ANATOMICAL AND CHEMICAL CHARACTERIZATION OF *ALSTONIA BOONEI* FOR PULP AND PAPER PRODUCTION

ANATOMSKE IN KEMIJSKE LASTNOSTI LESA VRSTE *ALSTONIA BOONEI* ZA PROIZVODNJO CELULOZE IN PAPIRJA

Kojo Agyapong Afrifah[1*], Enoch Adjei-Mensah[1]

─── *Abstract / Izvleček* ───

Abstract: *Alstonia boonei*, an abundant lesser utilized species within the West African Subregion, was evaluated as an alternative raw material for pulp and paper production. The basic density (BD), fibre characteristics [fibre length (FL), fibre diameter (FD), lumen diameter (LD) and wall thickness (WT)], derived anatomical indices [Flexibility Ratio (FR), Slenderness Ratio (SR), Rigidity Coefficient (RC), Luce's Shape Factor (LSF), Solids Factor (SF) and Runkel Ratio (RR)] and chemical composition (lignin, holocellulose, 1% NaOH solubility and ash contents) of *A. boonei* were studied to evaluate variation along the trunk (base, middle and top portions) and ascertain its suitability for pulp and paper production. Significant variations were observed in the density and fibre characteristics along the trunk of the tree. Although the FD was large, the observed adequate FL, thin-wall and large LD implied easy beating of fibres and manufacture of dense, smooth and strong papers. The favourable SF, RR, FR, RC, and LSF values obtained for the fibres would produce papers with suitable burst and tearing strengths and folding endurance. Chemically the lower lignin (< 30%), ash and 1% NaOH solubility and the high holocellulose contents of *A. boonei*, will generate a higher pulp yield. *A. boonei* although a low-density species, will be desirable for pulp and paper production.

Keywords: *Alstonia boonei,* fibre characteristics, lesser utilized species, pulp, paper

Izvleček: Predstavljamo oceno primernosti lesa vrste alstonija (*Alstonia boonei*) kot alternativnega vira za proizvodnjo celuloze in papirja. Vrsta je pogosta v zahodni Afriki, a je manj uporabljana. Proučili smo osnovno gostoto lesa (BD), značilnosti vlaken [dolžino vlaken (FL), premer vlaken (FD), premer lumna (LD) in debelino celične stene (WT)], anatomske indekse [prožnost (FR), vitkost (SR), koeficient togosti (RC), Luceov faktor oblike (LSF), stopnjo masivnosti (lesnatosti) vlaken (SF), Runklovo razmerje (RR)] in kemično sestavo ter lastnosti (vsebnost lignina in holoceluloze, topnost v 1 % NaOH in vsebnost pepela). Ocenili smo njihovo varibilnost vzdolž debla (spodnji, srednji in zgornji del) in ugotovili primernost lesa za proizvodnjo celuloze in papirja. Ugotovljene so bile znatne razlike v gostoti lesa in lastnostih vlaken vzdolž debla. Čeprav je bil premer vlaken velik, dolžina vlaken, tankost sten in veliki premeri lumnov omogočajo primerno formacijo vlaken ter izdelavo gostega, gladkega in močnega papirja. Ugodne vrednosti SF, RR, FR, RC in LSF vlaken bi omogočile izdelavo papirja z ustrezno odpornostjo proti trganju ter prepogibno stabilnostjo. Kemijsko gledano nižja vsebnost lignina (< 30 %), pepela in 1 % topnost v NaOH ter visoka vsebnost holoceluloze v vlaknih *A. boonei* omogočajo večji izkoristek pri izdelavi celulozne kaše (pulpe). Čeprav je *A. boonei* lesna vrsta z nizko gostoto, bi bila primerna za proizvodnjo celuloze in papirja.

Ključne besede: *Alstonia boonei*, značilnosti vlaken, manj uporabljana lesna vrsta, celuloza, papir

1 INTRODUCTION
1 UVOD

Paper is a versatile commodity that contributes to the growth and development of every country, and the level of development of a country can even be related to its paper consumption trends (Darkwa, 1996). The global consumption of paper has been estimated to be around 400 million tons per year and about 7.2 billion trees are harvested to satisfy this need for production of different types of paper (for writing, printing, wrapping, communication, education and packaging) (Tiseo, 2021). Continuous supply of paper to meet these increasing demands would require alternative suitable raw materials to supplement the dwindling traditional raw material sources.

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[1] Department of Wood Science & Technology, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science & Technology, Kumasi, Ghana.
* e-mail: kagyapong@gmail.com

Fibre morphological and chemical compositions are essential in determining the level of efficiency of wood species in pulping and the quality of pulp produced. Therefore, these characteristics are taken into consideration in the deployment of any lignocellulosic material for pulp and papermaking (Omotoso & Ogunsile, 2009; Ajuziogu et al., 2019; Ajuziogu & Ojua, 2020). Fibre morphological characteristics such as fibre length, wall thickness, lumen diameter and fibre diameter have been shown to differ widely in species and exert diverse influences on the fibre strength, inter-fibre bonding, strength properties and bulk density of the produced papers (Larsson et al., 2018). Woods with long fibres produce papers with high tear strength and are desirable in the paper industry (Anthonio & Antwi-Boasiako, 2017). Fibre wall thickness also affects the tensile and burst strengths as well as folding endurance of paper, which is the durability of paper when repeatedly folded under constant load (Ofosu et al., 2020). In addition to the absolute fibre dimensions, fibre derived indices such as Runkel Ratio, Slenderness Ratio, Coefficient of Rigidity, Flexibility Coefficient, Luce's Shape Factor and Solids Factor help derive better judgement about the suitability of wood for pulp and papermaking (Ofosu et al., 2020). For instance, wood species with a high Runkel Ratio usually have stiff fibres, poor bonding ability and produce bulkier paper, and vice versa (Ajuziogu et al., 2019).

Analysis of the chemical components is also necessary for the selection of the right material for pulp and papermaking. The basic structure of all woody biomass consists of holocellulose (cellulose and hemicelluloses) and lignin. These constitute about 90% of dry matter in wood, with the remaining being extractives and ash. The proportion of these wood constituents varies among species (Dehkhoda, 2008). High holocellulose content is desirable for high quality and yield of pulp (Zhan et al., 2015; Afrifah et al., 2020). By contrast, lignin is undesirable for pulp and papermaking, and has to be removed due to its negative impact on fibre strength and pulp yield (Tran, 2006).

Wood properties and quality affect the quality of pulp and the paper made from it. A classic example is the preference for softwood pulping over hardwoods because softwoods mainly contain tracheids and reputedly produce stronger papers than hardwood fibres. However, some studies have shown that certain hardwood pulps have some strength properties (such as tear index, tensile resistance, folding endurance) equal to or even greater than those of softwood pulps (Shackford, 2003). Therefore, it would be beneficial to assess some hardwood species to augment softwood pulps, especially the lesser-utilized ones such as *Alstonia boonei*.

Alstonia boonei, from the family Apocynaceae, is a pioneer tree very common on old farms and also in the swampy forest from Senegal through Ethiopia to Congo (Hawthorne, 2006). This species provides a myriad of ecosystem services such as firewood and timber. Its sapwood, which cannot be differentiated from the heartwood, is very wide (up to 200 mm), soft, and light in weight when dried. The wood is nearly yellowish-white when freshly cut, but darkens on exposure. It has a low lustre and no characteristic odour or taste. The wood is also liable to staining. It works easily with hand and machine tools, but because of its softness it is essential to use tools with sharp cutting edges. The wood can be glued, stained and polished satisfactorily (Orwa et al., 2009).

The basic density, anatomical properties and chemical composition that determine the pulp yield, pulp and paper quality of the wood of *A. boonei* are not well documented, even though it is an abundant species. This study therefore analysed these pulping characteristics to ascertain the potential of *A. boonei* for pulp and papermaking.

2 MATERIALS AND METHODS
2 MATERIALI IN METODE

2.1 SAMPLE COLLECTION AND PREPARATION
2.1 IZBOR IN PRIPRAVA VZORCEV LESA

Three trees of *A. boonei* all about 12 m high and 50 cm girth were collected from the farm of the Faculty of Renewable Natural Resources (FRNR) of the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana (6°39'53.66" N, 1°34'16.88" W). Disc samples (60 cm in height) were taken from the base (1 m from the ground up to 4 m), middle (4 m to 7 m) and top (7 m to 11 m) portions of the tree for processing, chemical and anatomical observations (Figure 1).
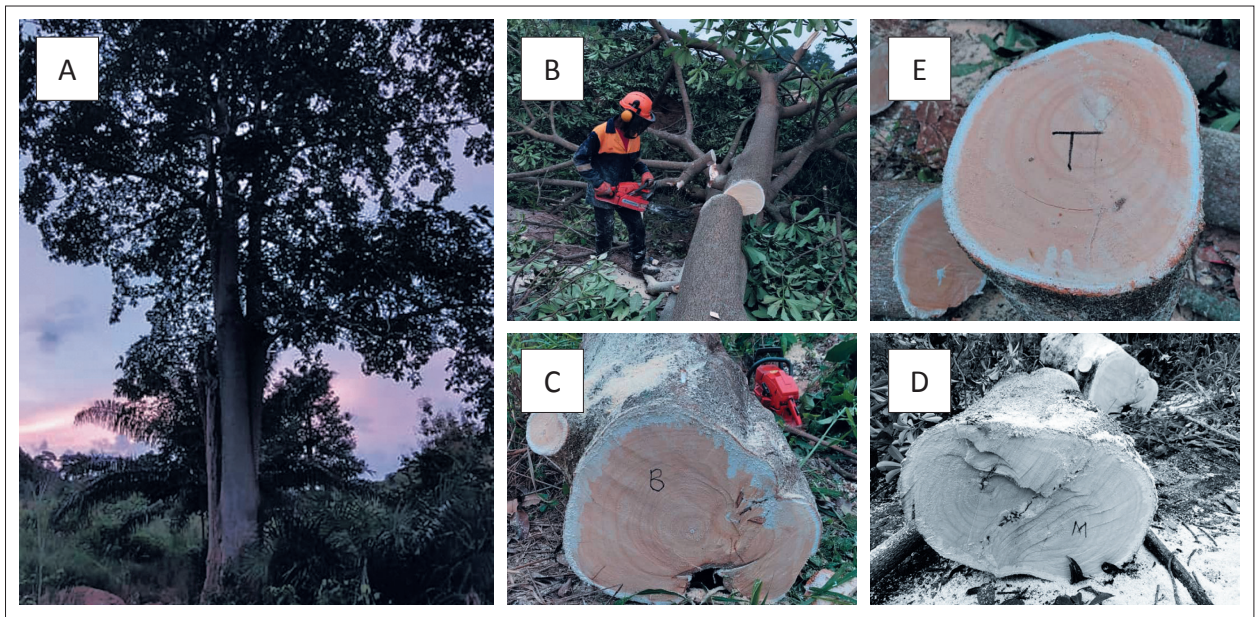
Figure 1. *Alstonia boonei*: living tree (A), harvested (B) and processed into base (C), middle (D) and top portions (E).
Slika 1. *Alstonia boonei*: rastoče drevo (A), posek drevesa (B) in krojenje debla na spodnji (C), srednji (D) in zgornji del (E).

2.2 BASIC DENSITY
2.2 OSNOVNA GOSTOTA

The test samples were processed into 20×20×20 mm sizes. A total of 54 samples were prepared from each tree. The dimensions of the 18 samples each from the base, middle and top portions of each tree were measured in all three principal directions (radial, tangential and longitudinal) and weighed before soaking in tap water for 24 hours.

The saturated volumes and wet weight of samples were determined after 24 hours. The samples were then oven-dried at 103±2 °C in a forced air oven to a constant weight after which dried weights and volumes of the samples were measured using a scale and electronic digital callipers, respectively. The basic density of *A. boonei* was determined according to TAPPI 258 om-11 (2011) using the relation (Equation 1);

2.3 MACERATION
2.3 MACERACIJA

Match-stick sized wood samples (5 each) were taken from the top, middle and base portions of the wood of each tree and placed into labelled test tubes. They were flooded with one-part Hydrogen Peroxide (6% w/v) to one-part Glacial Acetic Acid (1:1, v/v) and then incubated at 65 °C for six days. Wood samples were fully macerated at the end of the 6-day incubation period.

2.4 DETERMINATION OF FIBRE DIMENSIONS AND ANATOMICAL RATIOS
2.4 DIMENZIJE IN ANATOMSKA RAZMERJA VLAKEN

Images of fibres for fibre dimensions and anatomical ratios were captured from slides of macerated wood under an electronic microscope using Micron (USB2) (Figure 2). In all 75 straight fibres,

$$Basic\ Density = \frac{Oven - Dry\ Weight\ of\ Sample}{Saturated\ Volume}\ [kg\ /\ m^3] \tag{1}$$
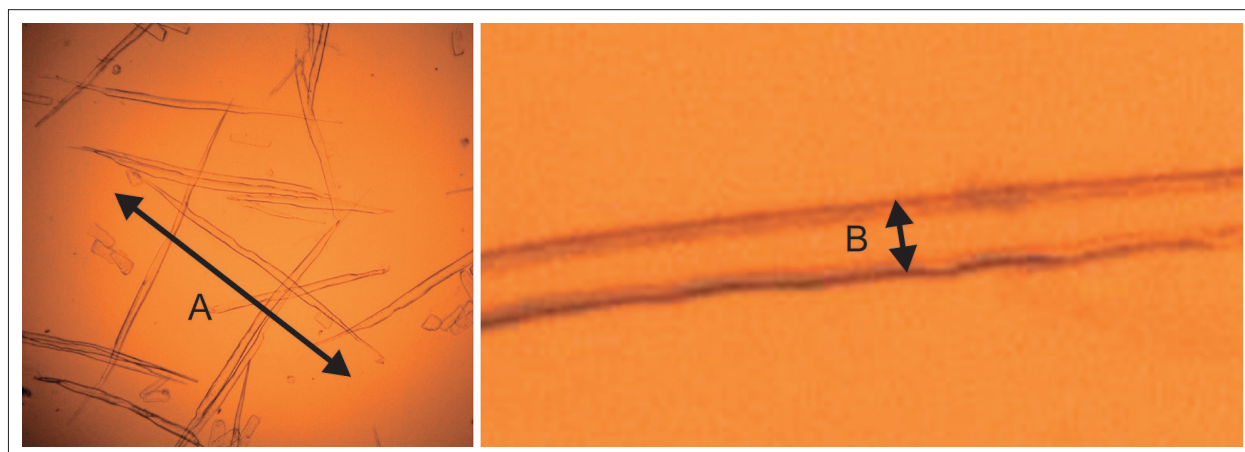
Figure 2. Micrographs of wood fibres of *Alstonia boonei* for measuring length (A) and diameter of fibres (B).
Slika 2. Mikrografije vlaken lesa vrste *Alstonia boonei* in merjenje dolžine (A) in premera vlakna (B).

25 from each portion (base, middle and top) were assessed per tree for fibre diameter, length, wall thickness, and lumen diameter using ImageJ software.

The determined fibre dimensions were incorporated in Equations 2 to 7 to calculate Slenderness, Runkel and Flexibility Ratios, Coefficient of Rigidity, Luce's Shape Factor and Solids Factor (Varghese et al., 2000; Hegde and Varghese, 2008; Rana et al., 2009; Afrifah et al., 2020).

2.5 CHEMICAL ANALYSIS
2.5 KEMIČNA ANALIZA
2.5.1 Preparation of Extractive-Free Wood
2.5.1 Priprava lesa brez ekstraktivov

Extractive-free wood was prepared for lignin and holocellulose determination according to ASTM D 1105 – 96 (2013). Air-dried samples of the base, middle and top portions of *A. boonei* were milled into powder with a Christy & Norris 8" Lab Mill. Extractive free samples of each portion were

$$Slenderness\ Ratio = \frac{Fibre\ Length}{Fibre\ Diameter} \tag{2}$$

$$Flexibility\ Ratio = \frac{Lumen\ Diameter}{Fibre\ Diameter} \tag{3}$$

$$Runkel\ Ratio = \frac{2 \times Cell\ Wall\ Thickness}{Lumen\ Diameter} \tag{4}$$

$$Coefficient\ of\ Rigidity = \frac{Fibre\ Wall\ Thickness}{Fibre\ Diameter} \tag{5}$$

$$Luce's\ Shape\ Factor = \frac{[(Fibre\ Diameter)^2 - (Fibre\ Lumen\ Diameter)^2]}{[(Fibre\ Diameter)^2 + (Fibre\ Lumen\ Diameter)^2]} \tag{6}$$

$$Solids\ Factor = \left[(Fibre\ Diameter)^2 - (Fibre\ Lumen\ Diameter)^2 \right] \times Fibre\ Length\ [\mu m^3] \tag{7}$$

prepared by placing a suitable quantity (10 g) of the powder in a Soxhlet extraction apparatus ensuring that the samples did not extend above the top of the siphon tube. The sample was extracted for four hours with a ratio of 1:2 alcohol acetone mixture in the Soxhlet extraction apparatus, after which the sample was washed with alcohol and extracted with 95% of alcohol (ethanol) for another four hours or longer until the ethanol siphoned over colourless. The sample was removed from the thimble and allowed to dry in the air until it was free of alcohol. The sample, free of alcohol, was then placed in the thimble and this time extracted with distilled water for six hours. The air-dried material after hot water extraction is the extractive free material which was used for further chemical composition analysis.

2.5.2 Lignin Content Determination
2.5.2 Določanje vsebnosti lignina

Lignin contents for the three portions of *A. boonei* studied were determined in accordance with ASTM D 1106 – 96 (2007). The extractive free specimen of 1 g was placed in a 50 ml beaker. The sample was mixed with 15 ml of cold (15 °C) 72% H_2SO_4, stirred continuously for at least 1 minute and placed in a water bath at 20 °C for 2 hours. The contents of the beaker were diluted in a 1-litre Erlenmeyer flask to 3% H_2SO_4 by adding 560 ml of distilled water and boiling for 4 hours. The volume of the mixture was maintained nearly constant by occasionally adding hot water. This was followed by filtration of insoluble materials, washing with 500 ml of hot water and oven drying for 2 hours at 105 °C until constant weight. Simultaneously, 1 g of unextracted moisture free sample was oven dried at 105 °C until constant weight. The percentage lignin content was calculated as;

$$Lignin = \frac{Dry\,Weight\,of\,Lignin}{Oven\,Dry\,Weight\,of\,Sample} \times 100\,[\,\%\,] \quad (8)$$

2.5.3 Holocellulose Content Determination
2.5.3 Vsebnost holoceluloze

Holocellulose contents in the three portions of the trees were determined in accordance with the methods presented in ASTM D 1104 – 56 (1978). For each material, a mixture of 8.6 g of sodium acetate, 5.7 ml of ethanoic acid, 6.6 g of sodium chlorite and 180 ml of distilled water was placed in a 250 ml conical flask and mixed with 2 g of its extractive free sample. The flask with its contents were covered and placed in a water bath in a fume chamber at a temperature of 60 °C for about 4 hours. The liquid in the flask turned yellowish while the sample turned whitish. The flask contents were filtered with weighed filter paper, washed with distilled water and oven-dried at 105 °C for 5 hours. Percentage holocellulose was calculated as follows (Equation 9);

$$Holocellulose = \frac{Oven\,Dry\,Weight\,of\,Residue}{Oven\,Dry\,Weight\,of\,Sample} \times 100\,[\,\%\,] \quad (9)$$

2.5.4 Ash Content Determination
2.5.4 Vsebnost pepela

Ash is the material remaining after the sample is ignited at a specified temperature. The percentage ash content of *A. boonei* was determined in accordance with ASTM D 1102 – 84 (2007). A weighed preheated crucible plus 2 g of specimen were dried in an oven at 100 to 105 °C to a constant weight. The crucible and contents were then ignited to 580 to 600 °C in a muffle furnace until all the carbon was eliminated. Heating and cooling were done until constant weight was recorded. The percentage of ash, based on the weight of the moisture-free wood, was calculated for the 3 replicates of each section of the tree with Equation 10;

$$Ash = \frac{w_1}{w_2} \times 100\,[\,\%\,] \quad (10)$$

where: W_1 = weight of ash;
W_2 = weight of oven-dry sample.

2.5.5 1% Caustic Soda (NaOH) Solubility Determination
2.5.5 Topnost v 1 % natrijevem hidroksidu (NaOH)

The 1% NaOH solubility determination was conducted on *A. boonei* in accordance with ASTM

D 1109 – 84 (2007). Two grams of moisture-free wood was mixed with 100 mL of 1% NaOH solution. The mixture was placed in a water bath boiling steadily and stirred at 10, 15, and 25 min intervals. It was then filtered and washed with 100 mL of hot water, then with 50 mL of acetic acid (10%) and thoroughly with hot water. The residue was dried at 103 ± 2 °C, cooled in a desiccator, and weighed. The weight percentage of matter soluble in 1% NaOH solution on moisture-free basis was then calculated for the 3 replicates of each section of the tree using Equation 11.

$$Matter\ soluble\ in\ 1\ \%\ caustic\ soda = \frac{W_1 - W_2}{W_1} \times 100\ [\ \%]$$
(11)

where: W_1 = weight of moisture-free wood specimen prior to test;
  W_2 = weight of dried specimen after treatment with 1% NaOH solution.

2.6 DATA ANALYSIS
2.6 ANALIZA PODATKOV

Data obtained from the study were set up in a completely randomized design and subjected to analysis of variance (ANOVA) using GenStat Release 10.3 (2011) and GraphPad Prism 5 (2007) analytical software. All post hoc mean separations were done using Fisher's protected least significant difference (LSD) at a maximum type I error rate (α) of 0.05.

3 RESULTS
3 REZULTATI

The basic densities for the base, middle and top portions of *A. boonei* are shown in Table 1. The mean basic density was 267.75 ± 36.01 kg/m³ with the base portion recording the highest (314.95 ± 10.2 kg/m³), followed by the middle portion (252.25 ± 14.7 kg/m³) and the top portion (236.04 ± 6.6 kg/m³) being the least (Table 1). Analysis of variance indicated significant differences ($p < 0.05$) between the three portions.

Table 1. Basic density and fibre characteristics of wood along the trunk of *Alstonia boonei*
Preglednica 1. Osnovna gostota in značilnosti vlaken vzdolž debla lesa vrste *Alstonia boonei*

Parameter	Portion		
	Base	Middle	Top
Basic Density (kg/m³)	314.95 ± 10.2[a]	252.25 ± 14.7[b]	236.04 ± 6.6[c]
Fibre Length (µm)	1421.38 ± 163.3[a]	1338.89 ± 218.5[b]	1184.99 ± 150.6[c]
Fibre Diameter (µm)	48.97 ± 6.3[a]	42.27 ± 7.9[b]	37.77 ± 5.6[c]
Lumen Diameter (µm)	33.18 ± 5.5[a]	27.71 ± 5.5[b]	23.00 ± 5.0[c]
Wall Thickness (µm)	7.90 ± 3.7[a]	7.28 ± 4.1[a]	7.38 ± 2.9[a]
Slenderness Ratio	29.51 ± 5.2[a]	32.60 ± 7.2[a]	31.92 ± 5.6[a]
Runkel Ratio	0.51 ± 0.3[a]	0.57 ± 0.4[a]	0.70 ± 0.4[a]
Flexibility Ratio	0.69 ± 0.1[a]	0.67 ± 0.2[a]	0.61 ± 0.1[a]
Rigidity Coefficient	0.16 ± 0.1[a]	0.16 ± 0.1[a]	0.19 ± 0.1[a]
Luce's Shape Factor	0.36 ± 0.2[a]	0.384 ± 0.2[a]	0.45 ± 0.2[a]
Solids Factor (µm³)	$1.83 \times 10^{-6} \pm 9.0 \times 10^{-5a}$	$1.42 \times 10^{-6} \pm 9.3 \times 10^{-5b}$	$1.08 \times 10^{-6} \pm 5.6 \times 10^{-5b}$

±: Standard deviation
Means with different superscripts denote significant differences and vice-versa at p < 0.05
±: Standardni odklon
Srednje vrednosti z različnimi nadnapisi pomenijo statistično značilne ali neznačilne razlike pri p < 0,05

An average fibre length (FL) of 1315 μm was observed for *A. boonei* with the base, middle and top portions of the tree recording 1421.38 ± 163.3 μm, 1338.89 ± 218.5 μm, and 1184.99 ± 150.6 μm, respectively. Highest values of fibre and lumen diameters were observed for the base portion (48.97 ± 6.3 μm, 33.18 ± 5.5 μm, respectively) of *A. boonei* (Table 1) with significant differences occurring between the three portions studied ($p < 0.05$). The fibre wall thickness ranged between 7.28 ± 4.1 to 7.90 ± 3.7 μm without significant differences between the three portions.

With the exception of the Solids Factor, there were no significant differences between the three studied portions of *A. boonei* for all the derived pulping properties or indices (Table 1). The base portion recorded the highest Solids Factor ($1.83 \times 10^{-6} \pm 9.0 \times 10^{-5}$ μm^3) with the middle and top portions recording equivalent values of $1.42 \times 10^{-6} \pm 9.3 \times 10^{-5}$ μm^3 and $1.08 \times 10^{-6} \pm 5.6 \times 10^{-5}$ μm^3, respectively (Table 1).

The results for the chemical compositions are presented in Table 2. The range of lignin, holocellulose, ash and 1% NaOH solubility contents for the base, middle and top portions of the trees were 25.48 – 25.95%, 66.47 – 67.58%, 1.08 – 1.35% and 10.55 – 13.29%, respectively. Statistical analysis indicated no significant differences in chemical contents at $p < 0.05$ for the portions of the trees studied (Table 2).

Table 2. Chemical compositions of wood along the trunk of *Alstonia boonei*

Preglednica 2. Kemijske lastnosti lesa vzdolž debla vrste *Alstonia boonei*

Chemical Properties	Portion		
	Base	Middle	Top
Lignin (%)	25.95 ± 0.1[a]	25.48 ± 0.1[a]	25.86 ± 0.12[a]
Holocellulose (%)	67.51 ± 1.95[a]	66.47 ± 1.85[a]	67.58 ± 2.71[a]
Ash (%)	1.35 ± 0.38[a]	1.09 ± 0.01[a]	1.08 ± 0.01[a]
1% NaOH solubility (%)	11.95 ± 2.7[a]	10.55 ± 2.8[a]	13.29 ± 1.6[a]

±: Standard deviation
Means with different superscripts denote significant differences and vice-versa at p < 0.05
±: Standardni odklon
Srednje vrednosti z različnimi nadnapisi pomenijo statistično značilne ali neznačilne razlike pri p < 0,05

4 DISCUSSION
4 DISKUSIJA
4.1 BASIC DENSITY
4.1 OSNOVNA GOSTOTA

Wood density is a complex physical property related to both the anatomical structure and the chemical composition of wood (Santos et al., 2012). The density of wood allows the prediction of a number of properties of wood, including the yield of pulp per unit volume (Adi et al., 2014). Generally, studies have shown that high density wood species give greater pulp yield (Bowyer et al., 2003). For instance, in a study of *Eucalyptus globulus* by Santos et al. (2008), "*E. globulus* with the highest wood basic density exhibited a much higher pulp yield (58.7%) than the *E. globulus* with the lowest wood basic density (49%)". Species of wood with less than 400 kg/m^3 basic density are classified as soft and low-density materials (Petro et al., 2016). Consequently, it is anticipated that pulp yield from *A. boonei* (mean basic density of 267.75 ± 36.01 kg/m^3) would be low, with the base portion which had the highest basic density (314.95 ± 10.2 kg/m^3) producing higher pulp yield.

4.2 FIBRE CHARACTERISTICS OF *A. BOONEI*
4.2 ZNAČILNOSTI VLAKEN LESA *A. BOONEI*
4.2.1 Fibre Length
4.2.1 Dolžina vlaken

Fibre characteristics and anatomical ratios can be used to predict the suitability of wood as raw material for pulp and papermaking (Adi et al., 2014).

The fibre lengths (1184.99 ± 150.6 to 1421.38 ± 163.3 µm) were within the range for hardwood fibres (700.0 to 1600 µm) and equivalent to those of industrial pulping species such as *Acacia mangium* Wild. (1,101 µm/1.101 mm) (Nugroho et al., 2012; Kiaei et al., 2014; Ofosu et al., 2020). Pulps with long fibres produce strong papers due to improved interlocking between the fibres (Ashraf et al., 2016; Ofosu et al., 2020). Consequently, the base portion with the longest fibres may produce stronger papers than the middle and top portions.

4.2.2 Fibre Diameter
4.2.2 Premer vlaken

Fibre diameters (FD) reported for hardwoods used for papermaking range between 20 – 40 µm (San et al., 2016). The observed mean FD for this study was higher (43.01 µm) with only the top portion (37.77 µm) falling within the range (Table 1). Fibres with a small diameter and thin wall are preferred for improved flexibility, high contact surfaces for fibres, good paper density and formation of stronger paper (Ashraf et al., 2016; Ofosu et al., 2020). In contrast, wood with large fibre diameters, as observed in the current study (37.77 - 48.97 µm), may produce papers with high void volume, and a bulky, coarse and poor printing surface (Kiaei et al., 2014).

4.2.3 Fibre Lumen Diameter and Wall Thickness
4.2.3 Premer lumnov in debelina
celičnih sten vlaken

The papermaking properties of wood are also influenced by the relationship between fibre lumen diameter and wall thickness. Fibres with lumen size greater than the double wall thickness are classified as thin-walled and produce papers that are dense, smooth and have high tensile and bursting strengths (Ofosu et al., 2020). By contrast, fibres with lumen size less than the double wall thickness are classified as thick-walled, while those having intermediate characteristics are classified as thin-to-thick-walled (Ofosu et al., 2020). Thick-walled fibres produce bulky papers with poor printing surface and poor strength properties. The results of the current study indicate that fibres of *A. boonei* are thin-walled (Table 1) and suitable for the manufacture of dense, smooth and strong papers. Additionally, because of the large fibre lumen of *A. boonei,*

it can be beaten easily due to improved liquid penetration into empty spaces and flattening of the fibres (Sharma et al., 2011; Ogunleye et al., 2017).

Differences were observed in the FL, FD, and LD morphological properties along the trunk of the *A. boonei*. Higher values were recorded in the base portion, and they decreased along the trunk to the top portion (Table 1). Similar results have been reported by several researchers who ascribed it to variations in the growth of the wood producing cells (e.g., variations in the length of the cambial initials as the cambium ages) along the trunk of the tree with the juvenile wood portions having lower fibre characteristics (Izekor & Fuwape, 2011; Anthonio & Antwi-Boasiako, 2017; Ofosu et al., 2020). Generally, the observed fibre characteristics of *A. boonei* indicate that it will be a suitable species for the manufacture of paper with good physical and mechanical properties.

4.3 MORPHOLOGICAL CHARACTERISTICS OF FIBRES
4.3 MORFOLOŠKE LASTNOSTI VLAKEN
4.3.1 Slenderness Ratio
4.3.1 Razmerje vitkosti

A fibrous material having an SR less than 33 has been reported as not suitable for quality pulp and paper production (Sharma et al., 2018; Ofosu et al., 2020). Low SR is indicative of short thick fibres which do not produce good surface contact for enhanced fibre-to-fibre bonding, thus reducing tearing resistance, bursting strength and double folding resistance of papers (Ogbonnaya et al., 1997; Sangumbe et al., 2018; Ofosu et al., 2020). The result for this study indicated low SR values for the wood of *A. boonei* (29.51 to 32.60) (Table 1), which were lower than the reported suitable range of 40 - 60 for hardwoods (Sangumbe et al., 2018). Based on the SR, *A. boonei* does not meet the desired requirement for a very good pulp and papermaking material.

4.3.2 Runkel Ratio
4.3.2 Runklovo razmerje

The Runkel ratio (RR) of a material is an important parameter for predicting the stiffness, flexibility and conformability of its paper (Ogunleye et al., 2017). RR also indicates the propensity for fibre-to-fibre bonding (Biermann, 1996; Bow-

yer et al., 2003). An RR of less than 1 is the best for quality paper, while greater than one results in papers of poor quality which are stiff, less flexible and bulky (Veveris et al., 2004; Ogunleye et al., 2017; Ofosu et al., 2020). Okoegwale et al. (2020) also claimed that when making paper with hardwood fibres an RR lower than 1 is desirable for good conformability and fibre-to-fibre contact for good bonding in paper.

Table 1 shows that the RR of the wood of *A. boonei* is less than 1, and thus can be used to produce quality paper. In line with the report of Ekhuemelo and Tor (2013) and Okoegwale et al. (2020), when RR is less than 1, it indicates that the cell wall is thin and the fibres are most suitable for paper production, while an RR of 1 indicates that the cell wall has medium thickness and is suitable for paper production, and an RR greater than 1 shows that the fibres have thick walls and are least suitable for paper production. The RR for *A. boonei* ranged between 0.51 to 0.71 (Table 1). These values were statistically not different for the three portions of the tree and fell within the range (0.4 to 0.7) that has been reported for hardwoods (Smook, 1997). This implies that *A. boonei* may produce paper with moderate burst and tensile indices.

4.3.3 Flexibility Ratio
4.3.3 Razmerje prožnosti

Flexibility Ratio (FR) has been reported to influence the burst, tearing and tensile strengths, as well as folding endurance of paper (Ververis et al., 2004; Sangumbe et al., 2018). Amidon (1981) also asserted that FR is the key to the development of the paper properties that affect printing. Fibres can be classified based on their FR into highly elastic (FR ≥ 0.75), elastic (FR = 0.50 − 0.75), rigid (FR = 0.3 to 0.5) and very rigid (FR = ≤ 0.3) (Ververis et al., 2004; Sharma et al., 2018; Ofosu et al., 2020). Elastic fibres produce writing and printing papers while rigid fibres are suitable for cardboards and packaging papers (Dutt & Tyagi, 2011).

Studies have shown that the flexibility index for hardwoods ranges between 0.55 to 0.7 and that for softwood averages around 0.75. According to Istas et al. (1954) and Takeuchi et al. (2016), fibres having an FR between 0.5 and 0.7 can easily collapse and be flattened during beating and paper drying, providing a large surface area for good bonding

leading to the production of good paper with high strength properties. The FR obtained in this study fell within that for hardwoods and ranged from 0.61 for the top portion to 0.69 for the base section of the trees. The wood of *A. boonei* can therefore be classified as having elastic fibres which can be used for making papers with high burst and tearing strengths and folding endurance.

4.3.4 Rigidity Coefficient
4.3.4 Koeficient togosti

This fibre property is important for determining the tensile, bursting and tearing strength properties of paper (Afrifah et al., 2020). A low rigidity coefficient (RC) is preferable for fibres producing quality papers with high tensile and bursting strength properties (Takeuchi et al., 2016). Research has shown that the desired RC for softwood and hardwood pulp are 13 to 20 (0.13 − 0.2) and 15 to 35 (0.15 − 0.35), respectively (Istek et al., 2009; Tutus et al., 2015). The RC reported for the portions of *A. boonei* ranging from 0.16 ± 0.1 to 0.19 ± 0.1 (Table 1) fall in the range of both softwood and hardwood pulps, and hence may produce papers with better strength properties.

4.3.5 Luce's Shape Factor
4.3.5 Luceov faktor oblike

Luce's Shape Factor (LSF) is an index for the resistance of pulp to beating. Therefore, a low value for LSF indicates a decreased resistance to beating in papermaking (Luce, 1970). Pirralho (2014) reported that LSF ranged from 0.39 to 0.74 in several *Eucalyptus* species used in making paper. Ohshima et al. (2005) also reported mean values of LSF of 0.37 for *E. camaldulensis* and 0.42 for *E. globulus*. The values for LSF in *A. boonei* ranging from 0.36 ± 0.2 to 0.45 ± 0.2 (Table 1) are comparable to those of *Eucalyptus* species which is suitable for pulp and papermaking.

4.3.6 Solids Factor
4.3.6 Stopnja masivnosti (lesnatosti) vlaken

Ona et al. (2001) reported values for the Solids Factor (SF) of 46×10³ μm³ and 91.2×10³ μm³ for 14-year-old *E. camaldulensis* and *E. globulus*, respectively. In addition, they found a significant negative relationship between SF and sheet density. The mean values for the SF observed for *Alstonia*

boonei (i.e. $1.08 \times 10^{-6} \pm 5.6 \times 10^{-5}$ µm^3 to $1.83 \times 10^{-6} \pm 9.0 \times 10^{-5}$ µm^3) were low (Table 1) and thus will positively influence the breaking length and sheet density of papers (Afrifah et al., 2020). Additionally, fibres of *Alstonia boonei* with these low SF will produce papers with good strength properties (Ofosu et al., 2020).

4.4 CHEMICAL ANALYSIS
4.4 KEMIČNA ANALIZA
4.4.1 Lignin Content
4.4.1 Vsebnost lignina

Lignin is undesirable in pulping and bleaching, and has to be removed. The removal of lignin requires high amounts of energy and chemicals (Zhan et al., 2015; Riki et al., 2019). High lignin content has greater bonding strength and creates difficulties in breaking fibre bonds and removing lignin during pulping (Tran, 2006). By contrast, lower lignin content implies greater fibre strength, higher yield of pulp, and the production of good quality paper (Enayati et al., 2009). The reported lignin contents of softwoods and hardwoods range between 21 – 37% and 14 – 34%, respectively (Kiaei et al., 2014; Zawawi et al., 2014). Table 2 presents the lignin contents at the base (25.95%), middle (25.48%) and top (25.86%) portions of the trunk of *A. boonei*. Although the results indicate a variation in lignin content from the base to the top of the trunk, there were no statistical differences ($p > 0.05$) between the various portions. Generally, the observed lignin contents for this study were lower (< 30%), and hence low amounts of energy and chemicals are required for its removal (Ververis et al., 2004).

4.4.2 Holocellulose Content
4.4.2 Vsebnost holoceluloze

Holocellulose is the combined composition of cellulose and hemicelluloses (Rowell, 2012). Wood with high holocellulose content is preferred for pulp and paper production, since it generates a higher pulp yield. Studies have shown that holocellulose content constitutes about 65 – 70% of the dry weight of plants (Zhan et al., 2015). The base (67.51 ± 1.95%), middle (66.47 ± 1.85%) and top (67.58 ± 2.71%) portions of *A. boonei* had relatively high holocellulose contents (Table 2). Analyses indicated no significant differences ($p=$

0.4314) in the holocellulose contents between the base, middle and top portions of the species. It can therefore be inferred that any portion of the wood of *A. boonei* would yield a high quantity of pulp for papermaking.

4.4.3 Ash Content
4.4.3 Vsebnost pepela

The inorganic constituent of lignocellulosic material is usually referred to as ash, and this is the residue remaining after combustion of organic matter at a temperature of 525 ± 25ºC. The ash content consists mainly of metal salts such as silicates, carbonates, oxalates and phosphate of potassium, magnesium, calcium, iron and manganese as well as silicon. High ash content is undesirable during refining and recovery of the cooking liquor (Rodríguez et al., 2008). High silica content, for instance, can complicate the recovery of chemicals during pulping. Nitrogen in the spent liquor can lead to generation of NOx in the chemical recovery furnace, while potassium in the fibre can combine with chlorine to form KCl, with a corrosive effect on metal parts in the furnace and boiler (Salmenoja & Makela, 2000). Low ash content, on the other hand, contributes to high pulp yield (López et al., 2004). The mean ash content (1.17%) observed in this study is low, consequently *A. boonei* is a suitable material for pulp and paper production and would result in high pulp yield.

4.4.4 1% Caustic Soda (NaOH) Solubility
4.4.4 Topnost v 1 % natrijevem hidroksidu (NaOH)

The solubility in 1% NaOH indicates the extent of fibre degradation from fungi during the pulping process. As the wood decays, the percentage of alkali-soluble material increases in proportion to the decrease in pulp yield. Hence high 1% NaOH solubility leads to low production of chemical pulp (Onggo & Astuti, 2005). The mean solubility observed for *A. boonei* is 11.93%, ranging between 10.55% to 13.29% for the base, middle and top portions of the trees studied (Table 2). This result is similar to those of *Pinus kesiya* (12.2%), *Eucalyptus cloeziana* (10.9%) and *Eucalyptus deglupta* (13.6%) (Tutus et al., 2015), but better than that of *Gmelina arborea* (15.1%) in terms of fibre degradation during pulping.

5   CONCLUSIONS
5   SKLEPI

Investigations on the morphological characteristics of fibres of the wood of *Alstonia boonei* revealed it as a potential species for pulp and paper production. Pulp yield is anticipated to be highest at the base portion due to its high basic density. Anatomically, the large fibre diameter implied the potential production of bulky paper with a high void volume and a coarse and poor printing surface. In contrast, the observed adequate fibre length, thin-wall and large lumen diameter would result in easy beating of fibres and manufacture of dense, smooth and strong papers. Derived anatomical indices showed low SR values indicating low tearing resistance, bursting strength, and double folding resistance of any papers produced. However, the obtained RR, FR, RC, SF and LSF values of the fibres classify it as elastic, which can produce papers with high burst and tearing strengths and folding endurance, with a quality printing surface. Chemically, the lower lignin content observed implies that less amounts of energy and chemicals will be required for its removal. The high holocellulose content, low ash content and adequate 1% NaOH solubility would result in high pulp yield, making *A. boonei* a suitable material for pulp and paper production.

6   SUMMARY
6   POVZETEK

Svetovna poraba papirja narašča zaradi povečevanja števila prebivalcev (Tiseo, 2021). Predvidevamo, da bo pomanjkanje lesa za pridobivanje celuloze ena od večjih težav, ki bo ovirala napredek papirne industrije (Ververis et al., 2004). Čeprav se trenutno za proizvodnjo celuloze izkoriščajo tudi drugi nelesni vlaknati materiali, je les zaradi ugodnih lastnosti še vedno glavna surovina za proizvodnjo celuloze in papirja (Pearson, 1998). Anthonio in Antwi-Boasiako (2017) navajata, da bi z raziskavami potenciala manj uporabljanih tropskih listavcev za proizvodnjo celuloze lahko razširili bazo virov za industrijo celuloze in papirja. Za stalno oskrbo s papirjem, ki bi zadovoljila naraščajoče potrebe, potrebujemo primerne alternativne in trajnostne materiale, ki bi dopolnili in nadomestili pomanjkanje tradicionalnih virov.

V tej študiji smo preučili primernost lesa alstonije (*Alstonia boonei*), ki je bila doslej malo znana za proizvodnjo papirja. Raziskali smo osnovno gostoto (BD), lastnosti vlaken [dolžina vlaken (FL), premer vlaken (FD), premeri lumnov (LD) in debeline celičnih sten (WT)], anatomske indekse [prožnost (FR), vitkost (SR), koeficient togosti (RC), Luceov faktor oblike (LSF), stopnjo masivnosti (lesnatosti) vlaken (SF), Runklovo razmerje (RR)] ter kemično sestavo in lastnosti (lignin, holoceluloza, topnost v 1 % NaOH in vsebnost pepela). Les *A. boonei* smo preučevali na različnih delih debla (spodnji, srednji in zgordnji del), da bi ocenili variabilnost proučenih parametrov vzdolž debla.

Vzorci lesa *A. boonei*, uporabljeni za študijo, so bili pridobljeni na farmi FRNR (Faculty of Renewable Natural Resources), KNUST (Kwame Nkrumah University of Science and Technology) v Gani.

Določitev osnovne gostote, karakterizacija vlaken in kemična analiza so bili opravljeni skladno s TAPPI 258 om-11 (2011), IAWA (1989), ASTM D 1105 - 96 (2013), ASTM D 1106 - 96 (2007), ASTM D 1104 - 56 (1978), ASTM D 1102 - 84 (2007) in ASTM D 1109 - 84 (2007). Pridobljene podatke smo analizirali z analizo variance (ANOVA) z analitičnima programoma GenStat Release 10.3 (2011) in GraphPad Prism 5 (2007). Post hoc analiza je bila opravljena z uporabo Fisherjeve najmanjše značilne razlike (LSD) pri stopnji napake tipa I (α) 0,05.

Povprečna osnovna gostota lesa je bila 267,75 ± 36,01 kg/m^3, pri čemer je bila največja gostota zabeležena v spodnjem delu (314,95 ± 10,2 kg/m^3), sledila je gostota v srednjem delu (252,25 ± 14,7 kg/m^3), najmanjša pa je bila v zgornjem delu debla (236,04 ± 6,6 kg/m^3) (preglednica 1). Rezultati morfoloških značilnosti vlaken so pokazali večjo povprečno dolžino (1421,38 ± 163,3 µm) in premer vlaken (48,97 ± 6,3 µm), premere lumnov (33,18 ± 5,5 µm) in debeline celičnih sten (7,90 ± 3,7 µm) v spodnjem delu debla *A. boonei*. Izračunani indeksi kažejo, da ima les *A. boonei* Runklovo razmerje od 0,51 ± 0,3 do 0,70 ± 0,4; razmerje prožnosti (0,61 ± 0,1 do 0,69 ± 0,1); koeficient togosti (0,16 ± 0,1 do 0,19 ± 0,1) in koeficient fleksibilnosti (0,19 ± 0,2). 1), koeficient vitkosti (29,51 ± 5,2 - 32,60 ± 7,2); Luceov koeficient oblike (0,36 ± 0,2 - 0,45 ± 0,2) in stopnjo masivnosti (lesnatosti) vlaken (1,08×10^{-6} ± 5,6×10^{-5} - 1,83×10^{-6} ± 9,0×10^{-5} µm^3) vzdolž debla (preglednica 1). Analiza kemične sestave lesa *A. boonei* je poka-

zala želeno vsebnost lignina (<30 %), holoceluloze (65 do 70 %), nizko vsebnost pepela (1,17 %) in topnost v 1 % NaOH, ki je znašala 11,93 %.

Glede na navedene ugotovitve je *A. boonei* mogoče uvrstiti med lesne vrste z nizko gostoto, primerne za proizvodnjo celuloze. Poleg tega omogoča les iz spodnjega dela z višjo gostoto in daljšimi vlakni večji izkoristek celuloze in izdelavo močnejšega papirja v primerjavi z lesom srednjega in zgornjega dela debla. Zaradi velikega premera vlaken *A. boonei* bi lahko izdelali voluminozen grob papir s površino, ki je manj primerna za tiskanje. Vendar pa lahko zaradi tanjših sten in velikih premerov vlaken pride do kompenzacije za izdelavo gostih, gladkih in močnih papirjev. Poleg tega je mletje lažje zaradi velikih lumnov vlaken, boljšega prodiranja tekočine v prazne prostore in sploščitve vlaken.

Runklovo razmerje, razmerje prožnosti, koeficient togosti, Luceov faktor oblike in stopnja masivnosti (lesnatosti) vlaken imajo vrednosti v razponih, ki so zaželeni za proizvodnjo celuloze iz lesa, zato bi iz lesa alstonije lahko izdelali tudi papirje z boljšimi trdnostnimi lastnostmi.

Kemijsko gledano nižja vsebnost lignina nakazuje, da bi bilo za njegovo odstranitev potrebno manj energije in kemikalij. Visoka vsebnost holoceluloze, nizka vsebnost pepela in ustrezna topnost v 1 % NaOH bi omogočili visok izkoristek celuloze, zato se je les *A. boonei* izkazal kot primeren material za proizvodnjo celuloze in papirja.

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