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Fibre dimension and chemical characterisation of naturally grown *Bambusa vulgaris* for pulp and paper production

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Abstract: Investigations were made on the fibre and chemical characteristics of *Bambusa vulgari*s Shrad. ex. Wendl in order to provide basic information on its potential use as a sustainable and alternative raw material for pulp and paper making. Nine culms of three different ages (2, 3 and 4 years) harvested were used for the study. Samples were collected from the base, middle and top portion along the culm length in accordance with standard procedures to investigate the chemical properties, fibre dimensions and derived morphological indices. Generally, age do not influence the fibre properties except the fibre length that varies along the culm length. The derived morphological indices vary similarly among different age of the culm. There were variations in the chemical properties among ages except the holocellulose which do not vary with age but varied along the culm length. Based on the studied fibre and chemical properties, *B. vulgaris* is suitable as raw material for pulp and papermaking since the fibre characteristics do not vary significantly with age and position along the culm. The result, however, did not indicate the suitability for pulp and paper based on its high density, high lignin and extractive content as it may pose problem in pulping. Nevertheless, *B. vulgaris* will produce good and strong papers due to its RR that is below 1 and SR which is more than 33 couple with its high fibre flexibility ratio, holocellulose and cellulose contents.

Key words: Bamboo, fibre length, Runkel ratio, extractives, cellulose content, pulp and paper

INTRODUCTION

Inadequate supply of long fibred raw material for pulp and paper production has been identified as one of the problems in the pulp and paper industries in Nigeria (Oluwadare, 2007). Over the years, Nigeria has depended solely on import of pulp and paper products. One of the need-driven-research in forest industry in Nigeria is to engage in the production of pulp for export (Ogunleye, 2014). However, increased population and high demand for wood and wood based products mounted pressure on the nation's timber resources that lead to rapidly dwindling of Nigerian natural forests. Bamboo, is a fast growing and high yield renewable resources, a neglected woody species which was commonly termed as weed which usually undergo annual burning, was found to be a very promising alternative to wood and other non-wood raw materials for pulp production. Presently, Bamboo in Nigeria is found in abundance and it is underutilized (RMRDC, 2004).

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Bamboo has been used extensively in China for the production of paper-grade and dissolving pulp (Cao *et al.*, 2014) due to its unique properties such as high growth rate, low resources cost, long or semi-long fibre and high cellulose content compared to most wood species (Man vu *et al*., 2004, Runge *et al*., 2012). Bamboo could be utilised as a sources for long- fibred raw material for pulp and paper production and at the same time reduce the current pressure on the timber resources. The production of pulp from fast growing non-timber species such as bamboo could serve as export product for foreign exchange which may improve the Nigerian economy.

The quality of pulp and pulp products depends on the properties of raw material such as the morphology of the fibres and the chemical composition (Cao *et al.,* 2014). Therefore, detailed information on the chemical and fibre characteristics of *B. vulgaris*, a dominant bamboo species in Nigeria is highly essential. The aim of this research was to investigate the fibre and chemical properties of *B. vulgaris* with the intent of promoting its utilization for pulp and papermaking in Nigeria.

MATERIALS AND METHODS

B. vulgaris was obtained from bamboo grooves on the Federal University of Technology, Akure Campus. (between 50^{o} 8$^{'}$ East; and 50^{o} 10$^{'}$ East and between 70^{o} 16$^{'}$ North and 70^{o} 19$^{'}$ North) . Culms of age 2, 3 and 4 years were harvested. Bamboo samples were obtained from clear defect-free culms. Three (3) representative culms from each age group were harvested making a total of nine (9) culms. The culms were carefully marked and labelled for easy identification according to ages and position along the culm length. The culms were divided into three equal parts; base, middle and top for fibre and chemical characterisation.

Density determination

The density was determined as per ASTM D 2395-93 (ASTM D, 1993) but with slight modification.

Fibre characterisation

Fibre characterisation of the bamboo culms were carried out following ASTM D 1030-95 (2007) and ASTM D 1413-61 (2007). Macerated fibres were mounted on slides and observed under a Reichet microscope. The fibre length, fibre diameter and lumen width of unbroken fibres were measured using an eye piece micrometer after calibrating with stage micrometer. The cell wall thickness (Fibre diameter – Lumen width/2); Slenderness Ratio (Fibre length/Fibre diameter); Flexibility coefficient (Lumen diameter/Fibre diameter); Runkel ratio (2 x Cell wall thickness/Lumen diameter), Rigidity coefficient (2 x Cell wall thickness/Fibre diameter), Luce's Shape Factor (Fibre diameter^2 – Lumen diameter^2 /Fibre diameter^2 + Lumen diameter^2) and Solid Factor (Fibre diameter^2 – Lumen diameter^2 x Fibre length) were computed from the measured fibre dimensions following the method of Saikia *et al.* (1997); Ogbonnaya *et al.* (1997) and Ohshima *et al.* (2005)

Chemical characterisation

The ash content, Alcohol-benzene solubility, hot and cold water solubility, Alpha (α) cellulose content and lignin content of *B. vulgaris* was determined according to TAPPI standards (T211om-9), (T 204 cm- 97), (T 207 cm – 99), (T 203 cm) and (T222 cm-88), respectively. N/10-NaOH Solubility was determined according to TAPPI standard T 212 om – 02. Holocellulose content according to TAPPI Useful Method 249-75 while the hemicelluloses content was determined by difference of holocellulose and α- cellulose content.

Statistical analysis

Variation in the fibre and chemical properties were evaluated by analysis of variance at $p \leqslant 0.05$. Duncan Multiple Range Test was used to compare mean values for the different ages and positions along the culm length.

RESULTS AND DISCUSSION

Density

The density of *B. vulgaris* were found to vary with age and along the culm length, the density varies from 709.63 Kg/m^3 to 937.95 Kg/m^3 and it increased from the basal portion of the culm to the top (Table 1). Previous work (Abd. Latif, 1993; Abd Latif and Liese, 2002; Ahmad and Kamke, 2005; Liese, 1998 and 1986; Malanit *et al*., 2008; Espiloy, 1987 and Santhoshkumar and Bhat, 2014) supported this finding. Similar to wood, bamboo density and fibre length determines the end product quality of paper as it is positively correlated with tear strength of paper (Fuglem *et al*., 2003). The preferred range for wood density in pulp and paper production is between 400 – 600 Kg/m^3 (Downes *et al*., 1997). The suitability of *B. vulgaris* is not guaranteed for pulp and paper based on its high density. Therefore the species may be mixed with low density wood or bamboo to complement the disadvantages posed by high density.

Table 1: Variation in the Fibre characteristics of *B. vulgaris*

Source of Variation		Density (kg/m^3)	Fibre length (mm)	Fibre diameter (μm)	Lumen width (μm)	Cell wall thickness (μm)
	2	755.22c	2.029a	13.952a	12.191a	0.896a
Age	3	877.23a	2.153a	17.311a	12.657a	2.327a
	4	782.21ab	2.106a	14.436a	12.410a	1.013a
	Base	772.70a	2.337a	14.683a	12.711a	0.986a
Position	Middle	811.82a	1.955b	17.064a	12.343a	2.361a
	Top	830.11a	1.995b	13.951a	12.203a	0.889a

Mean values (n=3); Means with the same letter in a column are not significantly different at ($p \leqslant 0.05$)

Fibre dimensions

The mean fibre length for *B. vulgaris* is 2.10 mm compared with softwood (3.6 mm), the fibre length of *B. vulgaris* is slightly shorter but longer than hardwood species such as *Gmelina arborea* (1.29mm) (Roger *et al*., 2007) initially used for pulp and paper making and even longer than that of *Eucalyptus spp.* (0.67 – 1.06 mm) a popular source of short fibre for pulp and paper industries (Dutt and Tyagi, 2011 and Ververis *et al.*, 2004). Properties such as density and fibre length are positively correlated with tear strength of paper (Fuglem *et al.,* 2003) and bursting strength and folding endurance (Ona *et al.,* 2001). Since the fibre length of *B. vulgaris* is similar to that of softwood tracheids and longer fibre results in greater resistance of paper to tear, therefore, it can be used as an alternative raw material for pulp and paper industries. From the result, the fibre length does not vary with age (Table 1), therefore, culms of any ages may be considered for pulp and paper production.

The fibre diameter, lumen width and cell wall thickness of *B. vulgaris* do not vary significantly among ages as well as along the culm length (Table 1). This was also observed for *B. blumeana* and *G. scortechinii* (Abd. Latif and Mohd Tamizi, 1992). Generally, the lumen width of *B. vulgaris* is wide. The cell wall thickness is almost similar to *Eucalyptus spp.* (3.29 µm – 3.86 µm) (Dutt and Tyagi, 2011) a conventional raw material for pulp. The range of cell wall thickness shows that *B. vulgaris* has thin walled fibres. Thus, paper made from the species is expected to have higher strength.

Derived Morphological Indices

There were no significant variation in all the derived morphological indices among the culms of 2, 3 4 ages and along the culm length (Table 2). The acceptable Runkel Ratio for papermaking fibre is less than 1 (Xu *et al.,* 2006). The fibres with RR below 1 are considered to be thin walled (Istek, 2006; Neto *et al.,* 1996 and Oluwadare and Sotannde, 2007) and good mechanical strength are usually obtained below 1 RR. From the morphological characteristics of *B. vulgaris,* it shows that it possess good fibre felting power since all the Runkel ratio values fall below 1. Therefore, the fibres are satisfactory for papermaking.

The mean slenderness ratio SR (144) of *B. vulgaris* extemely higher than what was obtained for *Eucalyptus grandis* (55.18), *Eucalyptus tereticornis* (52.66) and *Eucalyptus camadulensis* (53.33) which are conventional source of raw material for papermaking (Dutt and Tyagi, 2011, Pillai *et al.,* 2013), and *Gmelina arborea* (39.1) (Sharma *et al*., 2013) but comparable to most softwood species. The acceptable SR for papermaking fibre is more than 33 (Xu *et al*., 2006). The strength properties such as folding endurance were positively correlated with SR. SR lower than 0.7, it is not suitable for quality pulp and paper production (Yang, 1981). Hence *B. vulgaris* will produce good and strong papers compared to that of *Eucalyptus* and *Gmelina* since the SR is more than 33.

The observed average Flexibility coefficient of *B. vulgaris* is 0.85. FC is one of the most important derived indices to determine the strength properties of paper and is

Table 2: Variation in the derived histological characteristics of *B. vulgaris*

Source of Variation		RR	SR	FC	LSF	SF	RC
	2	0.150a	144.10a	0.876a	0.134a	9.87×10^{-5}a	0.128a
Age	3	0.333a	140.80a	0.809a	0.216a	4.24×10^{-4}	0.192a
	4	0.164a	145.5a	0.860a	0.150a	1.16×10^{-4}	0.140a
	Base	0.158a	158.20a	0.867a	0.144a	1.29×10^{-4}	0.135a
Position	Middle	0.340a	129.60b	0.801a	0.222a	4.19×10^{-4}	0.199a
	Top	0.149a	142.70bc	0.880a	0.134a	9.02×10^{-5}	0.127a

Mean values (n=3); Means with the same letter in a column are not significantly different at ($p \leqslant 0.05$)
RR = Runkel ratio; SR = Slenderness ratio; FC = Flexibility coeficient; LSF = Luce's shape factor and RC = Rigidity coefficient

governed by lumen diameter and fibre diameter. It determines the degree of fibre bonding in paper sheet. *B. vulgaris* fibres from all the 3 ages and along the culm length (Table 2) are more flexible than 0.55 – 0.75 hardwood and softwood (Smook, 1997) and therefore satisfies the requirement for pulp and papermaking

The average rigidity coefficient of *B. vulgaris* is 0.15 although lower to what was reported for *Eucalyptus tereticornis* (0.63), *Eucalyptus camadulensis* (0.53) but in the same range with that of *Eucalyptus grandis* (0.33) (Dutt and Tyagi, 2011). *B. vulgaris* has appreciable long fibre and less rigid with average rigidity coefficient of 0.15 and high flexibility with high slenderness ratio due to mean thin cell wall of 1.01 with narrow cell lumen and Runkel Ratio below 1. Paper produced from the species will be less stiff, more flexible and form lower bulk and well bonded paper.

The Luce Shape Factor and Solid Factor falls in the range obtained for other materials used for pulp and paper (Ogunleye, 2014 and Ogunkunle, 2010). Judging from the Luce Shape Factor and Solid Factor values, *B. vulgaris* is suitable for pulp and papermaking. Since there were no significant variation in all the derived morphological indices among ages and long the culm length, any age and part of the culm may be utilized for pulp and paper.

Chemical content of *B. vulgaris*

Ash content

The ash content of *B. vulgaris* increased with increase in age from age 2 through age 4 and along the culm length from base to top (Table 3). The ash content of *B. vulgaris* is comparable to those reported by Hisham *et al.* (2006) for *G. scortechinii* 1.90% - 3.50%, *P. pubescens*, 1.67% (Ireana, 2010) and *G. scortechinii* 0.88% - 2.86%. High ash is undesirable for pulping as they affect normal alkali consumption and pose problem at recovery of cooking liquor and operational problems in material handling, pulp washing and beating (Kristova and Karar, 1999) as well as interferes with bleaching (Dutt *et al.,* 2009)

Table 3: Variation in the Ash and Extractive content of *B. vulgaris*

Source of Variation		Ash (%)	Cold Water	Hot Water	Alcoho-benzene	10/N Na0H
Age	2	2.36a	5.21a	9.03a	5.30a	41.35a
	3	2.52a	3.83a	9.28a	5.47a	42.76a
	4	2.86a	4.27a	7.89a	5.90a	40.97a
Position	Base	2.35a	3.22a	8.95a	5.17a	42.16a
	Middle	2.72a	4.16a	8.94a	5.05a	39.27a
	Top	2.67a	5.94a	8.30a	6.45a	43.65a

Mean values (n=3); Means with the same letter in a column are not significantly different at ($p \leqslant 0.05$)

Extractive content

Cold and hot water and alcohol-benzene solubility of *B. vulgaris* varies from 1.76% - 6.63%, 4.05% - 11.96% and 3.98% - 7.14%, respectively (Table 3). With an average of 4.44% for cold and 8.73% for hot water and 2.14% for alcohol-benzene solubility. Considerable higher content of soluble compounds of *B. vulgaris* in hot water and dilute alkali may decrease the pulping yield and thus contribute to higher chemical consumption in pulping and higher load in pulping effluent.

The high extractive contents shows that *B. vulgaris* contain more substances like waxes, fats, resins, phytosterols, non-volatile hydrocarbons, low-molecular weight carbohydrates, salts and other water-soluble substances (Cao *et al.,* 2014) which may be converted to pitch and may adversely affect the runnability of process equipment by chocking the paper Fourdrinier wire. High extractive content of *B. vulgaris* may be a problem when considering it for pulp making

The NaOH soluble extractive content in *B. vulgaris* from the three age classes varies from 37.45% to 45.33%. There were no significant differences in the 10/N NaOH soluble extractives among the three ages and along the culm length from base to the top (Table 3). *B. vulgaris* was more soluble in alkaline solution than wood species. The 10/N NaOH solubility of the species indicates the extent of cellulose degradation during pulping and bleaching processes and this has been related to strength and other properties of pulp (TAPPI, 2002). Alkali charge must be kept low in order to preserve the cellulose content and enhance good pulp yield.

The holocellulose content in *B. vulgaris* from the three age series ranged from 74.80% to 82.79% (Table 4). The result of this study compares favourably with those reported by Wahab *et al*. (2013) for *G. levis* (85.08%), *G. wrayi* (84.53), *G. brang* (79.94%) and 74.62% for *G. scortechinii*. Hisham *et al.* (2006) reported a range of 78.60% - 82.30% for *G. scortechinii*, Ireana, (2010) got 74.56% for *B. blumeana* but higher than what was reported for *P. pubescens* (63.14% - 69.94%) by Li *et al.* (2007) and *Eucalyptus camadulensis* (55.6%), *Eucalyptus hybrid* (67.80%) and generally for softwood (67%) and hardwood species (75%) (Ashori, 2006). The holocellulose content of *B. vulgaris* shows that it has potential as an excellent material for pulp and papermaking.

Table 4: Variation in the chemical content of *B. vulgaris*

Source of Variation		Holocellulose	α - Cellulose	Hemicellulose	Klason Lignin
	2	79.81a	75.68a	4.13b	45.90a
Age	3	80.62a	67.07b	13.55a	36.40ab
	4	79.01a	67.62b	11.41a	29.24c
	Base	77.88a	68.38a	9.50a	33.83a
Position	Middle	79.80a	70.81a	9.01a	38.63a
	Top	81.76a	71.18a	10.58a	39.07a

Mean values (n=3); Means with the same letter in column are not significantly different at ($p \leqslant 0.05$)

The cellulose content of *B. vulgaris* in this study varied from 68.38% to 75.68% with the basal portion of age 3 having the lowest and the basal portion of age 2 having the highest (Table 4). Age seem to have apparent influence on the cellulose content with no significant difference along the culm length. The acceptable α-cellulose content for pulp production is above 40%. The range of *B. vulgaris* α-cellulose content (68.38% to 75.68%) were high and desirable and predicts good pulp yield and besides, paper mechanical strength especially tensile strength is directly proportional to cellulose content (Madakadse *et al.,* 1999). Therefore it is satisfactory for pulp production.

The hemicelluloses content of *B. vulgaris* are shown in Table 5. The hemicelluloses content is in the range of 4.13% - 10.58% almost in the same range with 8.66% - 18.88% of *Eucalyptus* spp. (Dutt and Tyagi, 2011). Hemicelluloses content of *B. vulgaris* is similar to that of wood (Gong, 2007). With the range of hemicelluloses better and quality strength paper can be produced.

The range of values (29.24% - 45.90%) for lignin content of *B. vulgaris* (Table 3) fall slighly within those (20.8 – 31.3%) reported for some pulp wood species. These values are high when considering it for pulp and paper production as hardness, bleachability and other pulp properties are associated with lignin content (Malik *et al.,* 2004). The high lignin content indicates a more intense delignification, high liquor consumption and long cooking cycle (Ogunsile and Uwajeh, 2009) as compared to wood (Cao *et al.,* 2014). Therefore, additional pulping time, higher temperature and chemical charge as with soft and hardwood will be required to reach a satisfactory Kappa number (Cao *et al.,* 2014).

CONCLUSION

The densities of *B. vulgaris* were found to vary with age and along the culm length. The suitability of *B. vulgaris* is not guaranteed for pulp and paper based on its high density. The species may be mixed with low density wood or bamboo to complement the disadvantages posed by high bamboo density. No significant variation existed in the fibre dimensions and their derived morphological indices among ages as well as along the culm length. The fibres flexibility, slenderness ratio and Runkel ratio satisfies the requirement for pulp and papermaking. Any portion of the culm from any age may be considered for pulp and paper production. The high holocellulose and cellulose content are desirable and predicts good pulp yield and good paper strength. However, high density, lignin and extractive content may pose problem when considering it for pulp making.

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