Moso bamboo scrimber processing technology and equipment can be used to produce the BLVL and its products in the form of bamboo fiber bundles from Ethiopian highland bamboo. The resulting material can be utilized for manufacturing floorboards, furniture, and

other products. However, due to the significant differences in material properties between highland bamboo and Chinese Moso bamboo, processing equipment must be improved to accommodate highland bamboo by targeting its unique characteristics. For instance, brooming equipment for making the bamboo fiber bundles can be enhanced to reduce issues like blade sticking and strip jumping.

Optimizing Forming Processes

In comparison to Chinese Moso bamboo, the highland bamboo BLVL boards presented a coarser and more irregular fiber texture and lower surface flatness. However, it was stronger. The elastic modulus of the BLVL made from highland bamboo was 13270 MPa, with a static bending strength of $X_{\text{mean}}=150.9$ MPa and $X_{\text{min}}=146.4$ MPa. These qualities meet the national standard GB/T 30364-2013 for Bamboo Scrimber Flooring. The horizontal shear strength index was slightly below standard. Optimizing the hot-pressing parameters for the boards in later stages of production may improve it.

5. Conclusion

The study focus was assessing the age-wise property test, machine and product compatibility of the Ethiopian highland (*Oldeania alpina*) and lowland (*Oxytenanthera abyssinica*) bamboos. The study observed that the effect of age and height position on the chemical composition, mechanical, anatomical and physical properties varies in different section and ages. It was found that content of cold water extract (CCWE), and content of hot water extract (CHWE) increased with age, while content of Benzene Alcohol Extract (CBAE), ash content, and holocellulose decreased slightly with age. The highland bamboo is a promising source of bioethanol due to its high holocellulose content. Specifically, the top portion of 2-3-year-old highland bamboo can be used for bioethanol production. The ash content showed only a slight decrease from 2-year-old to 3-year-old, ranging from 0.96% to 1.31%. This makes it suitable for producing carbon/activated carbon for water adsorption and electrochemistry. The compressive and bending properties of highland bamboo increase with age, but there are differences between the changes in compressive and bending properties. For example, the average compressive strength for 2 and 3-year-old highland bamboo was 80.79 MPa and 85.44 MPa, respectively. The compressive modulus values were 28.41 GPa and 30.54 GPa, respectively. The bending modulus and strength values of 2 and 3-year-old highland bamboo were found to be similar, with an average bending modulus of 24.67 GPa and 24.03 GPa, and bending strength values of 223.49 MPa and 213.55 MPa respectively. Similar to the compressive and tensile strength, the shear strength in bamboo is likewise affected by the

increasing proportion of vascular bundle from the bottom to the top of the bamboo stem. The physical properties testing revealed that the oven-dry and air-dry shrinkage in chordwise direction increased with the height increase, while the air-dry volume shrinkage had the opposite regular, which decreased with the height increase. The oven-dry and air-dry shrinkage in radial direction decreased from bottom to middle, then increased from middle to the top.

Similarly, the chemical composition of lowland bamboo (*Oxytenanthera abyssinica*) changes was observed with age. It is worth noting that the holocellulose content of lowland bamboo is slightly higher than that of highland bamboo. This bamboo can be used for pulp and paper production. Lowland bamboo that is 2 years old contains the highest amount of holocellulose and is a potential source of raw material for the pulp and paper industry. This also related with the fiber proportion decreased as the age increased, with a decrease of up to 30%. The results show that lowland bamboo has long fibers, with a mean length ranging from 1681.96 μm to 2221.86 μm . These long fibers contribute to the higher tearing resistance of paper produced from lowland bamboo. Meanwhile, the lowland bamboo has low ash content, which can be used as a raw material for carbon materials, and the optimal age for use was 3-year, as it had low ash content and highest klason lignin.

The research also focused on two high-end engineered bamboo products through machine compatibility testing. The Ethiopian highland bamboo (*Oldeania alpina*) is hollow and has a large diameter, which allows it to be processed into strips using a crushing machine in the factory before further processing. However, the Ethiopian lowland bamboo (*Oxytenanthera abyssinica*) has a small diameter and is solid, making it unsuitable for processing using a crushing machine to produce the desired product. Specialized cutters could be developed for this purpose. In contrast, Ethiopian highland bamboo, which is internally hollow and has a larger diameter, is preferable for manufacturing the BLVL and associated products. The lowland bamboo (*Oxytenanthera abyssinica*) is suitable for pulp and paper production as well as bio-energy. Unlike to the lowland bamboo, the BLVL made from the highland bamboo qualities meet the national standard of Chinese standards of GB/T 30364-2013 for manufacturing the 'Bamboo Scrimber Flooring'.

Generally, the study recommends using 2-year-old Ethiopian lowland bamboo for its high holocellulose content, long fibers, and good mechanical properties. The species performs better than *Dendrocalamus farinosus* and can be used for pulp and paper production. Similarly, highland bamboo (*Oldeania alpina*) has many applications similar to the Chinese

Moso bamboo species, including bamboo flooring, furniture, and large laminated bamboo products.

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Annexes

Annex 1. Protocol for bamboo sample collecting: physical and mechanical properties testing

The collection of bamboo samples for testing physical and mechanical properties should follow the guidelines set by the Chinese national standard GB/T 15780-1995 and the industry standard JGT 199-2007 for building and construction. The collection of bamboo samples for testing physical and mechanical properties should follow the guidelines set by the Chinese national standard GB/T 15780-1995 and the industry standard JGT 199-2007 for building and construction. According to these standards, samples of each bamboo species should be collected as described below:

1. For each species, collect samples from the most representative bamboo in the production area. The samples should be from bamboo culms aged 2, 3, and 4 respectively.
2. Measure and record the diameter at breast height (1.5 meters) of each selected culm.
3. The culms should be at least 50 mm in diameter (for lowland bamboo, a minimum of 40 mm is acceptable). To prepare the test material, select bamboo culms/poles and cut them at 1.5 meters from the ground. Then, cut two sections of 2 meters each, starting from the top. Mark the north-facing side before felling.
4. For sample preparation, cut 20 bamboo culms per age for each species, preferably with consistent diameters.
5. Adhere strictly to metrics and units. Ensure that all collected samples are healthy and free from defects or deformities.
6. Number each sample as 'code-age-sample number-section number', for example, 'S-2-1-1' represents section 1 of the first two-year-old *Oxytenanthera abyssinica* bamboo. The section next to 1.5m should be numbered as S-2-1-1, and subsequent sections should be numbered sequentially as S-2-1-2, S-2-2-1, S-2-2-2, and so on, as shown in Figure 1. Table 1 presents the section number (S. No.), code, and summary of bamboo species, as well as the location of the sample, age, and number to be collected.

Table 1. The code and the summary of bamboo species, location of sample, age, number that need to be collected.

| Code | Bamboo Species | Location of Sample collection | Age | Number of samples | Total sample numbers |
|------|---|-------------------------------|------------|-------------------|----------------------|
| S | Oxytenanthera abyssinica | Ethiopia | 2a, 3a, 4a | 20 every age | 60 |
| A | Oldeania alpina (Syn. Yushania alpina / Arundinaria alpina) | Ethiopia | 2a, 3a, 4a | 20 every age | 60 |

7. After cutting, the bamboo culm samples should be split into half and then oven dried at about 60 °C to a MC of about 7-12% and stored in dry area.

8. Please take some photos during the bamboo choosing and cutting process.

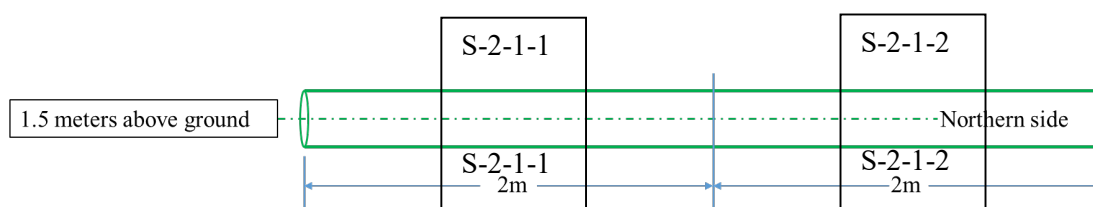


Figure 1. Scheme of bamboo samples selected, cut, and marked.

Annex 2. Protocol for bamboo sample collecting: *Trial production of laminated products*

The samples of three bamboo species should be collected as follows:

1. For each species, all bamboo samples should be collected in the most representative bamboo producing areas, the age of bamboo should be matured (~ 3 years of age). Since bamboo species are collected in different countries, it is recommended to mark the sample number with the initial letter of the name of each country. For example, the sample number marked “E” for bamboo species collected from Ethiopia. The bamboo species, sample

number, bamboo culm diameter, age, bamboo strip number and MC required are summarized in Table 1.

Table.1 the requirements of quantity and parameter for bamboo splits

| Bamboo species | Country/ Sample number | Bamboo culm diameter (mm) | Age | Bamboo split number | MC /% |
|------------------------|---------------------------|---------------------------|-----|---------------------|-------|
| Oldeania alpina | Ethiopia/E | 60 -100 | 3a | 1500 | 9-12 |
| <i>Oldeania alpina</i> | Ethiopia/ E | 60 – 100 | 3a | 1500 | 9-12 |

2. Bamboo must be straight, no obvious warping deformation, cracking and mildew.
3. Before bamboo harvesting, the diameter at **0.9 meter's height** should be measured, make sure the diameter at 0.9 meter's height of the chosen sample is larger than **2200 mm**.



Figure.1 the schematic diagram of bamboo culm

4. Bamboo splits should be made and air-dried. The gross dimension of each split is 2700 mm (length) × 23 mm (width) × 9 mm (thickness).



Figure.2 bamboo crashing

6. The samples will be sent to: National Engineering Research Center for Bamboo and Rattan (NERCBR), Taipinghu, Huangshan District, Huangshan 245716, Anhui Province, P.R. China. Tel: +86-13522518767

In Task 2, the bamboo samples will be collected for the manufacture of laminated bamboo products.

The laminated bamboo, as shown in figure 4, can be used as furniture, flooring, and decorative materials.



Figure.3 laminated bamboo

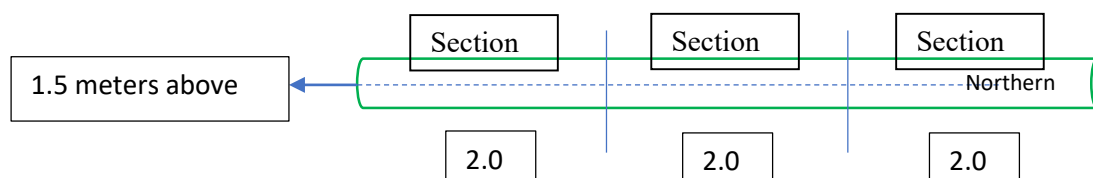
Annex 3. Protocol for bamboo sample collecting: *Trail production of bamboo Scrimber*

According to Chinese national standard GB/T 15780-1995 'Testing methods for physical and mechanical properties of bamboos' and Chinese industry standards of construction JGT 199-2007 'Testing methods for physical and mechanical properties of bamboo used in building', the samples of each bamboo species should be collected as follows:

1. For each species, all bamboo samples should be collected in the most representative bamboo producing areas, the age of bamboo should be **~3 years**.
2. Before bamboo harvesting, the diameter at **1.5 meter's height** should be measured, make sure the diameter at 1.5 meter's height of the chosen sample is larger than **~40 mm (always better to get the average size, 50 mm is advisable, if not go to a diameter till a minimum of 40 mm)**.

3. Before bamboo harvesting, the northern side of the bamboo should be marked on the bamboo culms.

4. Each bamboo should be felled at **1.5 meter's height**. For each species, at least **60** bamboos should be collected. Make sure the samples are healthy, no defect or damage in appearance.



5. Each bamboo should be cut into 3 culms from the bottom with each length of **2.0 meter**, each culm should be carefully marked and numbered sequentially as the samples. Make sure the northern side is marked on each culm. Each sample should be numbered as **“code-age-sample number-section number”**. e.g. “S-3-1-1” represents *Oxytenanthera abyssinica* bamboo (Ethiopia), three-year old, 1st sample collected, 1st section cut.

6. After cutting, the bamboo culm samples should be split into half (if applicable. Otherwise whole culm will be fine) and dried to 7-12% and stored in dry area.

7. Please take some photos during the bamboo choosing and cutting process.

8. Table 1 briefly summarizes the information of all bamboo samples requested.

Table 1. Total bamboo samples requested.

| Code | Bamboo species | Location | Length /m | Weight/Kg | Age | number | Moisture content /% |
|------|--|----------|-----------|-----------|-----|--------|---------------------|
| S | <i>Oxytenanthera abyssinica</i> | Ethiopia | 2 | 1200 | 3a | 60 | Air-dry |
| A | <i>Oldeania alpina</i> <i>Yushania alpina</i> | Ethiopia | 2 | 1200 | 3a | 60 | Air-dry |

Note: 1. The three types of bamboos A, B, and C are all selected from task 1; 2. Air-dry moisture content--prevent mildew during transportation.

In Task 3, the bamboo samples will be collected for the manufacture of Bamboo Scrimber (BLVL) Products as shown in following figures:



Bamboo Laminated Veneer Lumber (BLVL)



BLVL flooring

Annex 2.

Photos on sample collection and drying process





* with note

Statistical Institute of the Republic of Madagascar
 Institut National de la Statistique
 Direction des Recensements et des Enquêtes

| Sample code | Production (kg) | Initial wt. | Current wt. | Current wt. | Current wt. | Current wt. | Current wt. | Current wt. | Current wt. |
|-------------|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| CE 373 | 50.61 | 46.38 | 15.93 | 25.92 | | | | | |
| CE 442 | 50.81 | 39.36 | 29.62 | 39.82 | | | | | |
| CE 222 | 18.55 | 16.48 | 16.34 | 16.25 | | | | | |
| CE 232 | 45.66 | 38.25 | 39.92 | 37.92 | | | | | |
| CE 412 | 55.55 | 49.05 | 40.69 | 40.68 | | | | | |
| CE 532 | 21.87 | 19.88 | 19.64 | 19.63 | | | | | |
| CE 232 | 38.42 | 31.92 | 20.92 | 30.92 | | | | | |
| CE 232 | 42.38 | 31.21 | 20.92 | 30.92 | | | | | |
| CE 552 | 35.21 | 24.32 | 22.92 | 22.92 | | | | | |
| CE 112 | 35.23 | 32.10 | 32.22 | 32.19 | | | | | |
| CE 412 | 30.45 | 21.49 | 21.22 | 21.22 | | | | | |
| CE 412 | 21.52 | 12.31 | 16.95 | 16.94 | | | | | |
| CE 412 | 28.25 | 22.21 | 24.42 | 24.46 | | | | | |
| CE 232 | 28.29 | 21.48 | 24.99 | 24.89 | | | | | |
| CE 232 | 18.99 | 18.88 | 18.32 | 18.32 | | | | | |





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