THE CHARACTERISTICS OF FIBRES WITHIN COPPICED AND NON-COPPICED ROSEWOOD (*Pterocarpus erinaceus* Poir.) AND THEIR APTNESS FOR WOOD - AND PAPER - BASED PRODUCTS

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Abstract:
Rosewood (Pterocarpus erinaceus) is highly priced for furniture, flooring and cabinetry for its rich hue and durability. Its coppiced wood augments the timber for regular supply and sustainable utilization. Fibre morphology from macerated slivers within its coppiced and non-coppiced stems and their utilization potential were assessed. Derived ratios for the fibres were also calculated. The axial positions (butt, middle, crown) affected the fibre dimensions. Fibre length was greater for coppiced trees [i.e., 1663±11, 1488±5, 1511±10μm (for sapwood) and 1498±10, 1486±9, 1394±4μm (for heartwood)] than the non-coppiced [i.e., 1240±7, 1013±5, 1137±5μm (sapwood) and 1094±8, 1002±2, 1041±9μm (heartwood)]. In all, those for sapwoods were greater than heartwoods'. Significant differences (P<0.05) existed between fibre lengths from the coppiced (1394±4-1663±11μm) and non-coppiced trees (1002±2-1240±7μm). Fibre diameters for coppiced sapwood and heartwood were 23±1, 20±1, 22±0.8μm and 21.5±0.3, 20.7±0.5, 21.3±2μm and non-coppiced recorded 21±0.6, 20.7±0.3, 20.6±0.1μm and 21±0, 21±0.4, 21±0.8μm respectively. Their respective double wall thicknesses were 8.4±0.2, 7.2±0.2, 9.4±1μm and 8.2±0.2, 9±0.3, 9.1±0.4μm for coppiced wood, and 9.1±1, 7.8±0.1, 8.1±0.3μm and 8.5±0.3, 8±0.4, 8±1 for non-coppiced. Thus, radial stem position also influenced fibre morphology. The fibre indices [i.e., Runkel Ratio, Slenderness Ratio and Flexibility Coefficient for coppiced wood (0.6±0.06-0.85±0.06, 68±4-77±6, 56±4-64±2 respectively) and non-coppiced (0.64±0.12-0.8±0, 49±1-58±4, 57±3-62±2 respectively)] indicate the timber's aptness for pulp and paper. Besides, the Wood Industry could exploit the fibre characteristics of coppiced wood also for engineering of fibre-based products and structural applications.

Key words: burst strength; coppiced wood; Flexibility Coefficient; fibre-based product; Slenderness Ratio; wood composite.

INTRODUCTION

The earth's virgin forests have reduced to nearly one-fifth of their original cover. About 50% of tropical Africa forest zones is removed through anthropogenic activities and 40% in Latin America and Asia due to industrialization (Carr 2004). West Africa is endowed with rich pool of natural resources, chiefly forests, for development. Irrespective of their numerous values, the virgin forests are rapidly depleting. Pressure on the remaining has increased such that the timber species, which once dominated the international markets, are becoming scarce (Appiah *et al.* 2009). Desertification is documented as a key environmental hazard on the livelihoods of the people in the affected regions. Sub-Saharan Africa would likely lose two-thirds of arable lands by 2025 if strategies are not introduced to curtail deforestation (Albalawi & Kumar 2013, Agyemang & Abdul-Korah 2014). The quest to identify sustainable options to adapt or mitigate the aforesaid problems is indispensable. Forest regeneration (e.g. coppicing) aims to sequester atmospheric carbon efficiently (Kirkinen *et al.* 2007). Coppicing is a woodland management method whereby harvested trees (mostly hardwoods) are allowed to re-grow from stumps or roots. The re-growths are the coppiced shoots and the stump from which they invigorate is the stool (Fuller & Warren 1993). Temperate trees include *Alnus glutinosa* (L.) Gaertn, *Castanea sativa* Mill., *Betula pubescens* Ehrh., and species of *Fraxinus, Acer*, *Corylus, Quercus*, *Sallow, Tilia, Platanus* and *Ulmus*. Coppicing allows second timber rotation without replanting, lessens renewal cost and potentially supplies regular woody resources (Zbonak *et al.* 2007). Rosewood (*Pterocarpus erinaceus* Poir.), locally known as Kpatro/Krayie, coppices well (Orwa *et al.* 2009). It is sought-

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after in the West African arid forests for international trade. Its wood superior qualities make it ideal for furniture, decorative paneling, flooring, utensils, construction, exterior joinery, doors and windows. Its resin dyes traditional fabrics and the tree is for charcoal production because of its outstanding calorific value. The leaves are used as livestock fodder by integration in agro-pastoral systems (Dumenu & Bandoh 2014). Globally, it has poor supply due to over-exploitation. Thus, its rising demand has led to extensive, illegal and unsustainable harvesting such that many West Africa countries have enacted total ban on its trade, which unfortunately still lingers on (Coleman 2014, Hoare 2015). The local measures fail to address the regional and intercontinental drivers of its illegal trade.

Little or no information is accessible for wood property and quality from coppiced and the originally planted timber (Whittock *et al.* 2004). The two forms from *E. tereticornis* could be utilized for similar purposes such as furniture, heavy construction, framing, flooring and wood composites (Sharma *et al.* 2005). However, Schonau (1991) observed that density of coppiced trees of *E. grandis* was lower than their parents'; the latter resisted stresses more than the former since wood density has positive correlation with strength. Luostarinen *et al.* (2009) found fibres from coppiced *B. pubescens* longer and wider than their parent trees'. Wood properties largely determine its utilization or suitability for a particular application. Miller (1999) established that specific characteristics (e.g. density, fibre morphology) must be considered so as to use wood effectively. For instance, fibre dimensions relate to structural, physical and chemical properties of timber and affect many wood-products, drying, chemical process and pulping.

Fibres influence paper sheet properties including tensile, stretch, burst and tear strengths (Smook 1994, Kiaei *et al.* 2014). Fibre length affects the strength, surface and bonding properties of fibre products. Long fibres produce papers of superior tear resistance (Haygreen & Bowyer 1996). The most important "Fibre Derived Values" in pulping are Runkel Ratio (RR), Slenderness Ratio (SR) and Flexibility Coefficient (FC). These determine the paper-making potential of any woody species than its absolute fibre dimensions (Ververis *et al.* 2004). SR (ratio of fibre length and diameter) positively influences tear, burst, breaking-off and double folding resistance of paper sheets (Akgül & Tozluglu 2009). Fibres with great RR (ratio of double wall thickness and lumen width) are less desirable for pulp and paper-making (Jang & Seth 1998); the acceptable ranges for quality pulping are 0.25 - 1.5 (Shashikala & Rao 2009). Based on FC (ratio between lumen width and diameter), fibres are classified into high elastic (≥75), elastic (50–75), rigid (30-50) and very rigid (≥30) (Bektas *et al.* 1999). Rigid fibres are considered in fibre plate and rigid cardboard production (Akgül & Tozluoglu 2009). Fibres with low RR and great FC readily collapse and produce good surface contact in addition to fibre-to-fibre bonding, which allow for the manufacture of quality paper, fibre-, chip- and particle-boards (Nkaa *et al.* 2007). Variability in fibre characteristics for timbers exists, which affects their end-uses. Information regarding fibre anatomy could be employed to predict service utilization of wood. *P. erinaceus*, cherished much for construction due to its durability and rich hue, has good sprouting capacity but lacks information on the characteristics of its coppiced wood fibres. This has maintained the over-dependence on the threatened non-coppiced timber. Fibre characteristics within coppiced and non-coppiced *P. erinaceus* stems and their aptness for wood- and paper-based products were assessed. The findings would boost its coppiced wood utilization and mitigate the over-exploitation of the non-coppiced timber and ensure regular raw material supply to sustain the timber and wood-related industries.

MATERIALS AND METHODS
Sample preparation
Defect-free coppiced and non-coppiced *P. erinaceus* trees of 20-30 years (Height: 12-15m; diameter: 30-35cm) were sampled from the natural forest of the Kumawu Forest District (in Amidu of the Ashanti Region, Ghana). Billets (2m) were removed from the butt (2m above ground), the middle (2m along half of the stem), and the crown (2m to branch attachment) of each bole. Discs (60cm high) were obtained from each billet to study the variation in fibre anatomy along the boles. Radial samples were then selected from each disc (15-18cm) from the heartwood (5cm from the pith) and sapwood (4cm below the bark).

Wood maceration
Slivers of match stick size (2×2×20mm) were sampled from wood cubes (2×2×2cm) and transferred into heat-resistant tubes. Glacial acetic acid and 30% hydrogen peroxide (1:1) mixture were added to cover the samples. Each sample-solution mixture was incubated at 60°C for 24h. Fibres were washed thoroughly in distilled water, agitated to separate the cells and stored in ethanol. Macerated fibres were placed on a glass slide (standard, 7.5×2.5cm) by means of a medicine dropper, treated with glycerol solution, teased out and a cover slide (22×30mm) placed over the slide for the measurement of the fibres (IAWA 1989). Observation was under the light microscope (×4, ×40 objectives and ×10 eyepiece) and fibre dimensions under investigation [i.e., fibre length (L), lumen width (I) and diameter (D)] taken. Double wall thickness was calculated from the difference between the lumen width (I) and the fibre diameter (D) (IAWA 1989).

Derived Values and Ratios for fibres

The values obtained for fibre dimensions were used to compute the following Derived values: Flexibility Coefficient = (I/D) ×100; Runkel Ratio = (2W)/I; Slenderness Ratio = (L/D) (Ogunkunle & Oladele 2008, Samariha *et al.* 2011, Antwi-Boasiako & Ayimasu 2012).

Data analysis

Data from the fibre dimensions and their derived values were subjected to ANOVA and Fisher's Least Significant Difference (LSD) Test (at 95% confidence level) to compare their means.

RESULTS
Fibre length within coppiced and non-coppiced boles of *P. erinaceus*

Fibre length was greater for coppiced trees [i.e., 1663±11, 1488±5, 1511±10µm (for sapwood) and 1498±10, 1486±9, 1394±4µm (for heartwood)] than the non-coppiced [i.e., 1240±7, 1013±5, 1137±5µm (sapwood) and 1094±8, 1002±2, 1041±9µm (heartwood)] (Fig. 2 and 3). In all, those for sapwoods were greater than heartwoods' (Fig. 1). Significant differences (P<0.05) existed between fibre lengths from the coppiced (1394±4-1663±11µm) and non-coppiced trees (1002±2-1240±7µm) (Table1). Significant differences (P<0.05) existed between fibre lengths along the stem height for both trees. The differences were significant between heartwood and sapwood for both trees (Table 1).

Table1

ANOVA for fibre length within coppiced and non-coppiced boles of P. erinaceus

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	108943.10	54471.55	1227.34	<.001[***]
Radial position	1	72585.34	72585.34	1635.47	<.001[***]
Tree type	1	1579253.00	1579253.00	35583.23	<.001[***]
Axial*Radial position	2	34922.86	17461.43	393.44	<.001[***]
Axial*tree type	2	20182.25	10091.13	227.37	<.001[***]
Radial*tree type	1	233.58	233.58	5.26	0.031[*]
Axial*Radial*tree type	2	423.92	211.96	4.78	0.018[*]
Error	24	1065.17	44.38		
Total	35	1817609.22			

[***]Significant: P(<0.001) <0.05; [*]Significant: P(0.018, 0.031) <0.05
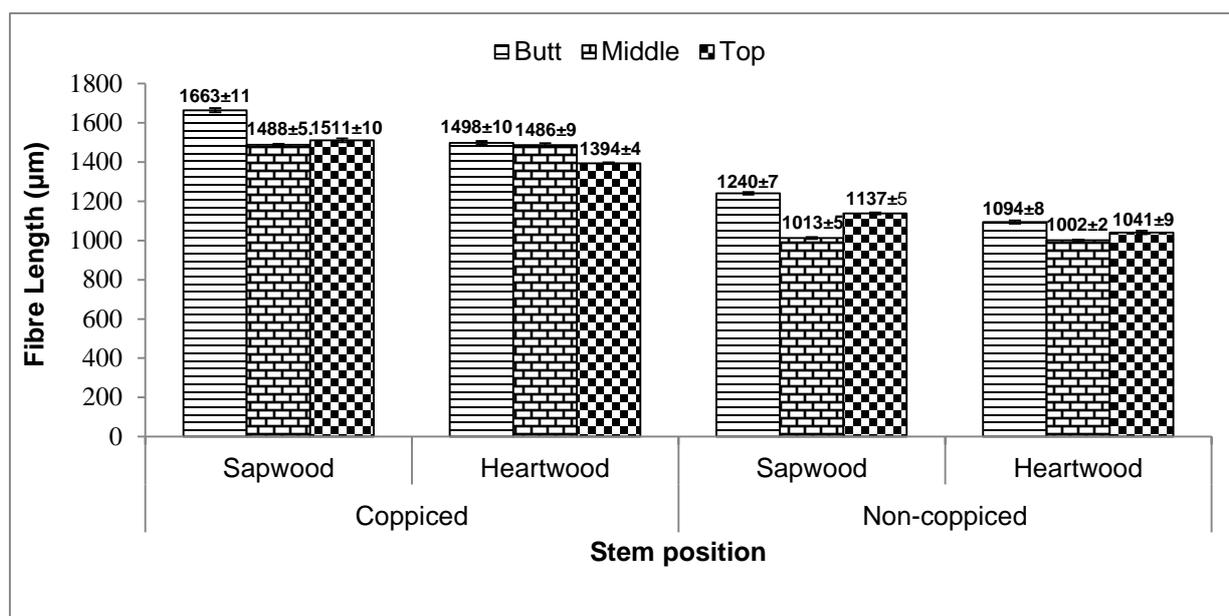

Fig. 1.
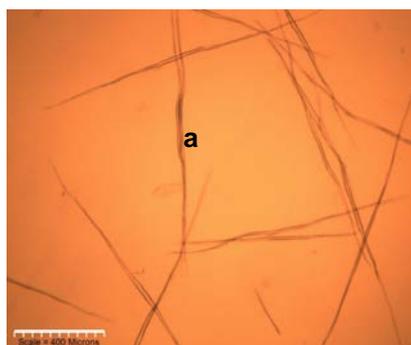*Fibre length within coppiced and non-coppiced boles of P. erinaceus.*

Fig. 2.
Micrograph of fibre (a) from coppiced P. erinaceus bole; Scale bar = 400µm.
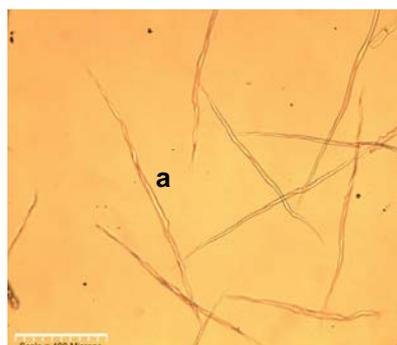

Fig. 3.
Micrograph of fibre (a) from non- P. erinaceus bole; Scale bar = 400µm.

Fig. 4.
Micrograph of fibre. Fibre lumen (L); fibre wall (a) from coppiced P. erinaceus bole; Scale bar = 80µm.

Fig. 5.
Micrograph of fibre. Fibre lumen (L); fibre wall (a) from non-coppiced P. erinaceus; Scale bar = 80µm.

Other fibre dimensions within coppiced and non-coppiced boles *of P. erinaceus*

Up the bole, fibre diameters for coppiced sapwood and heartwood were 23±1, 20±1, 22±0.8µm and 21.5±0.3, 20.7±0.5, 21.3±2 µm and non-coppiced recorded 21±0.6, 20.7±0.3, 20.6±0.1µm and 21±0, 21±0.4, 21±0.8µm respectively (Fig. 2). The difference along the stem height was significant ($p < 0.05$) (Table 2). No significant differences ($p < 0.05$) existed between fibre diameters from the coppiced and non-coppiced trees (Table 2) (Fig. 4 and 5). No specific trend was observed for the lumen width and double wall thickness for both trees (Fig. 6). However, the difference was significant ($p < 0.05$) for double wall thicknesses along (i.e., butt, middle, crown) coppiced and non-coppiced *P. erinaceus* boles (Table 4).

Table 2

ANOVA for fibre diameter within coppiced and non-coppiced boles of P. erinaceus

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	4.4839	2.2419	4.03	0.031*
Radial position	1	0.0544	0.0544	0.10	0.757
Tree type	1	1.5211	1.5211	2.73	0.111
Axial*Radial position	2	1.5739	0.7869	1.41	0.263
Axial*tree type	2	4.3172	2.1586	3.88	0.035*
Radial* tree type	1	1.3611	1.3611	2.44	0.131
Axial*Radial*tree type	2	0.5272	0.2636	0.47	0.629
Error	24	13.3667	0.5569		
Total	35	27.2056			

*Significant: P(0.031, 0.035) <0.05

Table 3

ANOVA for lumen width within coppiced and non-coppiced boles of P. erinaceus

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	0.6272	0.3136	0.85	0.438
Radial position	1	0.5136	0.5136	1.40	0.248
Tree type	1	0.3403	0.3403	0.93	0.345
Axial* Radial position	2	0.8672	0.4336	1.18	0.324
Axial*tree type	2	9.4106	4.7053	12.82	<.001[***]
Radial*tree type	1	3.6736	3.6736	10.01	0.004[**]
Axial*Radial*tree type	2	0.0572	0.0286	0.08	0.925
Error	24	8.8067	0.3669		
Total	35	24.2964			

[***]Significant: P(<0.001) <0.05; [**]Significant: P(0.004) <0.05

Table 4

ANOVA for double wall thickness within coppiced and non-coppiced boles of P. erinaceus

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	3.5272	1.7636	6.01	0.008[**]
Radial position	1	0.0803	0.0803	0.27	0.606
Tree type	1	0.6136	0.6136	2.09	0.161
Axial*Radial position	2	2.8606	1.4303	4.87	0.017[*]
Axial*tree type	2	4.4772	2.2386	7.62	0.003[**]
Radial*tree type	1	0.6136	0.6136	2.09	0.161
Axial*Radial*tree type	2	0.9372	0.4686	1.60	0.223
Error	24	7.0467	0.2936		
Total	35	20.1564			

[**]Significant: P(0.003, 0.008) <0.05; [*]Significant: P(0.017) <0.05
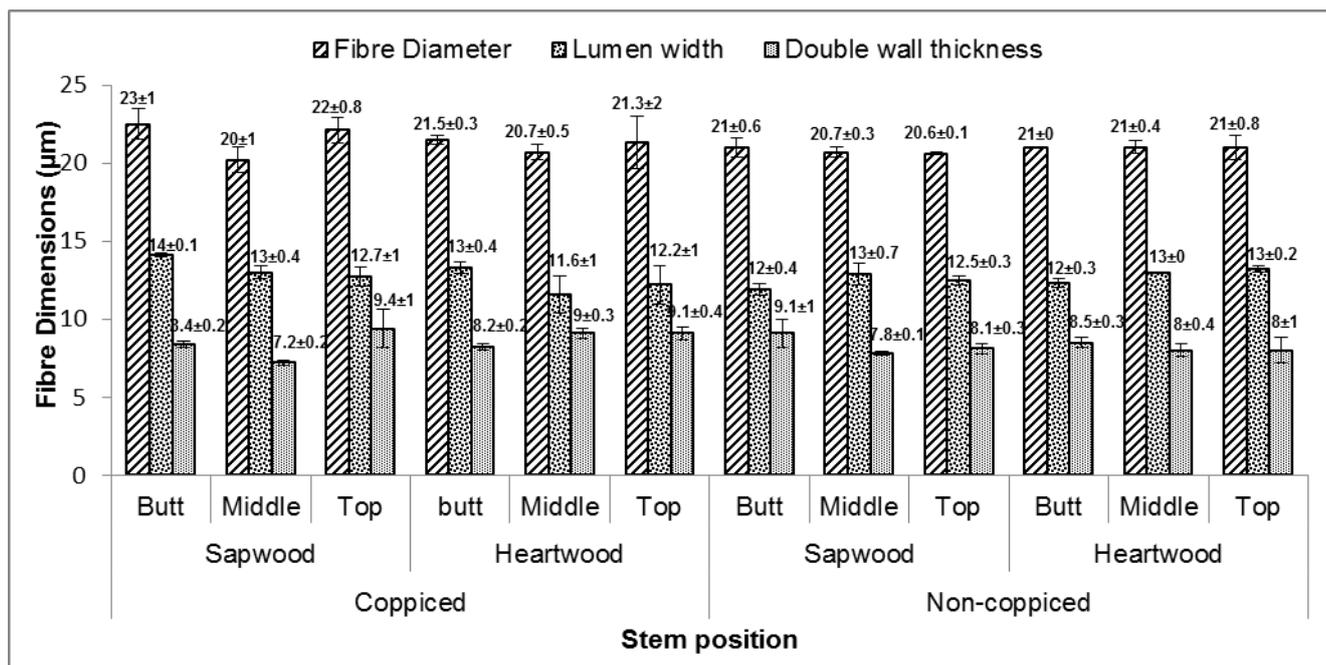
Fig. 6.
Fibre dimensions within coppiced and non-coppiced boles of P. erinaceus.

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Derived values within coppiced and non-coppiced boles of *P. erinaceus*

RR did not show clear trend along (i.e., butt, middle and top) coppiced boles but was greater at the butt than the upper portions for non-coppiced trees [i.e., 0.8 ± 0, 0.67 ± 0.06, 0.67 ± 0.12 (sapwood) and 0.72 ± 0.07, 0.71 ± 0.06, 0.64 ± 0.12 (heartwood) respectively] (Fig. 7); the difference was not significant ($p<0.05$) for both trees (Table 5). Heartwood recorded greater values than sapwood for coppiced trees and the reverse for those from non-coppiced (Fig. 7). No significant differences ($p<0.05$) existed between RRs from the coppiced and non-coppiced trees. The middle portions of both sapwood and heartwood of coppiced trees recorded greatest SR (i.e., 76 ± 0.5, 77 ± 6, 71 ± 9 and 72 ± 7, 74 ± 3, 68 ± 4 respectively), while the butt ends recorded the greatest for non-coppiced (i.e., 61 ± 2, 50 ± 0.2, 58 ± 4 and 55 ± 3, 49 ± 1, 51 ± 1 respectively) (Fig. 8); the difference was significant ($p<0.05$) for both trees (Table 6). Sapwood recorded greater SR than heartwood (Fig. 8); the difference was significant ($p<0.05$) for both trees (Table 6). Significant differences ($p<0.05$) also existed between SRs from coppiced (68 ± 4-77 ± 6) and non-coppiced trees (49 ± 1-61 ± 2) (Table 6). No clear trend was observed for FC along coppiced and non-coppiced boles (Fig. 8). Sapwood recorded greater FC than heartwood for coppiced trees and the inverse for non-coppiced trees (Fig. 8); the difference was not significant ($p<0.05$) (Table 7). No significant differences ($p<0.05$) also existed between FCs from the coppiced (56 ± 4-64 ± 2) and non-coppiced (57 ± 3-62 ± 2) trees (Table 7).

Table 5

ANOVA for Runkel ratio within coppiced and non-coppiced boles of P. erinaceus

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	0.01921	0.00960	0.75	0.482
Radial position	1	0.00147	0.00147	0.11	0.737
Tree type	1	0.01247	0.01247	0.98	0.333
Axial*Radial position	2	0.06334	0.03167	2.48	0.105
Axial*tree type	2	0.04384	0.02192	1.72	0.201
Radial*tree type	1	0.08507	0.08507	6.66	0.016[*]
Axial*Radial*tree type	2	0.02104	0.01052	0.82	0.451
Residual	24	0.30667	0.01278		
Total	35	0.55310			

[*]Significant: P(0.016) <0.05

Table 6

ANOVA for Slenderness ratio within coppiced and non-coppiced boles of P. erinaceus

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	124.02	62.01	3.49	0.047[*]
Radial position	1	134.17	134.17	7.55	0.011[*]
Tree type	1	3194.13	3194.13	179.76	<.001[***]
Axial*Radial position	2	21.37	10.68	0.60	0.556
Axial*tree type	2	203.59	101.79	5.73	0.009[**]
Radial*tree type	1	2.30	2.30	0.13	0.722
Axial*Radial*tree type	2	9.11	4.56	0.26	0.776
Residual	24	426.45	17.77		
Total	35	4115.14			

[***]Significant: P(<0.001) <0.05; [**]Significant: P(0.009) <0.05; [*]Significant P(0.047, 0.0110) <0.05

Table 7

ANOVA for Flexibility Coefficient within coppiced and non-coppiced boles of P. erinaceus

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	7.561	3.780	0.84	0.445
Radial position	1	13.938	13.938	3.08	0.092
Tree type	1	2.778	2.778	0.61	0.441
Axial*Radial position	2	38.291	19.145	4.24	0.027[*]
Axial*tree type	2	107.461	53.730	11.89	<.001[***]
Radial*tree type	1	40.534	40.534	8.97	0.006[**]
Axial*Radial*tree type	2	9.524	4.762	1.05	0.364
Residual	24	108.447	4.519		
Total	35	328.532			

[***]Significant: P(<0.001) <0.05; [**]Significant: P(0.006) <0.05; [*]Significant: P (0.027) <0.05

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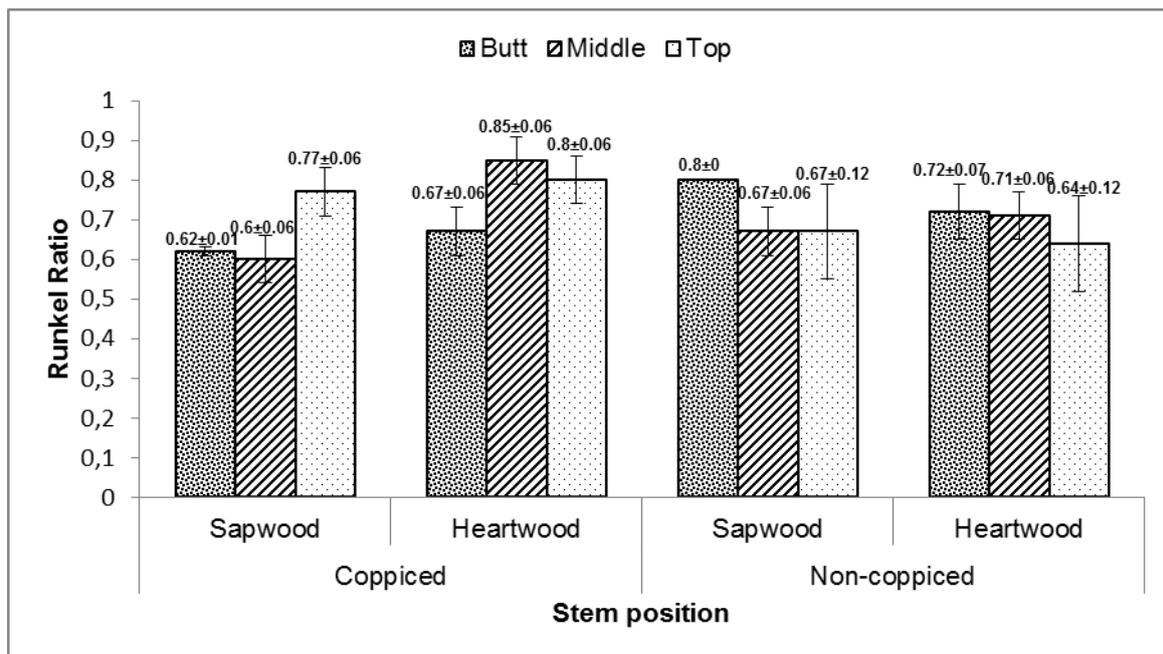
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Fig. 7.
Runkel Ratio within coppiced and non-coppiced boles of P. erinaceus.
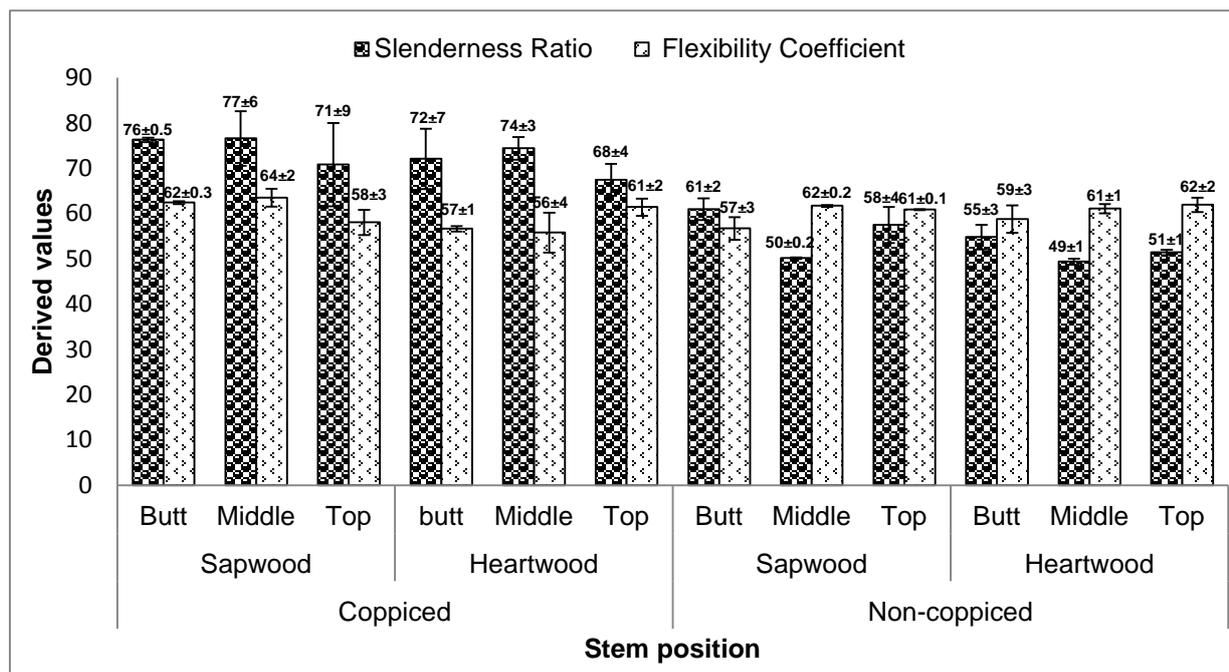

Fig. 8.
Derived ratios within coppiced and non-coppiced boles of P. erinaceus.

DISCUSSION
Fibre characteristics within coppiced and non-coppiced boles of *P. erinaceus*

Juvenile wood is often related with shorter fibres, thinner cell walls and greater microfibril angles than mature wood (Moya & Tomazello 2007). It is formed under the conditions of apical meristem action on the cambium in stems of both softwoods and hardwoods (Zobel & van Buijtenen 1989, Nawrot *et al*. 2014). With age, butt ends of stems are away from the crown and no longer affected by the apical meristem. Thus, away from the juvenile wood zone, wood cells with characteristics of mature wood are formed at the butt (Nawrot *et al*. 2014). Greater fibre lengths and diameters recorded at the butt than the upper portions for both coppiced and non-coppiced trees could therefore be attributed to the mature characteristics of wood at the butt ends. Besides, wood is differentiated from the vascular cambium comprising fusiform and ray initials,

which give rise to axial cells (e.g. fibres) and transverse cells (e.g. rays) respectively. Hence, these cells could be responsible for the greater fibre lengths and diameters at the butt than at the upper portions for both trees since secondary growth at the butt is less influenced by the primary meristem than at the crown. Nordahlia *et al.* (2011) found the fibre characteristics at the butt of 10-year-old *A. excelsa* to be greater than the upper portions. Similarly, the butt portions of coppiced and non-coppiced *P. erinaceus* recorded longer and wider fibres than the upper portions. However, several factors including physiological (e.g. transpiration, assimilation) and environmental (e.g. nutrient supply) influences could affect variation in fibre dimensions along the bole and could have accounted for the greatest double wall thickness at the crown of coppiced *P. erinaceus* (Fig. 6).

Fibre length increases with cambial age or distance from the pith (Izekor & Fuwape 2012), this is due to the existence of great amount of juvenile wood around the pith, which is typical of short fibres (Roque & Fo 2007). Moreover, molecular changes (e.g. cell division) and physiological changes (e.g. transpiration, assimilation) that occur in the vascular cambium during cell differentiation could be responsible for the greater fibre lengths recorded in the sapwood (active xylem tissue) than in the heartwood (dead xylem tissue) for both trees (Plomion *et al.* 2001, Roger *et al.* 2007).

Longer and wider fibres of coppiced trees than those from non-coppiced could be attributed to the shorter period of cell formation in the former than in the latter (Rao *et al.* 2003, Veenim *et al.* 2005). In asexual propagation including coppicing, rooted cutting and tissue culture, vegetative materials are taken from a parent tree in which cells have attained a certain age compared with sexual propagation where cells grow anew, thus, contributing to longer period for cell formation (Rao *et al.* 2003, Nordahlia *et al.* 2011). In coppicing, the stools are already established, where cells are formed, while germination has to take place in non-coppiced trees before the growth of cells, which requires time for their formation. This gives coppiced trees longer and wider fibres than their non-coppiced counterparts. Generally, auxin that has been produced from the apical meristems in softwoods causes tracheid enlargement (Kozlowski & Pallardy 1997). Phytohormones are responsible for early growth in trees (Ye & Zhong 2015) and are expected to be abundant in coppiced trees during development, which might have contributed to their longer and wider fibres than non-coppiced trees. Luostarinen *et al.* (2009) found fibres of coppiced *B. pubescens* to be longer and wider than their parent trees. Similarly, longer and wider cells were observed for coppiced trees than those from non-coppiced in this current study. This makes the former a potential supplement to the latter for end-uses including paper, wood composites and furniture manufacturing.

Fibre morphological indices
Runkel Ratio (RR) is essential for pulp and paper properties in terms of conformity and pulp yield (Ohshima *et al.* 2005). RR recorded for coppiced (0.6±0.06-0.85±0.06) and non-coppiced (0.64±0.12-0.8±0) *P. erinaceus* trees were within the acceptable limit (0.25-1.5) for pulp and paper-making (Runkel 1942). Mostly, fibres with greater RR are stiffer, less flexible and form bulkier paper of lower bonded area than fibres with lower RR (Ashori & Nourbakhsh 2009). This effect is related to the degree of fibre collapse during pulping, paper-making or wet pressing, which is affected by the cell wall thickness and degree of refining that fibres undergo prior to paper-making (Hubbe *et al.* 2007). Thus, fibres with acceptable RR ensure good inter-fibre bonding and produce papers with great strength including burst (i.e., resistance to rupturing), tear (i.e., resistance of a paper sheet to a tearing force) and tensile (i.e., maximum stress to break a strip of paper sheet). Moreover, fibres with RR <1 would collapse and provide a large surface area for bonding, hence, the better production of fibre-based products (Jang & Seth 1998). Fibres with great RR (>1) indicate poor and weakened fibre-to-fibre bonding during sheet or paper formation, resulting in low tensile, burst and tear strengths (Bektas *et al.* 1999) and would produce porous papers (Iwenofu 1979). The mean RR [0.73 (coppiced) and 0.71 (non-coppiced)] in this study is closer to 0.99 range recorded for *A. macrophylia* and *D. guinensis* (Ezeibekwe *et al.* 2009) but greater than for *Gmelina* (0.28) (Ogunkunle 2010), which are commercially used for pulp and paper-making. Coppiced and non-coppiced *P. erinaceus* trees are, therefore, expected to have increased mechanical strength and thus more suitable for writing, printing, wrapping and packaging purposes.

Slenderness Ratio (SR) is more useful for determining the paper-making potential of woody species than its absolute fibre length (Ogunkunle & Oladele 2008). A great degree of fibre SR suggests a combination of an average length with conspicuously small cell diameter and could provide better forming and well-bonded paper (Ashori & Nourbakhsh 2009). The acceptable value of SR for pulp and paper-making is >33 (XU *et al.* 2006). Thus, the SR recorded for the coppiced and non-coppiced *P. erinaceus* falls within the acceptable limit for pulp and paper-making. SR has positive influence on strength including tear, burst, breaking off and double folding resistance (Akgül & Tozluglu 2009). The bigger the SR, the stronger is the resistance to tearing. Usually, most softwood species have great SR and are preferred for pulp and paper manufacturing. For example, *Pinus kesiya* has 56.51 (Dutt & Tyagi 2011). However, some hardwoods have greater SR than some softwood. Coppiced *P. erinaceus* recorded greater mean SR (73) than the *P. kesiya*

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(56.51) and could be classified as one of the hardwoods with great SR. Nevertheless, both coppiced and non-coppiced trees can produce papers of desirable qualities based on their SRs.

Based on Flexibility Coefficient (FC), fibres are classified into high elastic fibres (≥75), elastic fibres (50–75), rigid fibres (30-50) and very rigid fibres (≥30) (Bektas *et al.* 1999). Rigid fibres do not have efficient elasticity and are considered for fibre plate and rigid cardboard production (Akgül & Tozluoglu 2009). Fibres with FC >50% are suitable for pulp and paper-making. FCs for coppiced and non-coppiced *P. erinaceus* fall within the 50-75 category and their paper strength is expected to be great. Strength of fibre-based products is often enhanced with small RR and big FC and this could be due to the fact that such fibres would readily collapse and produce good surface contact in addition to fibre-to-fibre bonding, which produces quality end products- paper, fibre-, particle- and chip-boards. In contrast, high RR and low FC fibres tend to retain their tubular structure to a large extent during beating and sheet-forming process leading to a least fibre-to-fibre bonding (Nkaa *et al.* 2007). Elastic fibres of coppiced and non-coppiced *P. erinaceus* are expected to have good fibre flexibility and a better chance of forming well bonded papers.

Utilization potential of coppiced and non-coppiced *P. erinaceus*

Fibre length of coppiced (1394±4-1663±11μm) and non-coppiced (1002±2-1240±7μm) *P. erinaceus* would be classified as medium-long and medium fibres respectively (IAWA 1989). Hardwood fibres are generally shorter than those of softwood (Hurter 1988). Nevertheless, several hardwood fibres with short (<900μm) to medium (900-1600μm) lengths are commercially used in pulp and paper-making. For instance, *G. arborea* Roxb (short-medium hardwood fibre) is the primary source of pulpwood in West Africa and Brazil (Martin 1984). *Eucalyptus* spp. are valued globally for short-fibered pulp (Dutt & Tyagi 2011). Coppiced and non-coppiced *P.erinaceus* fibres could be commercially used in pulp and paper-making since they compare well with those of the aforementioned hardwoods. Oluwadare & Ashimiyu (2007) stated that structural characteristics of the component fibres, particularly their lengths and strength properties, are essential parameters in wood quality evaluations including suitability for fibre-based products, furniture and structural lumber. Fibre length is an important factor in hardwood sheet properties because it affects bursting, tensile and tearing strengths made from unbeaten or beaten fibres and their stretch characteristics (Horn & Setterholm 1990). Desch & Dinwoodie (1996) reported 1mm for hardwoods (and 1.5 - 3.0mm for softwoods). Oluwadare & Ashimiyu (2007) reported 0.65mm fibre length for *L. leucocephala*. Fibre lengths under this current study (1.1 - 1.5mm) therefore fall within the pulpable range in erstwhile studies for hardwoods. They are also suitable for length specification for other fibre-based products, furniture and structural purposes comparable to those of aspen (1.04mm), birch (1.85mm), beech (1.20mm), oaks (1.4mm) and red gum (1.7mm) (Smook 1994).

Fibre diameters for coppiced (20±1-23±1μm) and non-coppiced *P. erinaceus* (20.6±0.1-21±0μm) respectively (Fig. 6) (Fig. 4 and 5) fall within the range recorded for *G. arborea* (18.5-27.5μm), *Ficus* spp. (18.69-28.93μm) and *P. falcataria* (15.4-21.2μm), which have been reported to have good pulping properties (Roque & Fo 2007, Ishiguri *et al.* 2009, Ogunkunle 2010). Smook (1994) reported pulpable width between 9–40μm and highlighted that fibre diameter influences pulping by increasing bonding sites since wide fibres are easily crushed during beating (i.e., mechanical treatment of fibres) especially when the lumen is wide. Fibre diameters for coppiced and non-coppiced *P. erinaceus* currently studied meet pulp specifications and both wood samples are expected to respond well to beating (Smook 1994, Haygreen & Bowyer 1996). Moreover, both trees are expected to have great density based on their diameters and double wall thicknesses and, thus, would be suitable for end-use applications such as building, furniture production, fibre-boards, particle-boards, veneer, bridge construction, cabinetry among others.

Fibre lumen influences wood density, moisture relations and suitability for pulping, as it predicts cell wall thickness and the ability of the fibres to collapse during beating (Smook 1994). Panshin & de Zeeuw (1980) noted that the lumen also affects rigidity of fibre-based products. Wide lumen fibres allow easy beating to yield strong products, while narrow lumen resists beating thereby weakening inter-fibre bonds, which result in weak products (Jozsa & Middleton 1994). Oluwadare & Ashimiyu (2007) recorded a pulpable lumen width of 9.87μm for *L. leucocephala* and 13μm was reported for *Gmelina* (Ajala 1997). Coppiced and non-coppiced *P. erinaceus* fibres recorded greater lumen widths (11.6±1-14±0.1 and 12±0.3-13±0.7μm respectively) than *L. leucocephala,* and compare well with *Gmelina,* which is a good predictor of their suitability for paper-making. Fibres with wide lumen and thin walls tend to flatten into ribbons during paper-making, have enhanced inter-fibre bonding between them and good strength characteristics (Oluwadare 1998, Osadare 2001). Nonetheless, since the wider the lumen the greater the amount of moisture held by capillary forces, wide-lumen fibres tend to collapse easily during drying and are more dimensionally unstable. Wide-lumen fibres easily absorb moisture into their cavities, and create favourable environment for bio-degraders (e.g. decay fungi) (Antwi-Boasiako & Ayimasu 2012). Coppiced and non-coppiced *P. erinaceus* would resist problems of fibres with extremely wide-lumen based on their lumen widths.

The acceptable range for hardwood fibre wall thickness is between 3.0–7.0μm for pulping (Khristova *et al.* 1998). IAWA (1989) would classify the mean fibre walls of *P. erinaceus* coppiced (4.5μm) and non-coppiced (4.2μm) (Fig. 4 and 5) as thick (i.e., over 4μm). Fibre wall thickness mostly influences the specific gravity of hardwoods, their mechanical properties (Hale 1969, Butterfield & Meylan 1980) and pulpability (Fujiwara *et al.* 1991). Oluwadare & Ashimiyu (2007) observed that cell wall thickness and fibre length have the greatest influence on the strength properties of unbeaten pulp. Fibre wall thickness affects the rigidity and strength properties of papers made from hardwood fibres (Panshin & de Zeeuw 1980). Since fibre wall-thickness relates with specific gravity and other strength characteristics (e.g. MOE, MOR, compression parallel to the grain) (Haygreen & Bowyer 1996), this could contribute to explaining the great density of *P. erinaceus*, and would be suitable for building, railway sleepers, flooring, cabinetry, furniture production, bridge construction among others. Moreover, its thick-walled fibres would resist grazing or nibbling by bio-degraders, which could explain its durability. Coppiced and non-coppiced *P. erinaceus* would have great pulp yield and suitable digestibility since fibre wall thickness relates substantially to pulp yield (linearly) and digestibility (inversely) (Ona *et al.* 2001).

CONCLUSION
- The fibre lengths for the coppiced *P. erinaceus* (1394±4-1663±11μm) and the non-coppiced samples (1002±2-1240±7μm) were classified respectively as medium-long and medium fibre hardwoods. These would be suitable for furniture and structural purposes similar to other valuable plant species such as aspen, birch, beech and oak.
- Runkel Ratio, Slenderness Ratio and Flexibility Coefficient for coppiced (0.6±0.06-0.85±0.06, 68±4-77±6, 56±4-64±2 respectively) and non-coppiced (0.64±0.12-0.8±0, 49±1-58±4, 57±3-62±2 respectively) indicate the timber's suitability for pulp and paper production, as they compare well with those of some commercially important pulpwoods (e.g. *Gmelina*, *Eucalyptus*).
- The Timber Industries could exploit the fibre length (1394±4-1663±11μm) and double wall thickness (7.2±0.2-9.4±1μm) of coppiced *P. erinaceus* for structural applications and engineering of fibre-based products.
- Coppicing should be promoted for timbers (e.g. *P. erinaceus*), which have the capacity to; this would contribute to produce enough raw materials to sustain the Timber Industry.

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