The Effects of Chemical Compositional Variability on Sustainable Applications of *Borassus aethiopum* Trunks

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The study aims to evaluate the chemical compositional variability within the male and female *Borassus aethiopum* trunks to ascertain their influences and possible applications. The specimens for the study were prepared from the radial and axial portions and extracted with a Soxhlet apparatus. The varieties were analyzed for the hot water, ash content, 1% NaOH, alcohol-acetone extracts, lignin, and α-cellulose. The total extractives, lignin, and α-cellulose decreased consistently from the peripheries to the cores, unlike the ash content. Thus, total extractive decreased from 4.41 to 1.83% and 3.25 to 1.18% for the male and female, lignin from 36.88 to 29.06% and 39.53 to 28.60%, α-cellulose: 40.09 to 28.02% and 37.01 to 24.40% respectively but the ash content increased from 0.65 to 3.39%, 0.85 to 5.64% for the male and female respectively. There were significant differences along the boles for the total extractives, lignin, and α-cellulose unlike the ash content at the peripheral portions. From the results, the peripheries possess the potentials to resist moisture permeability, biodegradation, enhance mechanical properties, dimensional stability, and other wood qualities positively for commercial utilization than the cores. This will enhance the sustainability of forest biodiversity by limiting the pressure on the primary wood species.

**Keywords:** biodegradation, *Borassus aethiopum*, chemical composition, cores, moisture permeability, peripheries, sustainability, varieties

**INTRODUCTION**

The tropical deforestation is of global concern towards biodiversity conservation. The escalating utilization of primary and lesser-used timber products, logging activities, fuelwood collection, charcoal production, human settlements, and overexploitation beyond annual allowable cut (AAC) are the major drivers of deforestation particularly in Africa (Kissinger et al., 2011, Damnyag, 2012). The forest resources in Ghana continue to decline in quality and quantity due to indiscriminate tree felling, poor timber processing methods, and illegal logging. These are resulting in biodiversity loss and subsequent forest degradation. These distresses in the timber industry have caused a lack of mature trees prompting renewing research into other forest resources that can be potential alternatives to sustain primary timber species and forest biodiversity.

The chemical composition of lignocelluloses biomass such as total extractives, lignin, and α - cellulose play essential roles in plant survival by providing defense mechanisms against predation by insects, herbivores, and microorganisms. The potential application of wood is attributable to one or more active chemical substances found in the wood tissues (Oliveira et al., 2016). The

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Arecaceae family includes several tropical palms such as Borassus aethiopum Mart is Non-Timber Forest Product (NTFP) grouped into male and female varieties. Borassus aethiopum grows between 7–20m in height and sometimes 30m, considered as African tallest palm characterized by a crown. The male variety produces flowers that cannot develop into fruits, unlike the female variety that develops fruits for consumption and other medicinal purposes. (Jatau, 2008, Oliveira et al., 2016).

The two varieties of Borassus aethiopum as monocot and non–woody materials have periphery (dermal), core (sub-dermal), and central (pith) zones. They contain vascular bundles and parenchyma cells embedded in axial and radial positions along the bole (Fathi, 2014). About 60% of cellulose fibers originate from non-woody raw materials such as annual plants and agricultural residues. These non-woody fibers contain more cellulose and less lignin fraction (Sridach, 2010; Baptist, 2013). The naturally growing non-woody plants suitable for wood industry such as palms, Bambusa vulgaris, Hibiscus cannabinus L., Arundo donax L., and Borassus aethiopum have varying physical and chemical characteristics that can be compared to some softwood and hardwood species. The varying characteristics depending on the soil and the growing conditions, which could involve the climatic conditions (Azeez, 2018).

Renewable forest resources such as Elaeis guineensis, Cocos nucifera, Bambusa vulgaris, and Phoenix dactylifera L. is getting more attention as potential alternative materials to solid wood. These non-woody materials are also used for applications such as lumber, particleboard, pulp and paper, wood-cement composites, wood-plastic composites, and oriented strand boards unlike the Borassus aethiopum (Hegazy et al., 2015, Nasser et al., 2015, Usman et al., 2016). According to Ayarkwa (1997) and Asafo-Adjeie et al. 2012, Borassus aethiopum trunks are locally used for wattle and daub construction, wall plates, rafters, fences, stakes in farming, firewood, canoes, lintels, and bridges. The effective and sustainable use of Borassus aethiopum trunks requires scientific research into their chemical compositions to attain comprehensive data that can be compared to other palms, conifers, and deciduous wood species.

The chemical composition of lignocelluloses biomass consists of three principal polymers: polysaccharides (cellulose: 40-50%, hemicelluloses: 20–30%) and lignin (20-30%) with organic compounds called total extractives (2-10%) as well as minimal ash content that ranges 0.1–5% (Reiniati, 2009). These chemical constituents generally vary between and within wood species due to differences in age, height, growth, site, and environment. The chemical constituents particularly polysaccharides, lignin, and extractives have an immense influence on the physical, mechanical, and durability characteristics of wood (Rivera et al., 2015, Roiito et al., 2016, Routa et al., 2017). Lignin as a class of complex organic polymer forms important structural materials in the formation of woody and non-woody cell walls. It ensures the possibility of the wood’s vascular tissue to conduct efficient moisture (Yang et al., 2016). Aside cellulose and lignin, total extractive is the most influential chemical factor that can affect the quality of woody and non-woody materials. The quantity of total extractives has much influence on wood processing and related applications. The wood used in the soil, above ground or immersed in water is exposed to bacteria, fungi, insects, and marine organisms, and the principal contribution of total extractives in wood is their natural resistance against these biodegrades. The extractives also add quality to wood density, geometric stability, and some mechanical properties (Hakkila and Verkasalo, 2009; Routa et al., 2017).

Palm trunks differ from coniferous and deciduous wood species with alteration in polysaccharides, lignin, and total extractives. Research into the chemical composition of palm trunks revealed high variability in polysaccharides, lignin, and extractive content (Sulaiman et al., 2009, Hashim et al., 2011). Findings by Sahari et al., 2012; Nasser et al., 2016 on Elaeis guineensis trunks recorded total extractives in the range of 6.3–25.15% and ash content (2.4-5%) but considerable lignin (30.32-46.4%), and α-cellulose (39.37-40.6%). Similar proximate chemical composition of Cocos nucifera and Phoenix dactylifera L. trunks studied by Poulter and Hopewell, 2010; Hindi et al., 2010, Fathi, 2014 found total extractives, lignin, α-cellulose, and ash content in the range of 10-16.44%, 25.1–31.30%, 33–48%, and 0.25–2.4% respectively. The chemical compositional analysis was carried out with the American Society for Testing and Materials (ASTM) methods. The considerable total extractives and lignin in palms influence the odor, color, rigidity, toxicity, and enhance resistance to decay caused by biodegrades. The α-cellulose as a major chemical component in woody and non-woody plants provide strength and stability to enhance mechanical characteristics. However, extreme α-cellulose and Moisture Content (MC) in parenchyma cells result in decaying characteristics. The study investigated the chemical compositions along the boles of the male and female Borassus aethiopum. This was to identify the variability within the varieties and their potential effects on the wood towards utilization by the wood industry.

MATERIALS AND METHODS

Preparation of Borassus aethiopum varieties

Two defect-free each variety between the ages of 35 and 40 based on their cultivated period were randomly harvested from Kobereso semi-deciduous forest zone in the Offino-North District of Ashanti Region in Ghana for the study. The diameter along the boles was between 0.20m to 0.50m from the breast height with a height range of 15 - 18m. The samples were collected from the three main portions along the boles as depicted in Figure 1 and air-dried for the study.
Chemical compositional analysis

The specimens for the analysis were prepared from the peripheries and cores at the base, middle, and crown. The samples were air-dried to 12–14% MC, milled with Wiley mill, and sieved. The total extractives, lignin, and α-cellulose were determined using a Soxhlet apparatus. The following ASTM methods: ASTM D 1105–96 (Reapproved 2007), ASTM D 1106–96 (Reapproved 2007), ASTM D 1103–60 (Reapproved 1977), and ASTM D 1102 – 84 (Reapproved 2007) were used to determine the total extractives, lignin, α-cellulose, and ash content respectively. The content of the lignin and α-cellulose were conducted with extractive free *Borassus aethiopum* based on the oven-dried weight of each residue while the α-cellulose test was carried out with air-dried holocellulose. Total extractives and ash content were determined using unextracted wood samples. The ash content of the samples was calculated as a percentage of the original quantity of the samples based on oven-dry weight. Three replicates from the base, middle, and crown (i.e. nine samples) from each bole at the peripheries and the cores were used for the chemical compositional analysis. The percent of each chemical composition (%) of the study was calculated according to the formula:

\[
\% = \frac{W_2}{W_1} \times 100
\]

Where: \(W_1=\) weight of original oven-dried wood (g), \(W_2=\) weight of oven-dried residue (g).

Chemical composition for total extractives

An amount of 10g air-dried *Borassus aethiopum* ground sample that passed through a number 60 (250μm) sieves and retained by number 80 (180μm) sieve was placed in an extraction thimble ensuring that it did not extend above the level of the top of the siphon tube. The sample was extracted for 4 hours with an alcohol-acetone mixture (1:2) in the Soxhlet extraction apparatus. The excess solvent was removed with suction and wood in the thimble washed with alcohol to remove the excess acetone. The sample in the thimble was returned to the extractor and extraction continued with 95% alcohol (about 200ml) for 4 hours until the alcohol siphoned over colorless. The sample was removed from the thimble and spread out on a thin layer and allowed to dry in the air until it was free of alcohol. The dried alcohol-free sample was returned into the thimble and extracted with 200ml of hot water as was done for alcohol for 4 hours. The material after hot water extraction was air-dried thoroughly and used as extractive-free material for the determination of lignin and α-cellulose.

Chemical composition for lignin

A 1g oven-dried sample of extractive-free *Borassus aethiopum* was placed in a 150ml beaker and 15ml of cold sulphuric acid (72%) was added slowly while stirring. The reaction was continued for 2 hours with frequent stirring in a water bath maintained at 20°C. The specimen was transferred by washing with 560 ml of distilled water into a 1,000 ml Erlenmeyer flask, diluting the concentration of the sulphuric acid to three percent. The apparatus was placed in a boiling water bath for 4 hours. The flask was removed from the water bath and the insoluble material allowed to settle overnight. The contents of the flasks were filtered by vacuum suction into a fritted-glass crucible of known weight. The residue was then washed free of acid with 500ml of hot distilled water and then oven-dried at 103 ± 2°C. The crucible was cooled in a desiccator and weighed to constant weight.

Chemical composition for α-cellulose

Air-dried holocellulose material from each part of the stem was first obtained and placed in a 250ml Erlenmeyer flask with a small watch glass cover. The sample was treated with a total of 25ml of 17.5% NaOH within 45 minutes. First, a 10ml portion of the 17.5% NaOH was added to the sample, thoroughly mixed, and placed in a water bath maintained at 20 °C. The sample was manipulated with a glass rod 2 minutes after the addition of the first 10ml portion. Five minutes after the addition of the first portion, an additional 5ml portion was added and thoroughly mixed. Five minutes later, the next 5 ml portion was also added followed by the addition of the last 5ml portion and thorough mixing 15 minutes after the addition of the first portion. The mixture was allowed to stand at 20 °C in the water bath for 30 minutes, making a total of 45minutes NaOH treatment. Following the NaOH treatment, 33ml of distilled water previously maintained at 20 °C was added to the mixture, and the content of the beaker thoroughly mixed and allowed to stand at 20 °C for 1 hour. The contents of the flask were filtered through vacuum suction into a fritted-glass crucible of known weight. The residue was washed first with 100ml of 8.3% NaOH, then with distilled water, and treated with 15ml of 10% acetic acid for 3 minutes. The residue was washed free of acid with distilled water. The crucible was oven-dried at 103 ± 2°C, cooled in a desiccator, and weighed until a constant weight was obtained.
**Ash content**

Empty crucibles were ignited in a muffle furnace at 600°C, cooled in a desiccator, and weighed to the nearest 0.1mg. A 2g sample of air-dried *Borassus aethiopum* was put in the crucibles to determine the weight of the crucibles and the specimen. The crucibles and their contents were placed in a drying oven at 103 ± 2°C, cooled in a desiccator, and weighed until the weights were constant. The crucibles and their contents were then placed in the muffle furnace and ignited until all the carbon was eliminated. They were then heated slowly at the start to avoid flaming while protecting the crucible from strong drafts at all times to avoid mechanical loss of the test specimen. The temperature of the final ignition was 580-600°C. The crucibles with their contents were then removed to a desiccator and the cover replaced loosely, cooled, and weighed. The heating was repeated until the weight after cooling was constant to within 0.2g.

**RESULTS AND DISCUSSION**

**Total extractives**

The total extractives within wood vary from species to species and within identical species. Extractives could range from 2-10% or 3-30% but sometimes up to 40% depending on the tree species (Rooit et al., 2016, Routa et al., 2017). For instance, the typical content of extractives in Scots pine, Norway spruce, and silver birch stem wood were found in the range of 2.5% to 4.5%, 1.0% to 2.0%, and 1.0% to 3.5% respectively on a dry basis (Alen, 2011). Wood extractives have diverse functions: they provide energy and protect trees from micro-biological attacks. Greater amounts of extractives in wood prevent or minimize attacks by destructive organisms including termites, beetles, and decay-fungi if the extractives are toxic or repellent (Koehler et al., 2003, Routa et al., 2017). Findings from the study depicted in Figure 2 confirm variable total extractives along the boles of both *Borassus aethiopum* as had been identified by researchers for wood species.

Both varieties recorded a consistent decreasing trend up the boles. Radially, the peripheries had the greatest extractives at the base (i.e., 4.41% for male; 3.25% for female) but least at the cores of the crown (i.e., 1.83% for male; 1.81% for female). Axially, the male had a decreasing extractive content up the crown (4.41 to 1.83% for the periphery at the base and the core of the crown respectively). A similar decreasing trend up the bole was attained by the female variety (3.25 to 1.81% respectively). Within the peripheries, vascular bundles have less MC due to the permanently aspirated pits and extractives are considerably deposited in the pit membranes. The presence of these extractives in sufficient quantities at the peripheries prevent or minimize the severity of attacks by biodegrades and reduce excessive moisture impermeability. This makes the peripheries naturally moisture repellent, has less dimensional changes, more resistant to biodegrades (i.e. being more durable), and more useful commercially than the cores.

**Lignin content**

Lignin serves as “glue” in wood and usually ranges between 20-30% for softwoods and 18-25% for hardwoods. Adequate lignin content in wood provides rigidity, resistance to biodeteriogens, and impermeable to moisture (Sim et al., 2015, Lourenço and Pereira, 2018). Halimahton and Ahmad, 1990 observed that lignin in *Elaines guineensis* stem was evenly distributed along the trunk except that the core was deficient whilst the peripheries of the base and middle had excessive amounts. This confirms the results of the study showed in Figure 3.

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**Figure 2:** Total extractives within male and female *B. aethiopum*

**Figure 3:** Lignin content within male and female *B. aethiopum*
The lignin content within both varieties decreased up the boles. That is, the peripheries had the greatest lignin content in the range of 36.88–32.83% for the male, 39.53–29.06% for the female, and least at the cores (i.e., 34.13–29.31% for the male and 35.63–28.60 for the female). The quantity of lignin decreased linearly from the base within the peripheries up the crown and cores (36.88–29.31%) for the male and (39.53–28.60%) for the female. The availability of lignin in woody and non-woody plants serve the function of minimizing the accessibility of cellulose and hemicellulose to microbial enzymes and confer mechanical strength by creating a cross-link with other cell wall components. Therefore, the sufficient lignin concentration at the peripheral zones than the cores of both varieties from the study confirm findings from the previous authors cited. This can decrease moisture permeability through the vascular bundles, augment nutrients transport, cement, minimize microbiological degradation, enhance wood quality, and natural durability. These strengthen the peripheries’ natural defenses and durability against biodegradation by impeding the penetration of destructive enzymes.

**Alpha-cellulose**

The α-cellulose has been identified as the main lignocelluloses carbohydrates ranging between 40–50%. This drives termites towards the wood components, serves as reinforcing material, and greatly enhances the stiffness and mechanical strength of wood (Bowyer et al., 2003). Studies by Bakar et al., 1998; Fathi, 2014 identified a gradual decrease in α-cellulose from the periphery to the core for *Elaeis guineensis* and *Cocos nucifera* trunks at a mean value of 42% and 29.2% respectively. Khunrong, 2008 also reported 37.14% mean for *Elaeis guineensis* trunks which are in the range of most wood species. Results from the study shown in Figure 4 recorded consistent decreasing values up the bole for both *Borassus aethiopum*. Radially, (i.e. from the periphery to the core), the peripheries at the base had the greatest amount of 40.09% for the male and 37.01% for the female than the cores: 28.02% for the male and 24.40% for the female at the crown. Axially, (i.e. from the base to the crown), the male recorded this trend: Base: 40.09% > middle: 34.11% > crown: 29.53% for the peripheries, while the cores had similar trend: Base (34.20%) > middle (30.05%) > crown (28.02%). An identical trend was identified for the female (37.01% > 35.38% > 25.97% for the periphery at the base, middle, and crown respectively). The core also recorded 36.10% for the base, 29.36% for the middle, and 24.40% for the crown.

**Figure 4: α- cellulose within male and female B. aethiopum**

Both varieties had consistent decreasing trends (40.09–28.02% and 37.01–24.40% for the male and female respectively from the peripheries of the base to the cores of the crown). Being the principal nutrient for termites, wood structures with excessive α-cellulose and MC are avidly consumed and destroyed by termites and other insects. A sufficient amount of α-cellulose and moisture at the core portions along both varieties are factors that attract biodegrades to feed and attack the core portions. This makes the cores less durable, dimensionally unstable, and potentially less useful in exterior and structural applications than the peripheries.

**Ash content**

The chemical properties of wood ash vary significantly depending on factors including soil type, source of biomass, combustion type, the temperature used for its production, age, and climatic conditions of the species (Lanzendorfer, 2015; Neina et al., 2020). Ash from woody and non-woody plants often serve as an insect repellent, soil enrichment and are useful as a polish and abrasive cleaner. The amount ranges between 0.1 and 1.0% but sometimes up to 5% (Ndlovu, 2007). Imbeah, 1998 reported that ash content is highly variable within trees, being greatest at the pith and decrease towards the bark. Research on *Elaeis guineensis* trunks by Bakar et al., 1998 noted greater ash content at the inner zones (cores) than at the peripheries. Similar results in Figure 7 depict an increasing range from 0.65 to 3.39% for the male and 0.85 to 5.64% for the female; all from the periphery of the base to the core of the crown.
Along the periphery, the male recorded the greatest ash content at its crown (2.45%) but lowest at the base (0.65%). However, its core recorded the greatest at the crown (3.39%) and lowest at the base (1.31%) (Table 1). The trend was similar for the female as greatest at its crown (2.83%) and lowest at the base (0.85%) for the peripheries. Its core also had 5.64% at the crown and 1.49% for the base. Generally, the peripheries and cores of both varieties recorded a consistently increasing trend from the base to the crown. The lower ash content at the peripheries than the cores along the boles can be ascribed to an embedded cellular structure at the peripheries compare to the porous voids at the core zones. This positively influences the physicochemical, mechanical, and durability characteristics of peripheral zones than the cores for various essential applications.

**STATISTICAL ANALYSIS**

The analysis of variance (ANOVA) using Complete Randomized Design (CRD) was employed to test the differences between the variables using OriginPro 8.5 software. Subsequent Tukey’s Honestly Significant Difference (HSD) tests were used to determine significant differences at the 5% probability level (LSD 0.05) to detect the means differences among all the measured properties. The mean differences within both varieties are presented in Table 1 with standard deviations in brackets. Means that do not share a letter are significantly different.

<table>
<thead>
<tr>
<th>Varieties</th>
<th>Stem positions</th>
<th>Chemical properties</th>
<th>Ash content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radial</td>
<td>Total extractives (%)</td>
<td>Lignin (%)</td>
</tr>
<tr>
<td>Male Periphery</td>
<td>Base</td>
<td>4.41a (0.13)</td>
<td>36.88a(0.54)</td>
</tr>
<tr>
<td>(Dermal)</td>
<td>Middle</td>
<td>3.06b (0.02)</td>
<td>35.98h(0.49)</td>
</tr>
<tr>
<td>Crown Base</td>
<td>2.38c (0.30)</td>
<td>32.83h(0.39)</td>
<td>29.53c(0.73)</td>
</tr>
<tr>
<td>Core (sub-dermal)</td>
<td>Middle</td>
<td>2.62c (0.23)</td>
<td>34.13c(0.26)</td>
</tr>
<tr>
<td>Crown</td>
<td>1.83d (0.17)</td>
<td>33.90c(0.19)</td>
<td>30.05c(0.49)</td>
</tr>
<tr>
<td>Female Periphery</td>
<td>Base</td>
<td>3.25A (0.04)</td>
<td>39.53A(0.00)</td>
</tr>
<tr>
<td>(Dermal)</td>
<td>Middle</td>
<td>3.08AB (0.11)</td>
<td>36.31B(0.29)</td>
</tr>
<tr>
<td>Crown Base</td>
<td>2.04D (2.04)</td>
<td>29.06D(0.55)</td>
<td>25.97E(0.18)</td>
</tr>
<tr>
<td>Core (Sub-dermal)</td>
<td>Middle</td>
<td>2.95B (0.06)</td>
<td>35.63B(0.00)</td>
</tr>
<tr>
<td>Crown</td>
<td>1.81E (0.14)</td>
<td>33.59C(0.40)</td>
<td>29.36D(0.26)</td>
</tr>
</tbody>
</table>

*Values in the same column with the same letter are not significantly different (P<0.05)
The chemical constituents within both varieties showed better peripheral properties at the bases and middle in all cases along the boles. In most cases, significant differences exist radially (i.e. between the peripheries and the cores) (Table 1). Generally, there were variable chemical compositions within both varieties as was confirmed by cited researchers for palms, deciduous, and coniferous wood species. The lower total extractive, lignin, and α-cellulose but greater ash content at the cores and crowns than the peripheries at bases and middle of both varieties are due to the presence of porous parenchyma tissues at the cores and crowns unlike the embedded vascular bundles at the peripheries along the boles which create permanent aspirated voids at the peripheries than the cores. These increase porosity, moisture accumulation, minimize density, and mechanical characteristics, resulting in the cores and crowns less rigid, resistant to biodegradation (or less durable), dimensionally unstable, more permeable to moisture than peripheries at the bases and middle of both varieties. This makes peripheries particularly at the base and middle more suitable for use, especially in hazardous environments.

CONCLUSION

- The peripheries along the boles (i.e. from the base to the crown) particularly at the basal and middle portions were identified to possess considerable total extractives, lignin content, α-cellulose, and minimal ash content. These can enhance the bases and middle portions to become more resistant to biodegradation (durable). Therefore, they possess viable potentials for commercial applications such as furniture, flooring, poles, doors, and other enhanced structural works in the wood industry.

- The chemical characteristics of the cores from the base to the crown within both varieties indicate the potential possibility for interior applications like parquet, stools, shelves, wardrobes, ceiling, and packaging. This is due to their minimal total extractives, lignin, α-cellulose, and optimal ash content that can render the cores more susceptible to bio-attacks and moisture absorption is minimal.

- The commercialization of both varieties in the wood industry will reduce the excessive dependence on the primary timbers and sustain the forest biodiversity.

ACKNOWLEDGMENT

Our profound appreciation to the staff of the Department of Wood Science and Technology, Faculty of Renewable Natural Resources (FRNR), Kwame Nkrumah University of Science and Technology, Kumasi, Ghana for their assistance. We also thank Ms. Agnes Ankomah Danso (Bio-Statistician, Crops Research Institute of CSIR, Kumasi) for the statistical guidance.

DECLARATION OF INTEREST STATEMENT

No conflict of interest exists.

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Accepted 30 May 2020


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