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TECHNICAL ROTATION AGE FOR NATURALLY-GROWN *BAMBUSA VULGARIS* FOR FIBRE, FUEL AND STRUCTURAL APPLICATION

NA Sadiku* & SO Bada

Department of Forest Resources Management, University of Ilorin, PMB 1515, Ilorin, Nigeria

**tundesalih@yahoo.com*

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Basic properties of *Bambusa vulgaris* from different ages were examined to determine the optimum technical growth rotation for fuelwood, source of fibre and structural application. Bamboo culm samples aged 2, 3 and 4 years were taken from naturally growing bamboo stock in the Federal University of Technology, Akure, Nigeria. The density, porosity, shrinkage, swelling, fibre morphology and derived fibre values obtained from the geometry of the fibre, the fuel, chemical as well as the strength properties were determined. All the tests were conducted following the standards of Technical Association of Pulp and Paper Industry (TAPPI) and American Standard for Testing Materials (ASTM). The result showed that the maximum density (877.23 kg/m^3) was attained at age 3 while the minimum culm density (755.22kg/m^3) was attained at age 2. The minimum culm density is slightly above the minimum wood density requirement of pulp and paper industry. No significant variations existed in the extractive content, fuel properties, fibre dimensions and the derived values among ages. However, significant variation existed in porosity, density, holocellulose, α-cellulose, hemicelluloses and lignin content among ages. The silica content and all the mechanical properties varied significantly among ages except compression strength perpendicular to grain. Considering the basic characteristics of *B. vulgaris* at different ages, the recommended optimum technical rotation age for cellulosic fibre production is 2 years. For structural application, 3–4 years is considered the harvesting age, as density and strength start decreasing after age 3 except modulus of elasticity (MOE), while culms may be harvested for fuelwood at any age as it is not necessary to use matured culm.

Keywords: Growth rotation, fibre morphology, calorific value, cellulose content, modulus of elasticity, modulus of rupture

INTRODUCTION

One of the fundamental questions in forest economics is when is the best time to harvest a forest stand. Forest rotation, or optimal rotation age represents the number of years which have passed between the establishment of a stand and its final harvesting at the end of the regeneration period. The harvesting or rotation age of a plantation depends mainly on the growth rate of the species and the intended uses. According to Rezende et al. (2005), different methods are available to determine the optimal rotation age of a forest, but the most common criteria for determining the optimal forest rotation adopted in forestry is the rotation when stand achieves maximum sustained yield or maximum mean annual increment (Nautiyal 1988). As regards to technical rotation, the focus is to harvest when the forest had yielded the most material for special use, such as pulp and paper, structural material, fuelwood composite materials etc. Technical rotation of forest stand is achieved when the stand produces the best properties in terms of quality of stocks.

Bambusa vulgaris is the most important non timber forest species, suitable for diverse applications. Its strength, straightness and lightness combined with extraordinary hardness, size range, abundance, easy propagation and rapid growth, bamboo is suitable for an almost endless variety of purposes (Espiloy et al. 1999). The appropriate use of any material, to a large extent, depends on its properties (Kamruzzaman et al. 2008). For many purposes for which *B. vulgaris* is used, optimum quality of the material is governed by its properties. As with wood, the properties and uses of bamboos are influenced by structural changes related to aging (Liese and Weiner 1996, Li et al. 2007). According to Banik and Islam (2005), bamboo culms reach maturity between 3 and 4 years after cultivating, and bamboo culms from 3½ years of age is suitable for any utilisation (Wang et al. 2011). Harvesting bamboo culms at the right age and maturity is of great importance for the optimum quality suitable for several end uses. Most of the physical and mechanical properties of bamboo material change with increasing culm age (Liese 1998, Liese and Weiner 1997, Hidalgo 2003). As with wood, there is variation in the technical quality of bamboo within and among species, as well as between culms of different age classes within a species and within the different portions of the same culm.

For proper management of bamboo stand, matured culms should be harvested at the proper time to keep bamboo stands healthy and to promote the growth of new shoots. Properties of bamboo such as anatomical, physical and mechanical properties have been reported to be affected by age (Kamruzzaman et al. 2008, Azmy et al. 2011). Therefore, information on the properties of bamboo at different ages is required for appropriate end-use. As the newly produced culms undergo developmental changes of maturation with age, their quality and properties keep on changing until they get more or less stabilised. An understanding of variations in culm properties with age is essential not only to determine the appropriate age of optimum properties desired by the industry but also to predict the effects of reducing or increasing rotation on bamboo quality. The objective of this study was to determine the optimal technical rotation length for the best technical value of natural stands of *Bambusa vulgaris* based on the evaluated technical properties.

MATERIALS AND METHODS

Area of study

In this study, *Bambusa vulgaris* was obtained from bamboo grooves at the Federal University of Technology, Akure Campus Nigeria. The University lies between longitude 50 8’ E and 50 10' E of the Greenwich Meridian and between latitude 70 16' N and 70 19' N of the Equator.

Data collection

Culms of age 2, 3 and 4 years were harvested. Three representative culms from each age group were harvested, making a total of nine culms. The culms were carefully marked and labelled for easy identification according to ages. Thereafter, the experimental samples were prepared from the culms. The samples for proximate and chemical properties analysis were milled in their fresh state to pass BS 40-mesh sieve (425 μm) but retained on BS 60-mesh (250 μm sieve). They were later shade dried until constant moisture content was attained while the samples for the physical and strength properties were prepared following standard procedures.

Determination of physical and mechanical properties of *Bambusa vulgaris*

Bamboo density was determined following ASTM D 2395-93 (ASTM 1993), porosity according to ASTM D 2395-93 (ASTM 1993) and shrinkage and swelling percentages according to ASTM D 143-94 (ASTM 1994). Morphology of the bamboo fibres were determined following ASTM D 1030-95 (ASTM 2007) and ASTM D 1413-61 (ASTM 2007). Derived values were determined from the morphology of the fibres (cell wall thickness (CWT) = fibre diameter – lumen width/2; slenderness ratio (SR) = fibre length/fibre diameter; fibre flexibility (FF) = lumen diameter/ fibre diameter; Runkel ratio (RK) = cell wall thickness/lumen diameter x 2; fibre rigidity (FR) = cell wall thickness/fibre diameter x 2; Luce’s shape factor (LCF) as fibre diameter^2 = lumen diameter^2/fibre diameter^2 + Lumen diameter^2. Volatile matter was determined according to ASTM D3175-11 (ASTM 2008). The percentage ash content was determined according to TAPPI standard T211om-93 (TAPPI 1993). The gross calorific value of the samples of biomass materials was determined in accordance with ASTM Standard E711-87 (ASTM 2012). The fuel value index was determined by difference of calorific value and density and then divided by the ash content, alcohol-benzene solubility according to TAPPI standard T 204 cm- 97 (TAPPI 1997), hot and cold water solubility according to TAPPI standard T 207 cm-99 (TAPPI 1999), N/10-NaOH solubility according to TAPPI standard T 212 cm-02 (TAPPI 2002), holocellulose content according to TAPPI standard T 249 cm-85 (TAPPI 1985) and the α-cellulose content according to TAPPI standard T 203 cm-99 (TAPPI 1999). Hemicelluloses content was by difference of Holocellulose and Cellulose content. Klason Ligin Content according to TAPPI Standard

T222 cm-06 method (TAPPI 2006). The Silica content according to TAPPI standard method T245 cm-07 (TAPPI 2007). Both the compression strength parallel and perpendicular to grain were performed following ASTM standard D1037-94 (ASTM 1994) while the flexural strength test were carried out following ASTM D 3043-95 (ASTM 1995) but with some modifications owing to the varying nature of the bamboo thickness. Three observations were recorded for each samples tested.

Statistical analysis

Analysis of variance was used to evaluate the effect of age on bamboo properties at $p \leq 0.05$ percent probability level. Mean separation for the different age classes was carried out using Duncan Multiple Range Test (DMRT). Correlation analysis was used to determine the relationship between the age and the properties of bamboo

RESULTS AND DISCUSSION

Changes in culm physical characteristics with age

The result of the culm density, porosity, shrinkage and swelling of *B. vulgaris* are presented on Tables 1 and 2. As with wood, density is one of the most useful parameters of measuring the quality bamboo (Zobel and Talbert 1984). It can also be used as a predictor of yield and quality of pulp and paper products (Ogunleye 2014). *Bambusa vulgaris* density increased from age 2 to 3 and decline at age 4, porosity decreased from age 2 to 3 but later increased at age 4. There were significant variation in density and porosity among ages. Porosity of *B. vulgaris* has an advantage in preservative treatment to impart durability against biodeterioration. The density increased from age 2 to 3 and then decreased slightly at age 4. This may be due to the maturation of bamboo, which usually starts from early stage to the first 2–3 years with no further increment in properties as age advances (Abdul-Latif et al. 1996), and also increase in the fibre and parenchyma cell wall thickness from younger bamboo to older bamboo (Razak et al. 2007, Razak et al. 2010, Alvin and Murphy 1988). In addition, starch deposition and lignification process that occur in bamboo culms also increases with age (Razak et al. 2010). The variation in the density of *B. vulgaris* is similar to the findings of Espiloy (1987), Santhoshkumar and Bhat (2014) where they recorded variations in the densities of the studied bamboo. Razak et al. (2007) and Alvin and Murphy (1988) got similar findings for *Gigantochloa scortechinii* and *Sinobamboo tootsik*. All these processes contributed significantly to the increase in the density of older bamboo. Since there was significant difference in the density of *B. vulgaris,* from age 3 onwards, the density declined, therefore, age 3 is considered the rotation age for utilisation as structural material, pulp and paper production and bio-composite materials production.

The results obtained on the influence of age on the longitudinal, radial and tangential shrinkge of density of *B. vulgaris,* among the three age classes, are presented on Table 2. Longitudinal shrinkage increased from age 2 to 3 and later decreased at age 4, while radial, tangential and volumetric shrinkages decreased from age 2 to 3 and later increased at age 4. This trend is similar to observation of Wahab et al. (2012). The range of radial (4.54–8.70%) tangential (5.42– 18.34%) and volumetic shrinkage (10.48–25.83%) of *B. vulgaris* under study is similar to what was reported for *G. scortechinii* (Wahab et al. 2012). There were significant variation in the radial, tangential and volumetirc shrinkage of *B. vulgaris* among the three ages but that of longitudinal shrinkage was not different. The mean longitudinal, radial, tangential and volumetirc swelling of *B. vulgaris* varies from 0.24–0.87%, 3.00–7.71%, 6.20–11.20% and 9.52–44.22 % respectively. Contrary to the result of the shrinkage properties, all the swelling properties showed no significant variation among ages, the swelling of both old and young bamboo were similar (Table 2). The swelling result is consistent with the dimensional stability of other bamboo species such as *Dendrocalamus strictus* (Ahmad and Kamke 2005) and *Bambusa blumeana* (Toralde et al. 2013).

Table 1 Influence of age on the density and porosity *of Bambusa vulgaris*

Age (years)	Density (kg m^{-3})	Porosity (%)
2	755.22^{c}	42.60^{a}
3	877.23^{a}	29.44^{c}
4	782.21^{ab}	36.86^{ab}

Means in rows with the same superscript were not significantly different ($p \leq 0.05$)

Table 2 Influence of age on the shrinkage properties *of Bambusa vulgaris*

Source of variation	Level	Longitudinal shrinkage (%)	Radial shrinkage (%)	Tangential shrinkage (%)	Volumetric shrinkage (%)
Shrinkage (%)	2	0.88^{a}	7.69^{a}	15.17^{a}	22.24^{a}
	3	0.94^{a}	5.21^{c}	8.80^{b}	14.34^{b}
	4	0.90^{a}	5.60^{ab}	10.72^{b}	16.50^{b}
Swelling (%)	2	0.46^{a}	6.17^{a}	8.88^{a}	27.36^{a}
	3	0.42^{a}	6.24^{a}	8.83^{a}	22.10^{a}
	4	0.68^{a}	4.64^{a}	9.19^{a}	30.53^{a}

Means in rows with the same superscript were not significantly different ($p \leq 0.05$)

Changes in fibre morphology with age

The results obtained on the influence of age on the fibre morphology and derived values of *B. vulgaris* among the three age classes are presented on Table 3. The results indicated that 3 years old *B. vulgaris* had longer fibre than age 2 and 4. This shows that the fibre of naturally-grown *B. vulgaris* complete their growth in 3 years which is slightly different from the findings of Wang et al. (2011) that reported longest fibre for 1 or 2 year old bamboo. Age 3 will have best pulp quality than those of age 2 and 4 based on fibre properties, although DMRT shows no significant variation in fibre length. The fibre length of *B. vulgaris* from the three age classes were very close to that of softwood tracheids, therefore, they can be used as an alternative raw material for pulp and paper. Generally, the fibre characteristics did not vary with age of the culm, therefore, culms from any of the ages may be considered for pulp and paper or fibre-based composite production, with acceptable physical and mechanical properties since fibre length is positively correlated to strength properties. The insignificant variation in fibre lumen diameter among ages was also observed for *B. blumeana* and *G. scortechinii* (Abdul-Latif & Tamizi 1992). All the fibre characteristics increased from age 2 to 3 and decline at age 4, except the fibre diameter. The RR, LSF and rigidity coefficient (RC) increased from age 2 to 3 and decline at 4. The SR and flexibility coefficient (FC) decreased from age 2 to 3 and later increased at 4 years while only SF increased from age 2 to 4 years. The DMRT showed no significant variation in all the fibre morphology and all the derived values among the 3 age classes. Fibre length and diameter was observed to be longer and larger in older bamboo compared with younger bamboo (Zobel and van Buijtenan 1989, Bowyer et al. 2003). *Bambusa vulgaris* fibres from the three age classes have thin wall thickness and pass the RR < 1, SR > 33 and FC > 0.55 acceptable value for paper making fibre (Bektas et al. 1999). The LSF and solid factor (SF) falls in the range obtained for conventional materials for pulp and paper (Oluwadare and Sotannde 2001) and they also have low RC (0.2) which will enhance fibre bonding (Dutt and Tyagi 2011). Since no significant variation existed in the fibre and derived morphological values among the three age classes, *B. vulgaris* fibres from any age are satisfactory for papermaking

Changes in fuel and chemical characteristics with age

Table 4 and 5 shows the variation in fuel and chemical composition of *B. vulgaris* with age. Ash and silica content increased from age 2 to 4 years. The fuel value index (FVI), calorific value (CV) and FC decreased from age 2 to 3 but increased at age 4, while only volatile matter (VM) increased from age 2 to 3 and decline at 4. No significant variation existed in VM, fixed carbon (FC), Ash, CV and FVI among ages. Only silica content differed significantly among ages (Table 4). Hot water and N/10 NaOH solubility, holocellulose and hemicelluloses increased from age 2 to 3 and decline at 4. Alcohol-benzene solubility increased from age 2 to 4 similar to the result of Li et al. (2007) and Wang et al. (2011), they both reported an increase of alcohol - toluene extractives with culm age. However, report of Hisham et al. (2006) showed no specific trend for alcohol-toluene extractives. Cold water solubility decreased from age 2 to 3 but increased from

Table 3 Influence of age on the fibre morphology and derived morphological values of *Bambusa vulgaris*

	Age (years)	Fibre length (mm)	Fibre diameter (μm)	Lumen width (μm)	Wall thickness (μm)		
Fibre morphology	2	2.03[a]	13.95[a]	12.19[a]	0.90[a]		
	3	2.15[a]	13.98[a]	12.66[a]	2.33[a]		
	4	2.11[a]	14.44[a]	12.41[a]	1.01[a]		
		RR	SR	FC	LSF	SF	RC
Derived indices	2	0.150[a]	144.10[a]	0.876[a]	0.134[a]	9.87×10^{-5} [a]	0.128[a]
	3	0.333[a]	140.80[a]	0.809[a]	0.216[a]	9.92×10^{-5} [a]	0.192[a]
	4	0.164[a]	145.5[a]	0.860[a]	0.150[a]	1.16×10^{-4} [a]	0.140[a]

Means in rows with similar alphabet superscripts were not significantly different ($p \leq 0.05$); RR = Runkel ratio, SR = slenderness ratio, FC = flexibility coefficient, LSF = Luce's shape factor, SF = solid factor, RC = rigidity coefficient

Table 4 Influence of age on the fuel characteristics of *Bambusa vulgaris*

Age (years)	Properties					
	Volatile matter (%)	Fixed carbon (%)	Ash (%)	Silica content (%)	Calorific value	Fuel value index
2	93.77[a]	4.69[a]	2.36[a]	1.19[a]	3075.00[a]	2153.00[a]
3	94.58[a]	3.96[a]	2.52[a]	1.37[a]	2954.90[a]	1209.80[a]
4	93.52[a]	4.17[a]	2.86[a]	1.98[b]	3443.30[a]	1993.40[a]

Means in rows with the same superscript were not significantly different ($p \leq 0.05$)

age 3 to 4 (Table 5). There were no significant variation in the extractive content among ages. Holocellulose and hemicelluloses increased from age 2 to 3 and decline at 4. The α-cellulose decreased from age 2 to 3 and later increased at 4 while lignin content decreased from age 2 to 4. No significant variation existed in all the fuel properties; the volatile matter, fixed carbon, silica content, ash content, calorific value and fuel value index as well as the cold water, hot water, alcohol-benzene and 10/N NaOH soluble extractives showed no significant variation only silica content showed significant variation among the 3 age classes.

The highest holocellulose content was found in age 3. Although there were no significant variation among the three age classes but the holocellulose content increased with age from age 2 to 3 and start decreasing at age 4. The silica and ash content increased with increasing culm age from 2 to 4 years (Table 4). This go contrary to that of Li et al. (2007), they recorded the highest ash and silica content in 1 year old culms of *F. yunnanensis*. High ash content is less desirable for fuel as it is non-combustible and hence reduces the heat of combustion (Dutt et al. 2009). *Bambusa vulgaris* may be considered as good fuelwood and raw material for papermaking on account of comparatively low ash content (Bhatt and Tomar 2002). The α-cellulose, hemicelluloses and acid insoluble lignin showed significant variation among the three age classes. Only holocelluloses content was similar for all the ages (Table 5). Due to the lower lignin content, *B. vulgaris* will be easier to be de-lignified at lower alkali consumption with lower kappa number of pulp and hence lower requirement of bleaching chemical to achieve certain pulp brightness. The present result indicates that for the production of pulp and paper and biochemical application, technically, *B. vulgaris* can be harvested at 3 years rotation based on the highest holocellulose and hemicelluloses content or 4 years based on the lowest lignin content or 2 years based on the highest cellulose content or at any age for fuel wood and biochemical applications due to similar fuel properties and extractive content among ages.

Changes in the strength characteristics with age

The results obtained on the influence of age on the mechanical properties of *B. vulgaris* among the three age classes are presented on Table 6. The compressive strength perpendicular to grain and modulus of rupture (MOR) decreased

Table 5 Influence of age on the chemical characteristics of *Bambusa vulgaris*

	Age (years)	Properties			
Extractive contents		Cold water	Hot water	Alcoho-benzene	10/N Na0H
	2	5.21[a]	9.03[a]	5.30[a]	41.35[a]
	3	3.83[a]	9.28[a]	5.47[a]	42.76[a]
	4	4.27[a]	7.89[a]	5.90[a]	40.97[a]
Chemical contents		Holocellulose	α-cellulose	Hemicelluloses	Lignin
	2	79.81[a]	75.68[a]	4.13[b]	45.90[a]
	3	80.62[a]	67.07[b]	13.55[a]	36.40[ab]
	4	79.01[a]	67.62[b]	11.41[a]	29.24[b]

Means in rows with the same superscript were not significantly different ($p \leq 0.05$)

Table 6 Influence of age on the mechanical properties of *Bambusa vulgaris*

Age (years)	Properties			
	Compression perpendicular to grain (N mm^{-2})	Compression parallel to grain (N mm^{-2})	MOR (N mm^{-2})	MOE (N mm^{-2})
2	1096.40[a]	2240.80[a]	176.22[a]	19016[a]
3	901.45[a]	2251.90[a]	164.30[a]	19312[a]
4	1335.10[b]	2589.40[a]	208.00[b]	21617[b]

Means in rows with the same alphabet superscript were not significantly different ($p \leq 0.05$)

from age 2 to 3 and later increased at age 4 while compressive strength parallel to grain and modulus of elasticity (MOE) increased form age 2 to age 4 (Table 6). There were significant variability in the compressive strength perpendicular to grain, MOE and MOR while only compressive strength parallel to grain showed no significant variation among the 3 age classes. Generally, the strength properties seemed to be highest at age 4.

The result further showed that all the strength properties do not differ between age 2 and 3 but those of age 2 and 3 were significantly lower than that of age 4 (Table 6). This result is in line with the report of Rafidah et al. (2010) and Li (2004). The high strength properties of age 4 may be attributed to increase cellulose content and decreasing micro-fibril angle as well as higher content of vascular bundles which account for the higher density of bamboo and hence increase modulus strength (Li 2004, Rafidah et al. 2010). Maturity of culm is a prerequisite for the optimum utilisation of bamboo in construction and other structural uses. *Bambusa vulgaris* from age 4 is suggested to be suitable for structural application or fibre-based composites products such as medium density fibreboard, hardboard, oriental strandboard, particle board etc. with better physical and mechanical properties.

CONCLUSIONS

The age of the culm influenced the overall quality of *B. vulgaris* for fuelwood, pulp and paper or biochemical applications. All the properties of *B. vulgaris* varied significantly among the three age classes with significant variation in porosity, density, holocellulose, α-cellulose, hemicelluloses, lignin content and silica content of the culm among the three ages. However, no significant variations existed in the extractive content, fuel properties, fibre dimensions and the derived values. All the mechanical properties varied significantly among ages except compression strength perpendicular to grain. The findings of the work shows that the earliest time of harvest for maximum technical value was 2 years for pulp and paper production due to its high cellulose content, for structural application and engineered material production, *B. vulgaris* from age 4 proved to be most suitable owing to the highest strength properties of this age class while any age may be harvested for extractive and fuel since no significant variation existed in the fuel properties and extractive content.

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