ABSTRACT • Bamboo is the fastest growing plant currently known on earth, a property that enables it to be the best alternative as a future source of wood fiber. This study investigated the effect of site and culm height on the physical and chemical properties of *Yushania alpina* culms grown in Ethiopia. Matured *Yushania alpina* 3 to 5-year-old samples were harvested from Hagere-Selam and Rebu-Gebeya sites. The culms were subdivided into three equal lengths (bottom, middle, and top), and the variations in physical and chemical properties between the two sites and the culm heights of *Yushania alpina* were investigated. The results showed that the average values of MC, basic density, tangential and longitudinal shrinkage of *Yushania alpina* culms for Hagere-Selam and Rebu-Gebeya sites were (91.78 and 80.32 %), (0.65 and 0.63 g/cm³), (6.63 and 5.84 %) and (0.63 and 0.56 %), respectively. The average values of cellulose, lignin, extractive and ash contents in the culms for Hagere-Selam and Rebu-Gebeya sites were (52.84 and 50.71 %), (26.55, and 26.04 %), (8.41 and 8.02 %) and (1.95 and 2.17 %), respectively. The results revealed that the site affected the MC, basic density, cellulose, lignin, extractive, and ash contents of *Yushania alpina* culms but not the tangential and longitudinal shrinkage. The culm height of *Yushania alpina* affected MC, basic density, tangential shrinkage, longitudinal shrinkage, cellulose, lignin, extractive, and ash contents. In the case of both sites, the highest percentages of MC, tangential and longitudinal shrinkage, and ash content were observed at the base and lowest at the top of the culms. On the contrary, both sites observed the highest magnitude of basic density, cellulose and extractive at the top and lowest at the base of the culms. The variations in physical and chemical properties at different sites and culm heights influence the utilization of *Yushania alpina* culms for industries and end products.

KEYWORDS: bamboo (*Yushania alpina*), basic density, cellulose, lignin, moisture content, shrinkage

SAŽETAK • Bambus je trenutačno najbrže rastuća biljka u svijetu, što je čini najboljom alternativom za budući izvor drvnih vlakana. Ovom je studijom istraživan utjecaj staništa i visine bambusa *Yushania alpina*, uzgojenoga u Etiopiji, na fizička i kemijska svojstva njegove stabljike. Uzorci *Yushania alpina* stari tri do pet godina skupljeni su sa staništa Hagere-Selam i Rebu-Gebeya. Stabljike su podijeljene na tri jednake duljine (baza, sredina i vrh) na kojima su istraživane varijacije fizičkih i kemijskih svojstava stabljike s obzirom na dva staništa i visinu bambusa. Rezultati su pokazali da su prosječne vrijednosti sadržaja vode, guskoće te tangentnoga i uzdužnog utezanja...
The use of bamboo for various applications is governed by its properties, like any wood material. Moisture content, density, and shrinkage are physical properties that influence the dimensional stability, toughness, strength, working properties, and durability of bamboo and bamboo products (Liese and Köhl, 2015). The basic chemical properties found in bamboo are cellulose, hemicellulose, and lignin, which influence its utilization for different applications (Liese, 1985). The properties of bamboo culms are mainly affected by culm position, age, topography, and climate (Liese and Köhl, 2015; Tolessa et al., 2019). The physical and chemical properties of bamboo vary between species, sites, age, and different parts of culm positions (Santhoshkumar and Bhat, 2015; Liese and Köhl, 2015; Tolessa et al., 2019). Information on the physical and chemical properties of bamboo is necessary for assessing its suitability for various end products (Kamruzzaman et al., 2008; Tolessa et al., 2019). Such information will also enable increasing the utilization of bamboo species as substitutes for solid wood in wood-based industries.

In Ethiopia, the multiple uses of bamboo in industrial applications are not getting the most economic advantage, and its utilization is limited to domestic services (Mulatu and Kindu, 2010; Zenebe et al., 2014). This is due to insufficient basic information on its properties. Previously, few studies have been done on physical and chemical properties (Muche and Degu, 2019; Tsegaye et al., 2020; Dessalegn et al., 2021). There is still limited information about the variation of physical and chemical properties between sites, within culms, and along the culm heights of Y. alpina grown in Ethiopia. Therefore, this study investigated the effect of site and culm heights on the physical and chemical properties of Y. alpina grown at Hagere-Selam (Sidama Region) and Rebu-Gebeya (Amhara Region).
Hagere-Selam site lies on geographical coordinates of 6°29’0” North, 38°31’0” East; whereas Rebu-Gebeya coordinates are 10°33’0” North, 37°46’0” East.

2.1 Determination of physical properties

2.1.1 Determination of moisture content

Three centimeters long specimens representing two sites (Hagere-Selam and Rebu-Gebeya) and three culm heights (base, middle, and top) were cut from fresh *Y. alpina* to determine its initial moisture content.

Green weight of each specimen was measured using an analytical balance with a 0.01g accuracy (IS 6874, 2008). The specimens were then oven-dried at a temperature of (103±2) °C until attaining constant weight. The moisture content was calculated using Eq 1.

\[
\text{Moisture content (\%) } = \frac{W_g - W_{od}}{W_{od}} \times 100
\]  

(1)

Where \(W_g\) is the green weight of specimens and \(W_{od}\) is the oven-dry weight of the specimen.

2.1.2 Determination of basic density

Three centimeters long specimens, (representing 2 sites and three culm heights), were cut from fresh *Y. alpina* culms, 3-cm in length, to determine tangential and longitudinal shrinkage. For each specimen, the green weight and dimensions of wall thickness at four points and lengths at four points in green conditions were measured using an analytical balance and digital caliper with an accuracy of 0.01g and 0.01 mm, respectively (Figure 1). The specimens were oven-dried at a temperature of (103±2) °C. The repeated measurements for weight were recorded until constant weight was reached. Shrinkage was determined based on ISO 22157-2:2004 and IS 6874 (2008). The shrinkage was calculated using Eq 3.

\[
\text{Shrinkage (\%) } = \frac{D_i - D_f}{D_i} \times 100
\]  

(3)

Where \(D_i\) is the initial dimension of the specimens before oven-drying (mm) and \(D_f\) is the final dimension of the specimens after oven-drying (mm).

Table 1 Climate and altitude of Hagere-Selam and Rebu-Gebeya where *Y. alpina* culm samples were harvested

<table>
<thead>
<tr>
<th>Parameters / Parametri</th>
<th>Sites / Staništa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude m.a.s.l, m / nadmorska visina, m</td>
<td>Hagere-Selam</td>
</tr>
<tr>
<td>Annual average precipitation range, mm/year raspon prosječnih godišnjih padalina, mm/god.</td>
<td>1500-2850</td>
</tr>
<tr>
<td>Annual average temperature range, °C raspon prosječne godišnje temperature, °C</td>
<td>1000-1600</td>
</tr>
</tbody>
</table>

Table 2 Description of *Y. alpina* culms grown at Hagere-Selam and Rebu-Gebeya

<table>
<thead>
<tr>
<th>Parameters / Parametri</th>
<th>Sites / Staništa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height / visina, m</td>
<td>Hagere-Selam</td>
</tr>
<tr>
<td>Diameter / promjer, mm</td>
<td>13</td>
</tr>
<tr>
<td>Culm thickness / debljina stabljike, mm</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Basic density = \(\frac{\text{Ovendry weight [gm]}}{\text{Green volume [cm}^3\text{]}}\)  

(2)

2.1.3 Determination of shrinkage

2.1.3. Određivanje utezanja

Specimens representing 2 sites and three culm heights were prepared from round-shaped *Y. alpina* culms, 3-cm in length, to determine tangential and longitudinal shrinkage. For each specimen, the green weight and dimensions of wall thickness at four points and lengths at four points in green conditions were measured using an analytical balance and digital caliper with an accuracy of 0.01g and 0.01 mm, respectively (Figure 1). The specimens were oven-dried at a temperature of (103±2) °C. The repeated measurements for weight were recorded until constant weight was reached. Shrinkage was determined based on ISO 22157-2:2004 and IS 6874 (2008). The shrinkage was calculated using Eq 3.

\[
\text{Shrinkage (\%) } = \frac{D_i - D_f}{D_i} \times 100
\]  

Where \(D_i\) is the initial dimension of the specimens before oven-drying (mm) and \(D_f\) is the final dimension of the specimens after oven-drying (mm).

Figure 1 Position and direction measurement for wall thickness and longitudinal shrinkage

Slika 1. Mjerna mjesta i smjer mjerenja debljine stijenke i uzdužnog utezanja
2.2 Determination of chemical composition

The harvested bamboo culms were dried and converted into small-size strips suitable for further milling processes. Thereafter, they were placed in a hammer mill and Willey mill to reduce it to the appropriate size. Then the milled powder bamboo samples were filtered using a 40 mesh size (425 μm) and 60 mesh sieve (250 μm). The particles were stored in an airtight container labeled with the appropriate code for chemical analysis.

The chemical composition including extractive (alcohol-toluene solubility), ash, and lignin content were determined using the standard procedures of the American Society for Testing Materials (ASTM) (Table 3). Cellulose content was determined according to alkali extraction and Kurchner-Hoffer method (Brown, 1975). Toluene was used instead of benzene and reported as alcohol-toluene extractive (Tolessa et al., 2017). The amounts were expressed on a percentage basis of the starting oven-dry mass. The lignin content test was performed with extractive-free bamboo derived from the alcohol-toluene extractive test.

2.3 Statistical analysis

The data were analyzed statistically to assess significant differences between the two sites (Hagere-Selam and Rebu-Gebeya) and along the three culm positions of culms (Anokye et al., 2014). The variation of MC along the culm height was due to differences in anatomical structure and chemical composition between locations along the bamboo culms. On the other hand, the decreasing trend of initial MC might be due to a smaller proportion of vascular bundles at the bottom when compared to the top position of culms (Anokye et al., 2014). Density is among the main factors that affect the utilization of bamboo culm as raw material. The over-

### Table 4

| Mean-squares and statistical significances / Srednji kvadrati i statistička značajnost |
|---------------------------------|---------------------------------|--|--|--|--|
| **Source of variation** | **DF** | **Initial MC Početni sadržaj vode** | **Basic density Nominalna gustoća** | **Tangential Tagentno utezanje** | **Longitudinal Uzdužno utezanje** |
| Eisenov varijacije | | | | | |
| Site (S) / stanište (S) | 1 | 3272*** | 0.013** | 0.298** | 0.099** |
| Culm high (P) / visina stabljike (P) | 2 | 7904*** | 0.030*** | 17.626*** | 1.940*** |
| S: P | 3 | 31** | 0.000** | 0.014** | 0.000** |

* Not significant at p>0.1, * significant at p<0.05, ** significant at p<0.01, *** significant at p<0.001, DF-degree of freedom / "" nije značajno za p>0.1, * značajno za p<0.05, ** značajno za p<0.01, *** značajno za p<0.001, DF – stupanj slobode
all mean values of basic density for the Hagere-Selam and Rebu-Gebeya sites were 0.65 and 0.63 g/cm³, respectively. This shows that the culms harvested from the Hagere-Selam site were significantly denser than those from the Rebu-Gebeya site (Table 4). Generally, the density of bamboo ranges from about 0.4 to 0.9 g/cm³ depending on the anatomical structure reflected in the quantity and distribution of fibers around the vascular bundles (Zakikhani et al., 2017). The density of this finding was in the range of generally recognized values of bamboo density. The result shows that the culm height had significant effects on the basic density at p<0.001 level, whereas the site had a significant effect on basic density at p<0.01 level (Table 4). However, the table shows that the interaction effect between the site and culm height did not significantly affect the basic density at p>0.05 level (Table 4).

The results revealed that the basic density significantly increased along with the height of Y. alpina culms for both sites (Figure 2). Many researchers reported similar trends to this finding. They found an increase in basic density with increasing height of bamboo culms from the base to the top (Wahab et al., 2009; Santhoshkumar and Bhat, 2015; Vetter et al., 2015). The increase of basic density from the base towards the top position of the bamboo culm was due to the increase in the proportion of fibrous tissue and increased frequency of the occurrence of vascular bundles.

3.1.3 Shrinkage

Shrinkage is another main factor that affects the utilization of bamboo culm as a raw material in different wood industries. Unlike wood, bamboo begins to shrink from the very beginning of drying. The results revealed that the overall mean tangential or culm-wall shrinkage for the Hagere-Selam and Rebu-Gebeya sites was 6.63 % and 5.84 %, respectively (Figure 5). The overall mean longitudinal shrinkage for the Hagere-Selam and Rebu-Gebeya sites was 0.63 % and 0.56 %, respectively (Figure 5). Shrinkage of the Y. alpina culm grown at Hagere-Selam was higher in both tangential (culm-wall thickness) and longitudinal direction when compared to the Rebu-Gebeya site (Figure 5). This variation may be related to the initial MC and the culm-wall thicknesses of the bamboo culms (Siam et al., 2019).

The tangential and longitudinal shrinkage of Y. alpina culm at different heights for Hagere-Selam and Rebu-Gebeya sites is presented in Figure 3 and Figure 4, respectively.
The statistical analysis of variance revealed that site and culm height had a highly significant effect on tangential shrinkage at \( p<0.001 \) (Table 4). The same table shows that the culm height had a significant effect on longitudinal shrinkage at \( p<0.001 \), whereas the site had a significant effect on the longitudinal shrinkage at \( p<0.05 \). However, the interaction between the site and the culm height position had an insignificant effect on the tangential and longitudinal shrinkage at \( p>0.05 \) (Table 4).

The results showed that the tangential and longitudinal shrinkage of the culm decreased from the base to the top positions of \( Y. \text{alpina} \) for both sites (Figure 3, Figure 4). A similar trend was observed in \( Bambusa \) balcooa, \( Bambusa \) tulda, \( Bambusa \) salarkhanii, and \( Melocanna \) baccifera species grown in the Philippines (Kamruzzaman et al., 2008). These variations are associated with higher parenchyma cell content and fewer vascular bundles at the base positions. On the other hand, lower parenchyma cell content and a higher number of vascular bundles are found at the top positions of bamboo culms (Wahab et al., 2009).

### 3.2 Chemical composition

#### 3.2.1 Cellulose content

Cellulose is the main constituent of lignocellulosic wood material, and it is located predominantly in the secondary cell wall. The analysis of variance shows that the site and culm height had a significant \( (p<0.001) \) effect on the cellulose content of \( Y. \text{alpina} \) bamboo (Table 5). The same table shows that the interaction effect between site and culm height did not show a significant \( (p>0.05) \) effect on cellulose content (Table 5). The overall mean value of cellulose content in \( Y. \text{alpina} \) culms grown at Hagere-Selam was 52.84 %, which is statistically higher than the bamboo culms collected from the Rebu-Gebeeya site, which was 50.71 %. The results obtained from this study were higher than those found in the previous study on the same bamboo species (46.76 %) (Tsegaye et al., 2020). The cellulose content of this finding was in the range of softwood (40 – 52 %) and hardwoods (38 – 56 %). Normally, the cellulose content of bamboo ranges from 40 – 50 % (Fengel and Wegener, 1984). The results obtained in this study were in the range of the values mentioned above for woods and other bamboo species. Bamboo species with cellulose content in this range are suitable for pulp and papermaking, bioenergy, and biobased composite production (Hammert et al., 2001; Li et al., 2007). It can also be used for applications similar to those of softwood and hardwood.

In the case of both sites, statistically, the highest cellulose contents were observed at the top; followed by the middle and lowest at the bottom position (Figure 8, Figure 9). The percentage cellulose content of \( Y. \text{alpina} \) culms for both sites showed an increasing trend from the base to the top (Figure 8, Figure 9). The same trend to this finding was reported for the same bamboo species at age of three (Tolessa et al., 2019).
creased cellulose content was associated with the increase in cell wall thickness (Tolessa et al., 2017).

### 3.2.2 Klasson lignin content

#### 3.2.2. Sadržaj Klasonova lignina

Lignin is a phenolic substance consisting of an irregular array of variously bonded hydroxyl- and methoxy-substituted phenylpropane units. Statistically, the overall mean values of lignin content of *Y. alpina* culms collected from the Rebu-Gebeya site (26.04 %) differed insignificantly from the culms collected from the Hagere-Selam site (26.55 %) (Figure 7). The lignin content in different tropical bamboo species was reported in the range of 24.84 to 32.65 % (Razak et al., 2013). Fengel and Wegner (1984) investigated the ranges of lignin for softwoods (24 – 37 %) and hardwoods (17 – 30 %). The results obtained from this study were in the range of the above reports for bamboo, softwood, and hardwood. According to Zhang et al. (2022), the high lignin content of bamboo culms can provide excellent physical and mechanical properties. On the other hand, the high lignin content contributes to bamboo rigidity and makes it suitable for structural applications, such as construction and furniture-making.

The analysis of variance shows that the culm height had a significant effect on lignin content at *p*<0.01 (Table 5). The site showed a significant (*p*<0.1) effect on lignin content (Table 5). However, the interaction effect between the site and culm height did not show a significant (*p*>0.05) effect on the lignin content of the culms (Table 5). The results revealed that the highest percentage of lignin content was observed at the bottom; followed by middle and minimum at the top. A similar variation pattern was observed in the bamboo species (Tolessa et al., 2019). A similar variation pattern to this study was reported for *Melocanna baccifera* (Hossain et al., 2022).

### 3.2.3 Extractive content

#### 3.2.3. Sadržaj ekstraktiva

Non-structural chemical compositions found in wood and bamboo materials are known as extractives. On the other hand, extractives in bamboo are non-cell wall components with diverse chemical compositions such as resins, lipids, waxes, tannins, pentosan, hexosan, starch, and silica (Fengel and Wegener, 1984). According to the analysis of variance, site and culm height showed a significant (*P*<0.001) effect on the extractive content (Table 5). However, the interaction effect between the site and culm height did not show a significant effect on the extractive content of *Y. alpina* at *p*>0.05 (Table 5).

The overall mean value of extractive content in *Y. alpina* culms collected from Hagere-Selam was 8.41 %, which is insignificantly higher than the culms collected from the Rebu-Gebeya site, which was 8.02 %. Extractives in bamboo can enhance the structural rigidity of its cell wall and effectively resist diseases and pests/decay (Zhang et al., 2022).

Statistically, in the case of both sites, the highest extractive contents were observed at the bottom position; followed by the middle and lowest at the top position (Figure 8, Figure 9). The same variation pattern to this finding was reported in *Y. alpina* culms (Tolessa et al., 2019).

### 3.2.4 Ash content

#### 3.2.4. Sadržaj pepela

Ash is a term generally used to refer to inorganic substances such as silicates, sulfates, carbonates, or metal ions. The analysis of variance shows that the main effects of site and culm height had a significant effect on ash content at *p*<0.01 (Table 5). However, the interaction effects between the site and culm height did not show a significant effect on ash content at *p*>0.05 (Table 5). The overall mean value of ash content in *Y. alpina* culms collected from Rebu-Gebeya was 2.17 %, which is significantly higher than the culms collected from the Hagere-Selam site, which was 1.95 %. Liese and Köhl (2015) stated that bamboo growth sites affect the amount of ash in bamboo. This difference might be due to the topography, soil, and climate of the area where the bamboo culms are grown. Values lower than those determined in this study were reported for highland bamboo, namely 1.87 % (Tolessa et al., 2017).

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>DF</th>
<th>Cellulose</th>
<th>Lignin</th>
<th>Extractive</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site (S) / staniste (S)</td>
<td>1</td>
<td>40.87***</td>
<td>2.38</td>
<td>1.37***</td>
<td>0.45**</td>
</tr>
<tr>
<td>Culm height (P) / visina stabljike (P)</td>
<td>2</td>
<td>149.72***</td>
<td>27.92***</td>
<td>1.89***</td>
<td>5.01***</td>
</tr>
<tr>
<td>S:P</td>
<td>2</td>
<td>74**</td>
<td>0.45**</td>
<td>0.039*</td>
<td>0.022**</td>
</tr>
</tbody>
</table>

*Not significant at *p*<0.1, * significant at *p*<0.05, ** significant at *p*<0.01, *** significant at *p*<0.001, ‘·’ is significant at *p*<0.1, DF – degree of freedom, “” nije značajno za *p*>0,1, “” značajno za *p*<0.05, **” značajno za *p*<0.01, ***” značajno za *p*<0.001, “·” značajno za *p*<0.1, DF – stu- panj slobode.

---

**Table 5** Analysis of variance for cellulose, lignin, extractive, and ash contents in *Y. alpina* culms at different sites and culm heights

**Tablica 5. Analiza varijance sadržaja celuloze, lignina, ekstraktiva i pepela stabljike *Y. alpina* za različita staništa i visine stabljike**
et al., 2019). However, higher than these values were reported for the same bamboo species, namely 3.77% (Tsegaye et al., 2020).

Statistically, in the case of both sites, the highest ash contents were observed at the bottom position; followed by the middle and lowest at the top position (Figure 7, Figure 8). The same variation to this finding was reported in *Y. alpina* culms at the age of three (Tolessa et al., 2019). According to Tolessa et al. (2019), the ash content variation along the culm height varied with moisture content.
4 CONCLUSIONS

This study investigated the variation of physical and chemical properties in Yushania alpina culm with site and culm height. The Y. alpina culms grown at the Hagere-Selam had higher values of green moisture content (MC) and basic density compared to the culms collected from the Rebu-Gebyea. The green MC of Y. alpina culms decreased from the base toward the top positions for both sites. Similarly, the tangential and longitudinal shrinkage from green to oven-dry conditions of Y. alpina culms showed a decreasing trend from the base to the top for both sites. In contrast, the opposite tendency was observed in the basic density, which decreased from the top to the base positions of the bamboo culms for the two sites. Density is the most important parameter affecting its practical utilization. Based on density, most of the other characteristics of bamboo culms can be predicted. A significant effect of site and culm height on chemical properties was observed. The amount of cellulose and lignin content found was in the range of wood and other bamboo species. Consequently, Y. alpina culm can be a potential source of pulp and paper, and bioenergy, and is suitable for structural applications, such as construction and furniture-making and biobased composite production. Further study should be carried out on other potential bamboo species abundantly available in Ethiopia, such as lowland bamboo (Oxytenanthera abyssinica) and other introduced and exotic bamboo culms.

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