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Drying of Highland Bamboo (*Oldeania alpina*) Culms Grown in Ethiopia as Quality Enhancement

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ABSTRACT

Drying is an essential step in the manufacturing process of bamboo culms which enhances its quality. Even though in the case of Ethiopia, effective bamboo culm drying has not been practiced. This is due to limited information/technology regarding bamboo culm drying. Therefore, this study aimed to investigate the effective drying technologies and the effect of site and culm height on the drying characteristics of *Oldeania alpina* (*O. alpina*). For this study, matured 3-5 years old samples of *O. alpina* culms sectioned into three segments were collected from Hagere-Selam and Rebu-Gebeya, Ethiopia. The culms were stacked and dried using kiln and air-drying methods. The mean values of basic density in *O. alpina* collected from Hagere-Selam and Rebu-Gebeya sites were 0.65 and 0.63 gcm^{-3}, respectively. The average initial moisture content (MC) of Hagere-Selam and Rebu-Gebeya culms were 91.78% and 80.32%, respectively. The Hagere-Selam culm kiln-dried within 6.5 days while air-dried within 75 days to attain the final MC for kiln (10.15%) and air-drying (14.13%). The Rebu-Gebeya culm kiln dried within 5.4 days while they required 61 days for air-drying to attain the final MC for the kiln (10.60%) and air-drying (13.01%). The MC and drying time needed for drying the culms were significantly affected by site, culm height, and drying method. Drying *O. alpina* culms using kiln and air-drying methods was successful without significant drying defects. Well-seasoned culms of Hagere-Selam and Rebu-Gebeya are recommended for wider utilization in Ethiopia including furniture, flooring, handcrafts, etc.

INTRODUCTION

Bamboo is the fastest-growing plant currently known on earth which abundantly, grows in most of the tropical, subtropical, and mid-temperate zone (Chaowana, 2013; Srivaro, 2018; Das et al., 2018). Bamboo has good properties that enable it as the best alternative source of wood fiber (Kaur et al., 2016). Unlike timber, bamboo culms need a short rotation period (3-5 years) to be matured and used for furniture, flooring, and engineered bamboo products (Liese & Köhl, 2015; Atienza et al., 2020). In addition, bamboo has a higher strength-to-weight ratio compared to wood, which enables easy harvesting, transporting, and manufacturing of products (Anokye et al., 2014; Adewuyi et al., 2015 Chaowana et al., 2021).

The highland bamboo or African alpine bamboo called *Oldeania alpina* is indigenous to Ethiopia and endemic to tropical Africa (Bahru & Ding, 2021). It is also available in the highlands of some East African countries (Bahru & Ding, 2021). *Oldeania alpina* is the most cultivated and widespread bamboo species in - Ethiopia compared to Ethiopian lowland bamboo (*Oxytenanthera abyssinica*) (Mulatu & Kindu, 2010; Mekonnen et al., 2014). This is due to its suitability and ease of processing the culm which, is easily convertible into different products. The utilization of bamboo culms for different industrial and construction applications in Ethiopia has been limited to lower-value products such as the construction of traditional houses, rudimentary furniture, handcrafts, mats, fencing, beehives, and household utensils (Yigardu et al., 2016; Mathewos, 2017).

Globally, bamboo species can provide more than 1500 different uses (Zhaohua & Wei, 2018). It can be used for different applications from traditional utilization in rural areas up to industrial productions and other versatile uses (Muche & Degu, 2019). However, the multiple uses of bamboo in industrial applications in Ethiopia have not been getting the most economic advantage and are limited to domestic uses. This is due to limited studies on the bamboo culms' properties. Similar to other woody materials, the utilization of bamboo culms for various applications is governed by its properties such as anatomical, physical, mechanical, drying, etc. These properties vary among bamboo species, age, site, and culm positions (Wahab et al., 2009; Santhoshkumar, Bhat 2015). Previously studies were done on the anatomical, physical, and mechanical properties of *O. alpina* culms grown in Ethiopia (Muche & Degu, 2019; Dessalegn et al., 2021). Nevertheless, sufficient research has not been done on the proper drying of *Oldeania alpina* bamboo culms grown in Ethiopia.

Similar to timber, freshly cut bamboo culms may have more than 100% moisture content (MC) on a dry weight basis which influences the dimensional stability, density, strength, working properties, and durability characteristics of the bamboo culms (Liese & Köhl, 2015; Adam & Jusoh, 2019). As a result, this moisture could be reduced to equilibrium moisture content (EMC) by the process of drying/seasoning. Drying is an essential step for the manufacturing process of bamboo culm and bamboo-based products. If bamboo products are manufactured un-dried to the desired EMC then they develop high split, extreme shrinkage, dimensional changes, susceptibility to biological and physical degradations, and low quality (Anokye et al., 2014a; Lv, 2018; Lv, 2019).

Properly dried culms offer several benefits over green ones during further processing and when used to manufacture finished products (Wakchaure & Kute, 2012). For example, proper moisture reduction could minimize the shrinkage and swelling of culms to manageable amounts in service and further processing (Liese & Köhl, 2015; Lv, 2019) and as well as improve their properties (Anokye et al., 2014). Furthermore, finished bamboo products manufactured from properly dried culms are not susceptible to harmful effects and enhance culms' service life span (Liese & Tang, 2015; Vetter et al., 2015). Therefore, the objective of this study was to investigate effective drying technologies and the effect of site and culm height on the drying characteristics of *Oldeania alpina* culms grown at Hagere-Selam (Sidama Region), and Rebu-Gebeya (Amhara Region) of Ethiopia.

METHODS

Matured 3-5-year-old *Oldeania alpina* culms samples were selected and harvested from Hagere-Selam and Rebu-Gebeya, Ethiopia based on the potential availability of the bamboo species in the country (Table 1, Figure 1). The culms were cut at about 20 cm above the ground level during the dry season. Then, their branches were removed from the entire length of the culms and sectioned into three equal lengths (bottom, middle, and top) portions (Liese & Köhl, 2015). Finally, the culms were transported to the Forest Products Innovation Centre of Excellence at the green condition for further processing into samples for testing. Hagere-Selam is located $6^0$29'0"N, $38^0$31'0"E; whereas Rebu-Gebeya coordinates $10^0$33'0"N, $37^0$46'0"E.

Figure 1. Bamboo stands grown at Hagere-Selam, Sidama Region

Table 1. Altitude and climate of study areas and description of *O. alpina* culms

Parameters	Sites	
	Hagere-Selam	Rebu-Gebeya
Altitude m.a.s.l (m)	1500-2850	2300-4100
Annual average rainfall (mm)	1000-1600	900-1500
Annual average temperature (°C)	11-22	0-15
Height (m)	13	12
Diameter (cm)	7-9	5-8
Culm thickness (cm)	0.72	0.60

Basic density determination

Three centimeters long specimens, representing two sites and three culm heights with six replications were cut from fresh *O. alpina* culms. The green weights of the specimens were measured using an analytical balance with an accuracy of 0.01 grams. The volume of each specimen was determined based on the water displacement method. Then, they were oven-dried at 103±2°C for 48 hours (h) until the attainment of constant weights was obtained. Basic density was determined based on ISO 22157-1; ISO 22157-2: 2004) and IS 6874: (2008). Basic density was calculated using the following Equation.

$$\text{Basic density} = \frac{\text{Ovendry weight (g)}}{\text{Green volume (cm}^3\text{)}}$$

Method of drying and stacking of bamboo culms

Most drying methods that apply to timber are also suitable for bamboo (Liese & Tang, 2015). For this study, kiln and air-drying methods were applied. For each drying method, bamboo culms were stacked horizontally in vertical alignments separated by stickers which, are well-dried with the standard dimension (Simpson, 1991). During stacking, pockets or spaces were left at different positions (top-bottom, left-right, and center) for the two drying methods to distribute the control samples in each pocket which represent the culms in the stack and the drying process.

Culms for kiln drying were stacked out of the kiln on the transfer carriage having 2.7m length by 1.6m width by 0.30m above the ground which was later guided into the chamber of the conventional drying kiln machine (Figure 2a). While culms for air-drying were stacked under a shed in the air-drying yard (Figure 2b). The air-drying yard has stacking beds standing on firm foundations having a clearance of about 45cm above the ground level with a stacked dimension of 1.80m width by 4m length.

The kiln drying machine has a low drying temperature range of 40-70 ºC, controlled air circulation, and relative humidity that can be adjusted using psychrometers (dry bulb and wet bulb). It has also been equipped with reversible fans to force air circulation and air vents. A mild kiln drying schedule that was used for equivalently dense timber was used for this bamboo drying (Table 2). For the Kiln drying test, control culms were weighed, initial moisture contents (MC) and intermediate moisture contents were calculated, psychrometers regulated, steaming was done, and the direction of the fan changed three times in 24 h intervals. This process continued until the required final 12% MC was attained.

Table 2. Kiln Schedule used for *O. alpina* culms drying

MC (%)	Temperature (^{0}C)		Relative humidity (%)
	Dry-bulb	Wet-bulb	
100-70	38	35	80
70-60	42	37	70
60-50	44	39	65
50-40	50	40	60
40-30	53	42	55
30-20	55	43	50
20-10	60	45	40

Figure 2. Stacks of bamboo culms in kiln drying chamber (a) and under shed for air drying (b)

For air drying tests, the control samples were weighed and placed into the stack and this was repeatedly weighed at one-week intervals, and MCs were calculated until the final MC of the stack was less than or reached about the EMC.

Determination of initial and final moisture content

A total of 48 culm samples representing (two sites, three culm heights, and two drying methods) were selected for the determination of their drying characteristics. From each selected culm, two small sections of 3 cm lengths were cut from the ends of the culm and the remaining middle part was the control sample having a length of 100 cm (Figure 3) and they were used to monitor and characterize the drying process of the bamboo culms in both cases of the drying experiments (Simpson, 1991). The green weight of the 3 cm sections and the control sample culms were weighed. Then the control samples were placed horizontally in both kiln and air-drying stack pockets. While the 3cm sections were oven-dried at 103±2 ^{0}C for 48 h till constant weight was attained to determine the initial and final MC of the stacks (Tang et al., 2013).

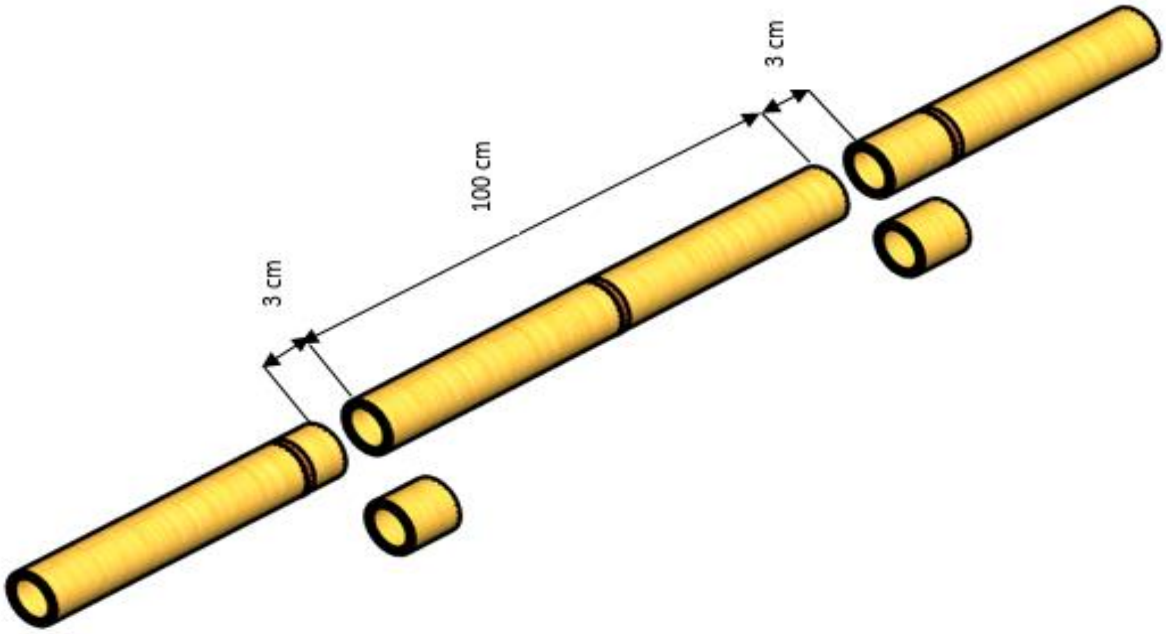

Figure 3. Method of cutting moisture sections and control culm samples

The moisture content of the sections was calculated using equations 1, 2, and 3.

$$MC_1\ (\%)=\frac{W_{g1}\text{-}W_{od1}}{W_{od1}}x100 \quad (1)$$

$$MC_2\ (\%)=\frac{W_{g2}\text{-}W_{d2}}{W_{od2}}x100 \quad (2)$$

$$AMC\ (\%)=\frac{MC_1+MC_2}{2} \quad (3)$$

Where: W_g: is green weight and W_{od}: is an oven-dry weight of the sections, AMC: is the average moisture content of MC_1 and MC_2

To calculate the MC of bamboo stacks at different stages and the final moisture content, first, the analytically calculated oven-dry weight of control samples was determined. The analytical oven-dry weight of control samples (W_{oc}) was computed using equation 4 and periodically, the control samples were reweighted and intermediate MCs were determined using equation 5.

$$Woc=\frac{Wg}{100+AMC\%}x100 \quad (4)$$

Where: W_g: is the green weight of the control sample

$$\text{Current MC}\ (\%)\ \frac{\text{Current weight-}W_{oc}}{W_{oc}}x10 \quad (5)$$

Determination of drying rate

The drying rate of *Oldeania alpina* culm was determined by the relationship between moisture losses over drying time (Tang et al., 2013). The drying rate was calculated using equation (6).

$$\text{Drying rate}\ (\%)=\frac{\text{Initial MC-Final MC (\%)}}{\text{Drying time (h)}}x100 \quad (6)$$

Determination of drying defects

A total of 48 culm samples (for two sites, three culm heights, and two drying methods) were randomly selected and their drying defects that occurred during dryings were visually inspected. The defects were expressed as a percentage of all samples in each drying method (Tang et al., 2013). Data analysis was performed using Excel Microsoft and R software, version 4.1.3. Descriptive statistics and analysis of variance (ANOVA) were conducted to analyze the data. Tukey's Honestly Significant

Difference (Tukey's HSD) was used for mean comparisons at $P < 0.05$.

RESULTS AND DISCUSSION

Basic density

Density is among the main factor that affects the utilization of bamboo culms as raw material in construction, industry, etc. The overall mean of basic density in *Oldeania alpina* culms collected from Hagere-Selam and Rebu-Gebeya sites were 0.65 and 0.63 gcm^{-3}, respectively. Normally, the basic density of bamboo culms ranges from 0.4 to 0.9 gcm^{-3} depending on its anatomical structure (Huang et al., 2015; Zakikhani et al., 2017). Statistical analysis showed that the culm height had a significant effect on the basic density (Mean square (MS) = 0.023078, F= 10.903, and (P= 0.000276). However, the site didn't show a significant effect on basic density (MS = 0.0036, F= 1.701, and P= 0.202103). The interaction effect of site and culm height also didn't show a significant effect on basic density (MS = 0.000233, F= 0.110, P= 0.895984). In the case of both sites, the basic density significantly increased from the bottom to the top of *Oldeania alpina* culms (Figure 4).

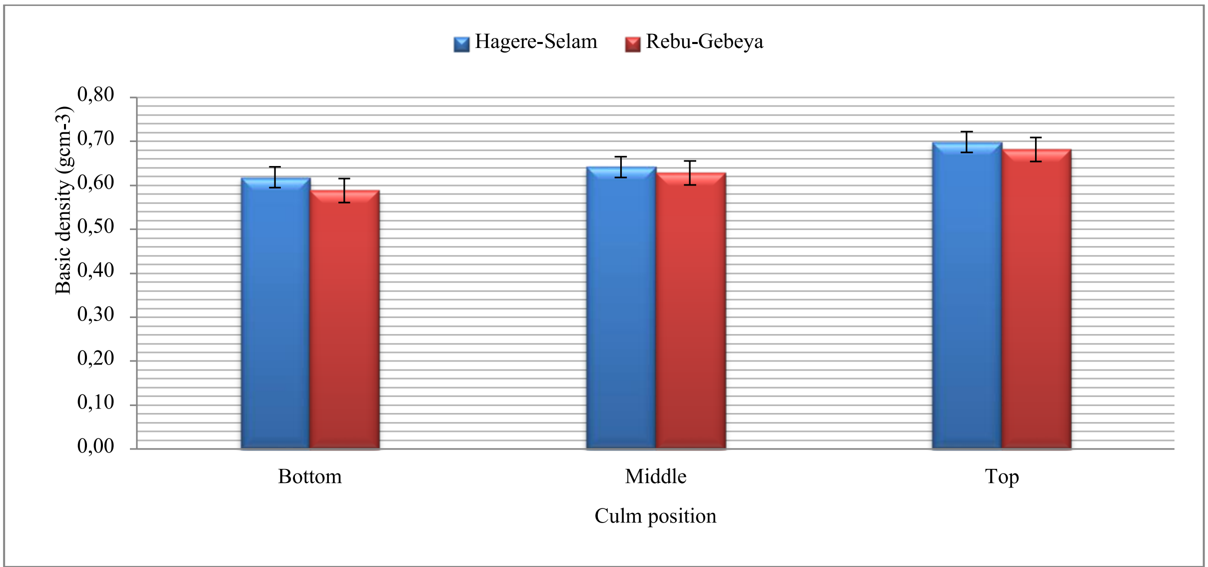

Figure 4. Basic density variation in *O. alpina* culm at different sites and culm heights

In the literature reported that the increase in basic density with increased culm height from the bottom to the top of bamboo (Daud et al., 2018; Gebremariam, 2018; Siam et al., 2019; Adam & Jusoh, 2019). The variation of the basic density from bottom to top could be associated with the increased proportion of fibrous tissue and frequency of vascular bundles; and also increased with the wall thickness of culms from the bottom to the top of bamboo (Santhoshkumar & Bhat, 2015; Vetter et al., 2015; Zhang et al., 2022). The density of bamboo influences its drying characteristics (Razak et al., 2010). Accordingly, the denser bamboo culm has a lower drying rate. This study confirmed that the Hagere-Selam bamboo culm was insignificantly denser than the Rebu-Gebeya culm. Consequently, the Rebu-Gebeya culm was an insignificantly faster drying rate than the Hagere-Selam culm. This variation could be associated with the wall thickness and initial MC of the bamboo culms (Liese & Tang, 2015).

Initial and final moisture content

The result revealed that the site and culm height had a significant effect on the initial MC of Oldeania alpina culms ($P < 0.001$) (Table 3). Whereas the initial MC was affected by the drying method at $P < 0.05$ level. However, there is no significant effect on the interaction effect between the site and the culm height on the initial MC of culms at P > 0.05 (Table 3). The interaction between the site and the drying method, the interaction between the culm height and the drying method, and as well as the interaction of all three factors/parameters didn't show significant effects on the initial MC of the culms at $P > 0.05$ (Table 3).

The method of drying appreciably affected the final MC of the culms at $P < 0.001$ (Table 3). Table 3 shows that the culm height had a significant effect on the final MC ($P < 0.1$). However, the site didn't show a significant effect on the final MC. The interaction effect between the site and the drying method had a significant effect on the final MC at $P < 0.01$ (Table 3). The interaction of site and culm height had a significant effect on the final MC at ($P < 0.1$). On the contrary, the interaction effect between culm height and drying methods, and the interaction of the three factors didn't show a significant effect on the final MC of *O. alpina* culms (Table 3).

The results revealed that *O. alpina* culms collected from Hagere-Selam had a higher value of initial MC compared to the culms collected from Rebu-gebeya (Table 4). This difference may be associated with the age and season of felling of bamboo culms (Daud et al., 2018). For this study, the bamboo culm samples were collected during the same season from both sites. But the ages of the culms collected from the two sites were in the ranges of 3 to 5 years old. This may be the case for the variation of initial MC between the two sites of this finding.

In the case of the two sites, the values of initial MCs were decreased from the bottom to the top of the culms (Table 4). Scholars reported a similar pattern of variation to this finding (Anokye et al., 2016; Gebremariam, 2018; Adam & Jusoh, 2019; Awotwe-Mensah et al., 2023). The variation of initial MC with the culm height was associated with an increase in vascular bundle proportion and parenchyma cell distribution from the bottom to the top of the bamboo culms (Wahab et al., 2010; Kamruzzaman et al., 2008; Hartono et al., 2022).

Table 3. Summary of ANOVA for drying characteristics of *O. alpina* culms

		Mean-squares and statistical significances			
Source of variation	df	Initial MC (%)	Final MC (%)	Drying time (h)	Drying rate (%)
Site (S)	1	1576^{***}	1.33^{ns}	398216^{***}	0.0015^{ns}
Culm height (P)	2	5490^{***}	$2.05^{\cdot}$	1057626^{***}	0.0007^{ns}
Drying method (DM)	1	178.0^{*}	122.46^{***}	26632261^{***}	2.7004^{***}
SxP	2	24.00^{ns}	$1.90^{\cdot}$	10007^{ns}	0.0001^{ns}
SxDM	1	0.000^{ns}	7.34^{**}	284592^{***}	0.0008^{ns}
PxDM	2	50.00^{ns}	1.47^{ns}	789255^{***}	0.0004^{ns}
SxPxDM	2	5.000^{ns}	1.38^{ns}	7501^{ns}	0.0001^{ns}

Note: ^{ns}-not significant at $P > 0.05$, *-significant at $P < 0.05$, **-significant at $P < 0.01$, ***- significant at $P < 0.001$, $^{\cdot}$-significant at $P < 0.1$ Where: df- degree of freedom.

Drying rate and drying time

The analysis of variance showed that the method of drying had affected the drying rate ($P < 0.001$) (Table 3). However, the site and culm height didn't show a significant effect on the drying rate. The interaction effects between the site and culm height, the site and drying method, culm height and drying method, and as well as the interaction between the three factors didn't show a significant effect on the drying rate of *Oldeania alpina* culms (Table 3).

The site, culm height, and drying method highly affected the drying time ($P < 0.001$) (Table 3). The interaction effects between the site and the drying method; as well as the interaction between the culm height and the drying method had a significant effect on the drying time of culms ($P < 0.001$). However, the interaction effect of the site and the culm height and the interaction of the three (site, culm heigh, and drying method) factors didn't show a significant effect on the drying time (Table 3). Table 3 showed that the culms collected from Rebu-Gebeya had an insignificantly faster drying rate than the Hagere-Selam culms. This may be associated with differences in density and structural features of the culms. Bamboo species with a higher density have a lower drying rate (Tang et al., 2013). Bamboo culms grown at Hagere-Selam had insignificantly denser than the Rebu-Gebeya culms (Figure 4). In the case of the two sites, the bottom portion had the slowest drying rate and longest drying time when compared to those of the middle and top positions (Table 4). This is due to the fact that the bottom portion had the thickest culm wall compared to the middle and the top ones (Vetter et al., 2015).

During kiln and air-drying, the Hagere-Selam culms took a longer time (6.5 and 75 days, respectively) than the Rebu-Gebeya culms (5.4 and 61 days, respectively) (Table 4). These differences could be associated with the initial MC and the wall thickness of the culms. The present study found that the Hagere-Selam culms had a more initial MC (Table 4) and thicker culm-walls (Table 1) than the Rebu-Gebeya culms. For both kiln and air drying, the bottom portion of the culms took a long time to dry when compared to the mid and top portions for both of the sites (Table 4). This variation could be associated with the increase in wall thickness and initial MC along the culm height from the bottom to the top portions of bamboo (Liese & Tang, 2015). This finding confirmed that the bottom portion had the highest initial MC compared to the middle and the top portion of the culms in the case of the two sites (Table 4).

Table 4. Drying characteristics variations of *O. alpina* culms between sites, drying methods, and culm heights (mean ± standard deviation)

Site	Drying method	Culm height	Initial MC (%)	Final MC (%)	Drying Rate per day (%)	Drying time (hours)
Hagere-Selam	Kiln	Bottom	108.60±4.56	10.13±0.30	0.504±0.024	196±17
		Middle	88.86±5.62	10.22±0.47	0.511±0.050	155±11
		Top	71.92±5.86	10.11±0.61	0.518±0.060	120±11
		Mean	**89.79±16.39**	**10.15±0.43**	**0.511±0.043**	**157±34**
	Air	Bottom	115.07±6.55	14.35±1.18	0.043±0.0026	2336±239
		Middle	92.64±3.35	13.76±0.63	0.045±0.0013	1764±99
		Top	73.58±5.92	14.28±0.95	0.047±0.0078	1302±252
		Mean	**93.76±18.38**	**14.13±0.90**	**0.045±0.005**	**1800±480**
Rebu-Gebeya	Kiln	Bottom	93.46±9.77	10.71±0.33	0.516±0.037	160±9
		Middle	78.79±7.13	10.64±0.60	0.527±0.030	130±18
		Top	63.11±5.55	10.46±0.93	0.548±0.034	96±7
		Mean	**78.45±14.69**	**10.60±0.61**	**0.530±0.033**	**129±29**
	Air	Bottom	101.60±8.27	14.24±1.31	0.046±0.001	1892±166
		Middle	83.00±5.80	13.07±0.93	0.048±0.005	1492±293
		Top	61.94±7.85	11.73±0.96	0.050±0.0016	1009±69
		Mean	**82.18±18.19**	**13.01±1.45**	**0.048±0.0040**	**1464±418**

In comparison to kiln drying, the air drying of *Oldeania alpina* culms appreciably took a longer time for both of the two sites (Table 4). The air drying depends largely on climatic conditions. During air drying method, there is little control of air circulation, temperature, and relative humidity because the weather cannot be regulated. While during kiln drying, air circulation, temperature, and relative humidity are regulated. Consequently, the dried bamboo culms are obtained at an optimal rate of drying and enhanced quality.

Drying defects

Defects may develop during and after drying bamboo culms (Wang et al., 2019). Some defects such as surface checks, collapse, and splits were observed during kiln and air-drying processes for Hagere-Selam (Figure 5a, Figure 5a), and Rebu-Gebeya (Figure 6a, Figure 6a). The bamboo culms grown at Hagere-Selam were more susceptible to drying defects than the Rebu-Gebeya culms This may be associated with culm wall thickness and initial MC of the bamboo. According to Liese & Tang (2015), bamboo culms with thick culms has more susceptible to defects during the drying process.

In the case of both sites, the bottom portion had significantly more drying defects compared to the mid and top portions. The bottom portion of culms with thicker walls was more susceptible to some defects than the top portion (Liese & Tang, 2015). The surface checks and splits may occur due to too rapid drying and season of culm drying (Liese & Tang, 2015). In comparison to air-seasoned culms, the kiln-dried ones were insignificantly more susceptible to drying defects in the case of the two sites. This may be due to the kiln drying schedule used. For this study, the mid-drying schedule has been used.

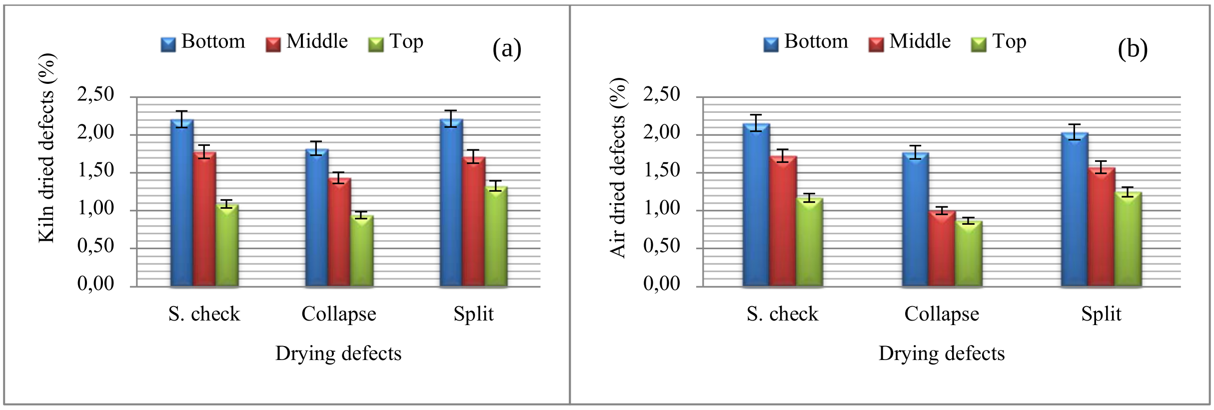

Figure 5. (a) Kiln and (b) Air-dried defects of *O. alpina* culm grown at Hagere-Selam

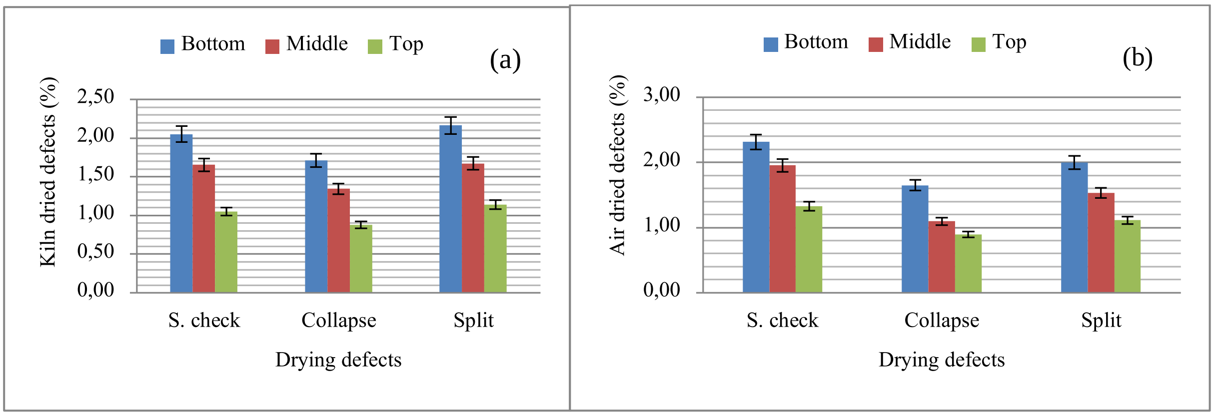

Figure 6. (a) Kiln and (b) Air-dried defects of O. alpina culm grown at Rebu-Gebeya

CONCLUSION

The present study provides valuable insights into the drying characteristics and potential defects of *Oldeania alpina* culms in Ethiopia, offering significant implications for the bamboo industry and the broader field of sustainable materials. The research demonstrates the successful drying of these bamboo culms using both kiln and air drying methods, with minimal occurrence of significant defects. Key findings of this investigation reveal that moisture content and drying time are notably affected by factors such as site, culm height, and drying method, while the drying rate primarily hinges on the chosen drying method. This highlights the importance of selecting the appropriate drying technique based on the specific requirements of the bamboo material. The values of initial MC, drying rate, and drying time were decreased from the base to the top position of *Oldeania alpina* culms for both sites. This valuable information guides optimizing bamboo processing and product development. The practical implications of this research extend beyond the study areas, as the findings are pertinent to regions with similar bamboo species and agroecological conditions. To maximize the quality, productivity, and service life of bamboo culms and products, matured bamboo culms should be harvested timely and dried as soon as possible to the desired MC level using either a kiln or air-drying methods is recommended. Further research shall be conducted on *Oldeania alpina* culm splits and other potential bamboo species available in Ethiopia including lowland bamboo (*Oxythenatera abyssinica*) and the numerous introduced bamboo species' culms properties and utilization. This comprehensive approach will contribute to the sustainable utilization of bamboo resources, supporting economic growth and environmental conservation.

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