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Xylem Anatomy of Coppiced and Non-Coppiced Rosewood (*Pterocarpus erinaceus*Poir.)in relation to their Utilisation

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Abstract: The African rosewood (*Pterocarpus erinaceus*)is an endemic timber across West Africa. However,its lumber is extremely exploited and threateneddue toits high performance and technological qualities. Coppiced wood contributes sustainably to the management of natural forest stands byaugmentingregular timber supply.*P. erinaceus*tissues and their proportions were determined from the Transverse, Radial and Tangential Sections. Its wood is diffuse-porous with no or indistinct growth ring boundary. It has simple-to-minutely bordered pits, tyloses in vessel lumina, with prismatic crystals existing in chambered axial parenchyma. Thick-walledfibres constitute the greatest proportion of the tissues.Fibre proportion was greater for non-coppiced wood than the coppiced,which decreased up their stems [i.e., 57±1, 55±0.6, 52±0 % (sapwood) and 60±1.2, 57±2, 55±0.3 % (heartwood) for non-coppiced and 52±0.6, 52±0, 50±0.3 % (sapwood) and 57±1, 53±0, 50±0.3 % (heartwood) for coppiced respectively].Their sapwood and heartwood vessel and parenchyma percentages increased up their boles. Vessel lumen diameter was greater for non-coppiced trees (92±1.2-126±2µm) than the coppiced (91±0.6-117±3µm). However, both have small-medium size vessels**(**91±0.6-126±2µm). Coppiced *P. erinaceus*xylem anatomy compares satisfactorily with that from the non-coppiced and those of several well-known hardwoods appreciated for furniture and construction works. Thus, the coppiced wood wouldsupplement its non-coppiced counterpart forconstructionand other related industrial applications.

Key word: *Coppiced wood,diffuse porous,fibre proportion,prismatic crystal, secondary xylem,tylose.*

Introduction

Tropical forests are endowed with multiple products and services, which meet the needs of human populations. Globally, there is surgingdemand for timber and non-timber forest productssuch that exploitative activities of forests have reached a worrying level to the extent that sustainability has become disputed[1, 2]. Yet, anthropogenicactivities (e.g., deforestation, illegal timber harvesting, agriculture, overgrazing and bush fires), in addition to the adverse effects of climate change, threaten many indigenous plant species of enormous importance[3], which put them at the risk of extinction. Desertification has long been documented as a key environmental hazard with adverse effects on the livelihoods of people in the affected regions. Sub-Saharan Africa will lose two-thirds of its arable lands by 2025 if strategies are not put in place to curb desertification[4, 5]. In response to this, the search for sustainable options in order to adapt or mitigate the afore-mentioned problems is paramountinmeeting the restoration needs of natural stands of timber species as well as the fight against climate change. An essential aim of forest regeneration currently is for carbon sequestration[6] and revival of degraded forests, which conserve vulnerable ecosystems.

Coppicing is one of the oldest forestry systems worldwide[7]. Coppices were usually used as a source of firewood until their present conversion to high forests owing to the increasing demand for quality timber[8, 9].It is a system of woodland management whereby harvested trees (mostly hardwoods) are allowed to re-grow from the stumps or roots. Coppicing allows second timber rotation without replanting; it lessens regeneration costs and increases the regular supply of timber[10, 11, 12]. *P. erinaceus*, locally called Kpatro/Krayie in Ghana, coppices well[13] and its products could be utilized for wood construction and engineering. *P. erinaceus* is widely exploited as timber and service wood, and it is also used as one of the preferred fuelwoods[14]. It has been projected to be the most heavily traded tropical hardwood in the world[15] owing to its high performance and technological characteristics. It is not only exploited for timber traded internationally but also for a wide spectrum of non-timber products including food, fodder, medicinal products, coupled with raw materials for crafts such as tannins, dyes, sap, resin, among others[14]. The natural stands of *P. erinaceus* are greatly exploited, which brings heavy pressure on the species and habitat. Besides, illegal and uncontrolled logging of the species, linked to international trade, has become the major threat over the years.

Globally, its supply is poor due to over-exploitation across West Africa, which represents the world's leading rosewoodproducing region. In 2016, this region accounted for 80% by volume of all rosewood log exports to China[2]. The vicious exploitation is not expected to slow down anytime soon, as China and Asia's middle classhas increased demand for rosewood-made furniture[16]. The consequences of uncontrolled exploitation of the species could lead to changes in its population structure and composition, with possible detrimental effect on regeneration capacity and loss of socioeconomic services to livelihoods. Accordingly, many countries (including Ghana) have enacted total ban on its harvesting and trade. Its over-exploitation in the savanna zones of Ghana led to the re-imposition of the ban on its harvesting, processing and export[17].Yet, illegal trade of the timber lingers on[18] because transportation or processing isoften in direct defiance of local, national and/or international laws[19]. Although evidence of illegal wood trading and logging has repeatedly been presented, inefficient conservation strategies and practices continue largely unabated[20, 21]. While the large variation in wood properties among different non-coppiced resources is well documented, often little or no information is accessible for the quality of wood from coppiced trees in particular *vis-à-vis* that from the originally-planted timber[10].Wood qualitybetween non-coppiced and coppiced wood of *Eucalyptustereticornis*revealed that both kinds of wood could be utilized for similar purposes such as furniture, heavy construction, framing, flooring and wood composites (e.g., plywood and veneer)[22].

Wood (Secondary xylem) anatomy is fundamental in the study of wood science, forestry and tree eco-physiology. Investigating its cellular composition is crucial for understanding the structure properties and the structure-function relationships[23, 24, 25].Specific characteristics (e.g. fibre anatomy) must be considered in order to use wood effectively[26]. [27] and[28] explained that understanding wood anatomy is required for efficient processing and development of wood-based products. It also offers an effective approach for timber screening and diagnosis[29]. However, variability in wood characteristics for timbers exists, which influences its utilization. Thus, information relating to wood anatomy could be employed to predict its service utilization. *P. erinaceus*, appreciated for construction due to its durability and beautiful grain, sprouts well. Yet, information on the wood quality from its coppiced wood is sparse.This has contributed to the over-harvesting of the non-coppiced timber, which is being currently threatened.Fibres from coppiced *Betula pubescens*were found to be longer and wider than their parent trees[30].

Xylem anatomy within coppiced and non-coppiced *P. erinaceus*stems was assessed so as to boost the utilization of the coppiced wood, lessen the over-exploitation of the non-coppiced timber, and ensure the regular supply of the wood to sustain the Timber-related Industries.

Materialand Methods

2.1 Sample preparation

Clear wood specimens of coppiced and non-coppiced *P. erinaceus*trees of 20-30 years old (diameter at breast height of 30-35 cm) were sampled from the natural forest of the Kumawu Forest District atAmidu,Ashanti Region, Ghana. Billets (2m) were removed from three axial stem positions: the butt (1.3m aboveground), middle (50% of stem height) and crown (2m to branch attachment). They were sawn and the slabs divided to obtain boards from the heartwood (about 5 cm from the pith) and sapwood (about 25 cm from the pith)at the three axial stem positions.

2.2 Anatomical studies of coppiced and non-coppiced *P. erinaceus*boles

The methodology for anatomical features adopted the IAWA List of Microscopic features for hardwood identification[31]. Wood sections were prepared from the sapwood and heartwood of the butt, middle and top of the stem of each timber for the determination of tissue (i.e., fibre, vessel, radial and axial parenchyma) proportions and vessel lumen diameter.

2.2.1 Wood sectioning

Wood specimens (about 2 cm^3) from the sapwood and heartwood of the butt, middle and top portions of coppiced and non-coppiced *P. erinaceus* were softened by boiling and immersed in distilled water[32, 33].Transverse, Tangential and Radial sections (20-30µm thick) were sliced with a microtome knife and stained with Safranin red. They were successively washed in ethanol with increasing concentrations of 50, 95 and 100%, while any excess stains were removed[33]. The sliced sections were mounted in Canada balsam on glass slides, oven-dried and examined under light microscope [×10 eye piece, ×4 Objective lens] at the Anatomy Laboratory of the Forestry Research Institute of Ghana (FORIG), the Council for Scientific and Industrial Research (CSIR). Images were captured randomly at 5 different locations on each slide with Micron (USB2) at a scale of 400µ.

2.2.2 Determination of tissue proportions and vessel lumen diameter

A 35-point scale grid with an area of 936144μm^2 per point was laid on each image using the Image J Software. The number of points that covered the tissues (i.e., fibre, vessel, ray and axial parenchyma) was counted and expressed as a percentage of the total points (i.e., 35). This represented the proportion (%) of each tissue in the wood[31]. Vessel lumen diameter was deduced from the Transverse Sections (TS) of micrographs with the aid of calibrationacross the inner walls of the vessels.

2.3Data analysis

Data on the anatomical properties were subjected to Analysis of Variance (ANOVA) to determine the significant differences ($p<0.05$) between the proportions of the different tissues from theradial and the axial stem positions of*P. erinaceus*. The significant differences ($p < 0.05$) between the means were also determined using the Least Significant (LSD).

Results

3.1 Anatomical characteristics

3.1.1 Description of the anatomy of coppiced and non-coppiced *P. erinaceus*

P. erinaceus is diffuse-porous wood with no or indistinct growth ring boundary. Vessels in tangential bands; solitary with simple perforation plates, and lumina blocked with tyloses (Plates 1 and 2). Fibres simple to minutely bordered pits, non-septate and thin- to thick-walled. Paratracheal axial parenchyma: winged-aliform, confluent in narrow bands or lines up to three cells wide (Plates 1 and 2). All rays storied, exclusively uniseriate and procumbent (Plates 3, 4, 5 and 6), Prismatic crystals existing in chambered axial parenchyma (Plates 3 and 4).

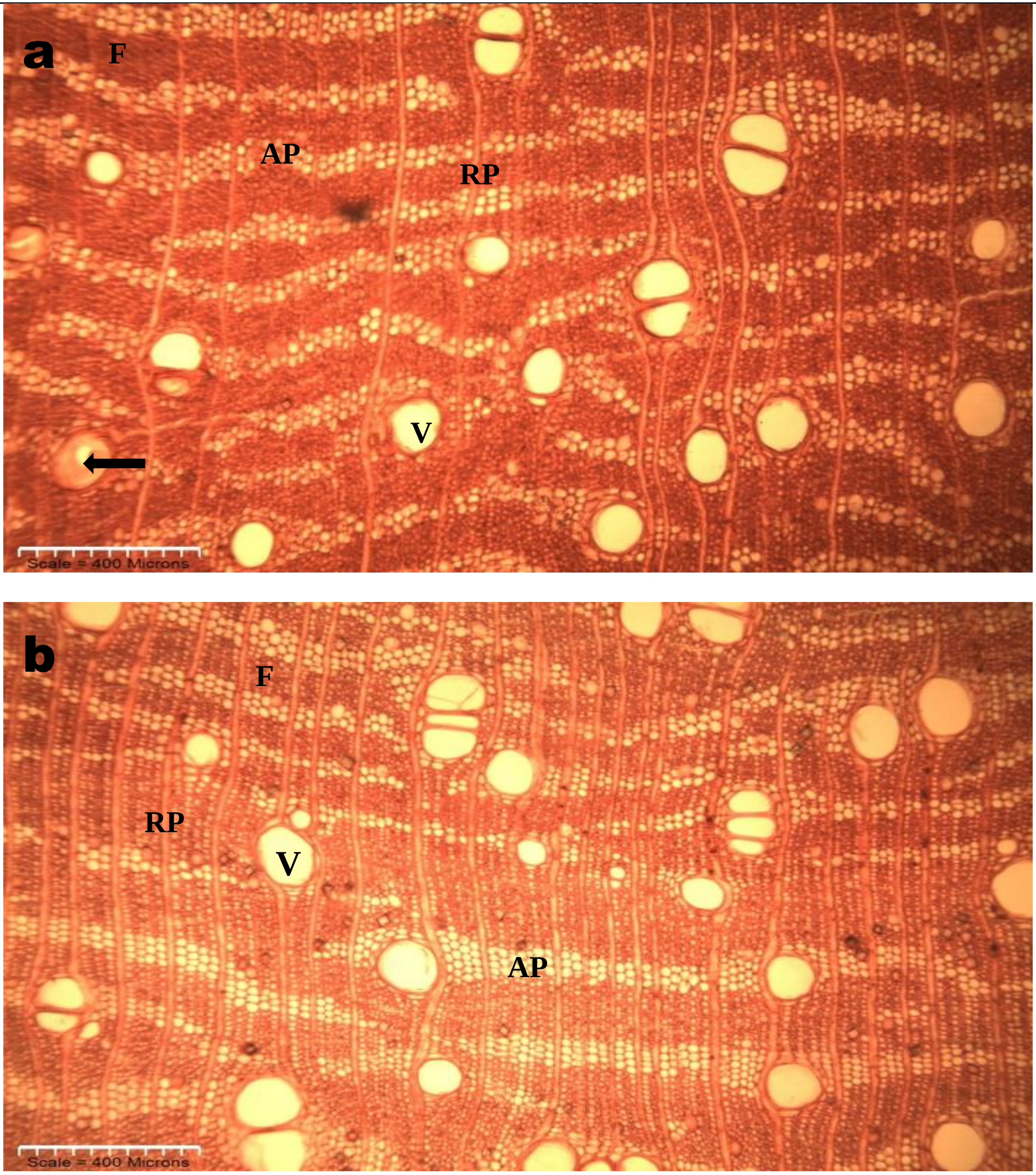

Plate 1: Transverse Section of coppiced *P. erinaceus* heartwood (a), sapwood (b), with vessels (V), fibres (F), ray parenchyma (RP), winged-aliform axial parenchyma (AP) and tyloses (arrowed). Scale bar = 400 µm.

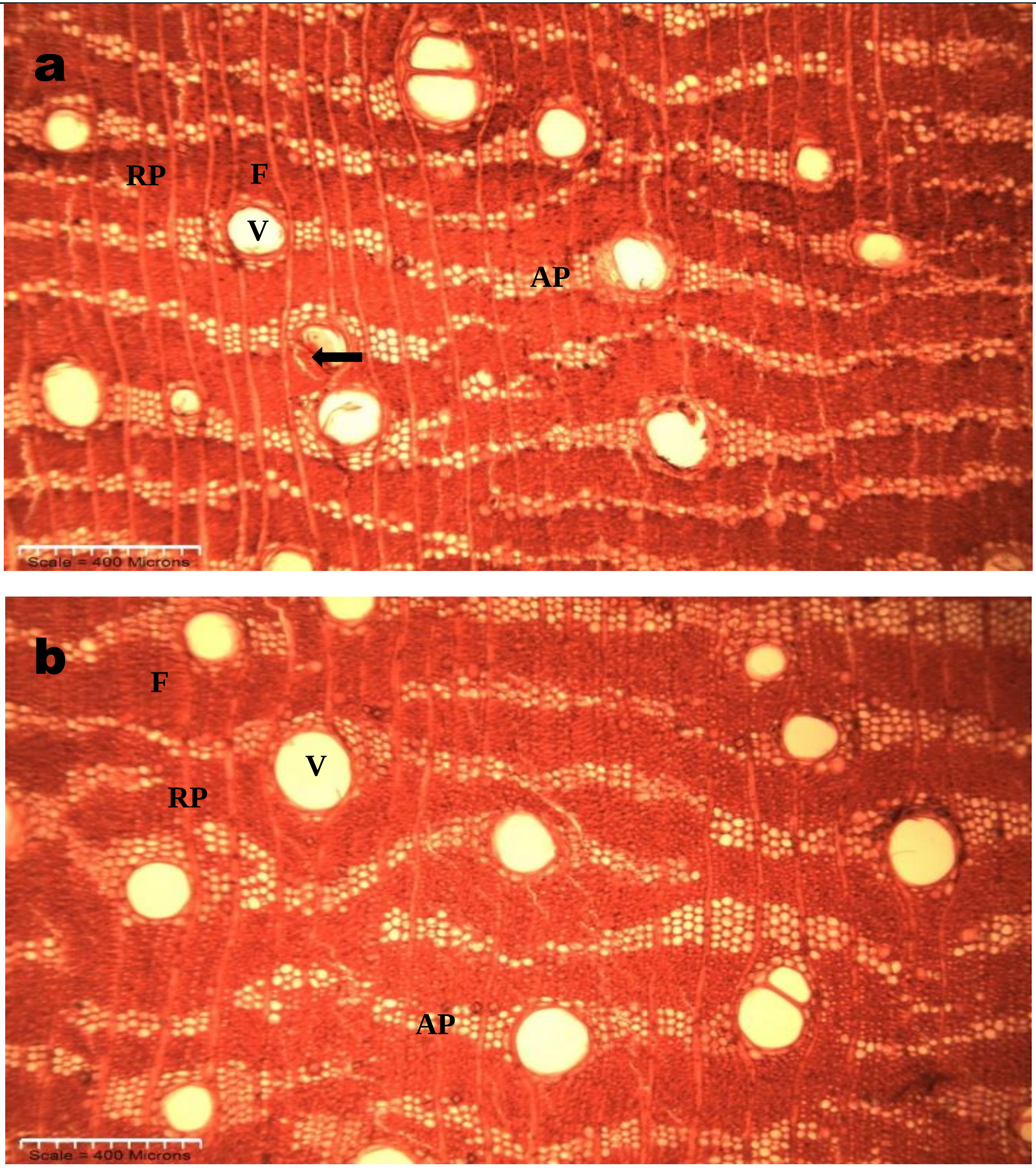

Plate 2: Transverse Section of non-coppiced *P. erinaceus* heartwood (a), sapwood (b), with vessels (V), fibres (F), ray parenchyma (RP), winged-aliform axial parenchyma (AP) and tyloses (arrowed). Scale bar= 400 µm.

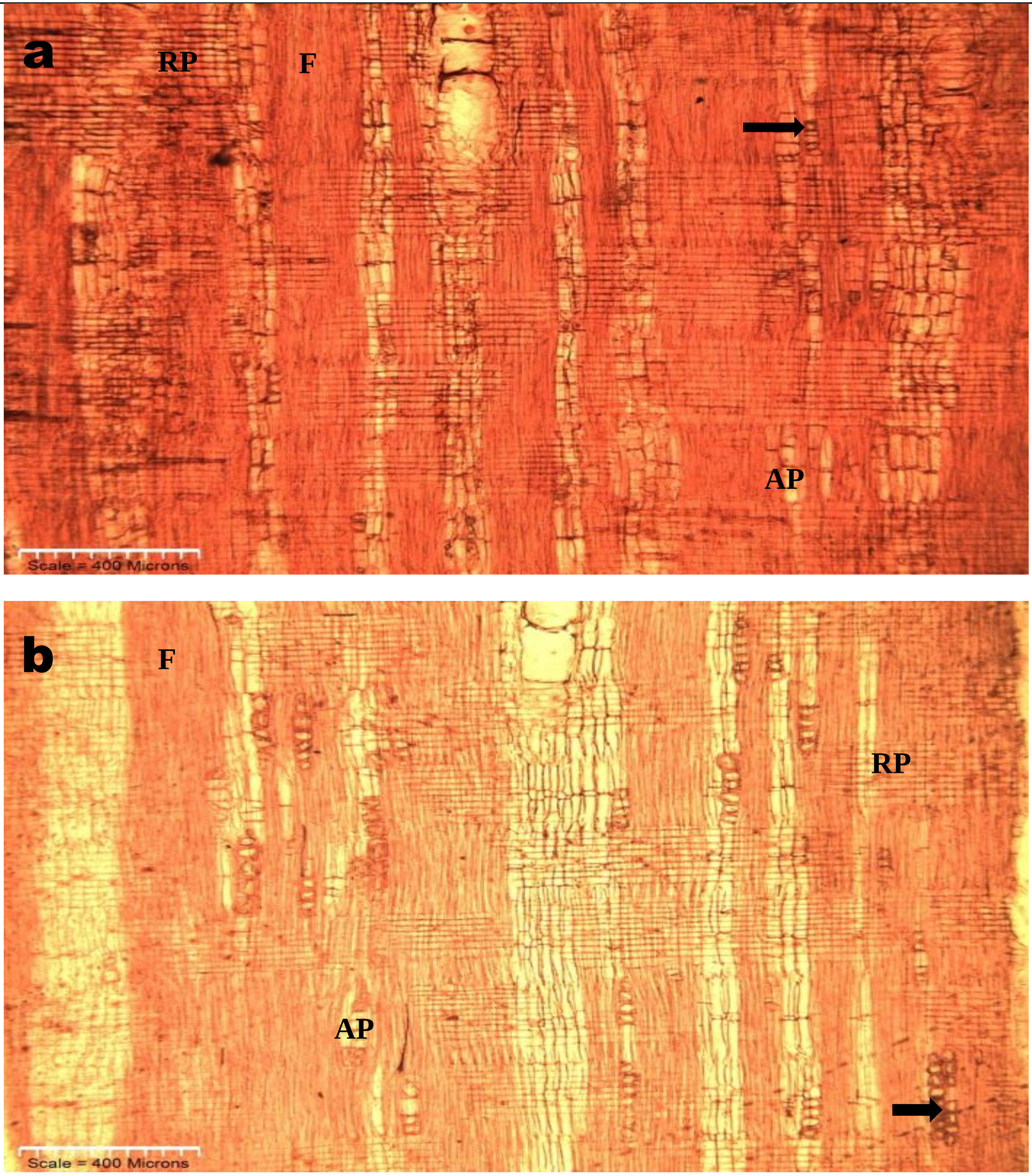

Plate 3: Radial Longitudinal Section of coppiced *P. erinaceus* heartwood (a), sapwood (b), with fibres (F), procumbent ray parenchyma (RP), axial parenchyma (AP) and prismatic crystals (arrowed) in chambered axial parenchyma. Scale bar = 400 µm.

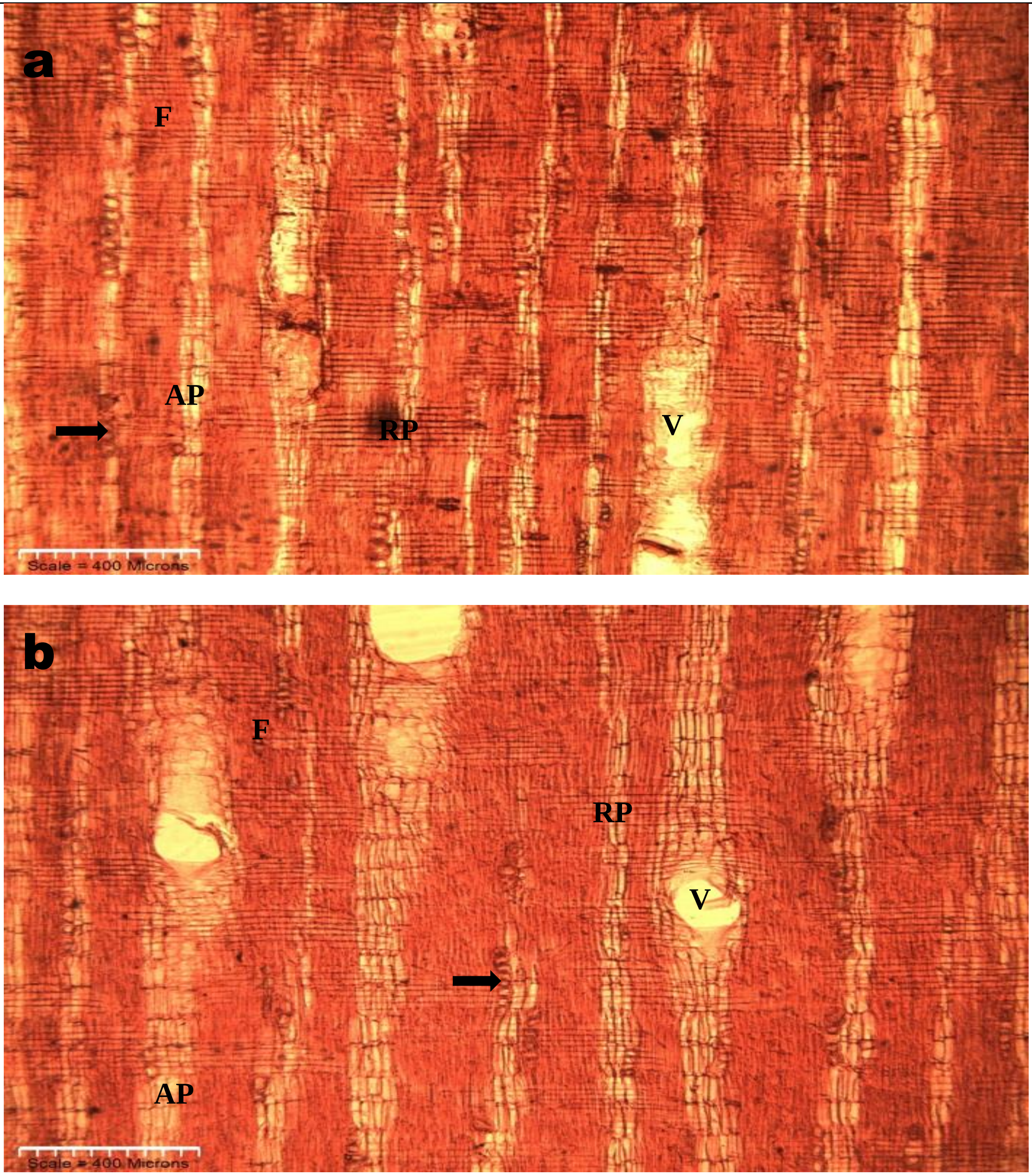

Plate 4: Radial Longitudinal Section of non-coppiced *P. erinaceus* heartwood (a), sapwood (b), with vessels (V), fibres (F), procumbent ray parenchyma (RP), axial parenchyma (AP) and prismatic crystals (arrowed) in chambered axial parenchyma. Scale bar = 400 µm.

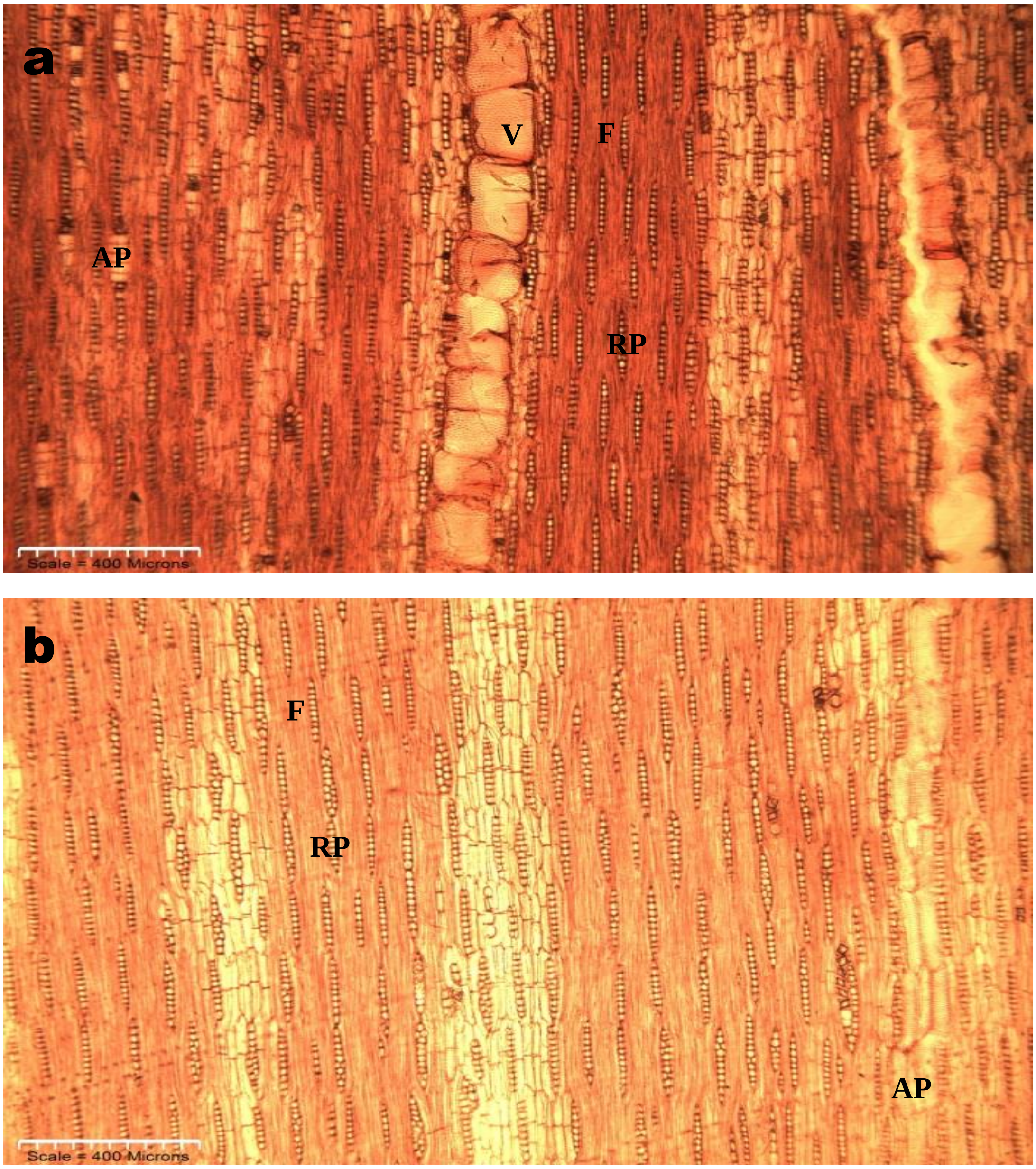

Plate 5: Tangential Longitudinal Section of coppiced *P. erinaceus* heartwood (a), sapwood (b), with vessels (V), fibres (F), ray parenchyma (RP) and axial parenchyma (AP). Scale bar= 400 µm.

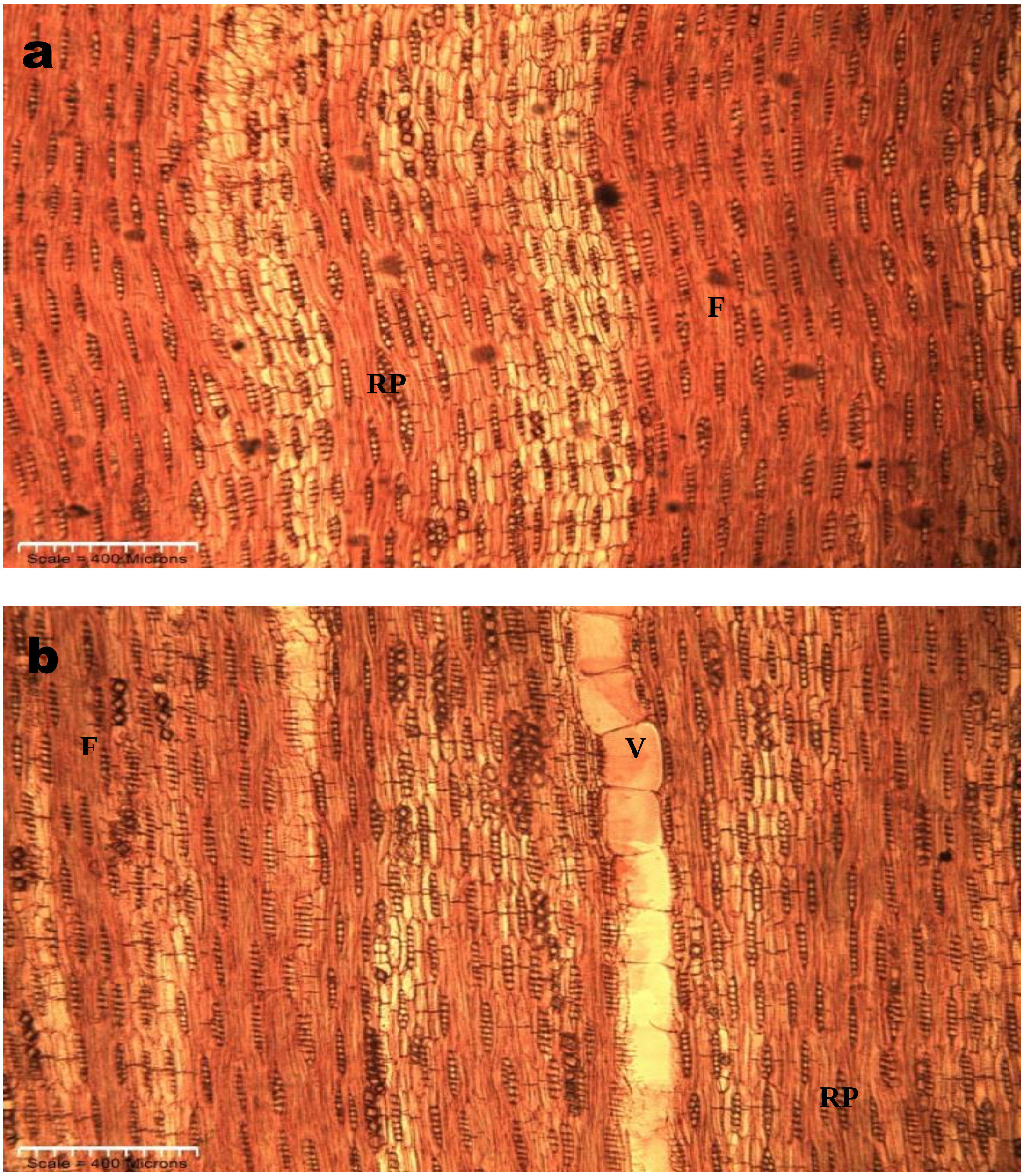

Plate 6: Tangential Longitudinal Section of non-coppiced *P. erinaceus*heartwood (a), sapwood (b), with vessels (V), fibres (F) and ray parenchyma (RP). Scale bar= 400 µm.

3.1.2 Vessel lumen diameter

Vessel diameter along the boles of the two trees types was greater for non-coppiced trees [i.e., 120±1.2, 121±0.3, 119±2 µm (for sapwood) and 100±0.3, 126±2, 92±1.2 µm (for heartwood)] than the coppiced [i.e., 112±4, 102±1, 117±3 µm (for sapwood) and 91±0.6, 104±2.3, 113±2 µm (for heartwood)]. Significant differences ($p<0.05$) existed between the vessel diameters from the coppiced and non-coppiced trees. Significant differences ($p<0.05$) also existed between vessel diameters along the stem height for both tree types (i.e., coppiced and non-coppiced). The differences in the vessel lumen diameter were significant ($p<0.05$) between those from the heartwood and the sapwood along each bole (Table 1).

Table 1: ANOVA for vessel diameter within the boles of coppiced and non-coppiced *P. erinaceus*

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	355.389	18.07	18.07	<.001***
Radial position	1	1034.694	105.22	105.22	<.001***
Tree type	1	406.694	406.694	41.36	<.001***
Axial*Radial position	2	966.722	483.361	49.16	<.001***
Axial*Tree type	2	1412.389	706.194	71.82	<.001***
Radial*Tree type	1	84.028	84.028	8.55	0.007**
Axial*Radial*Tree type	2	322.389	161.194	16.39	<.001***
Error	24	236.000	9.833		
Total	35	4818.306			

***Significant: P(<0.001) < 0.05; **Significant: P(0.007) < 0.05.

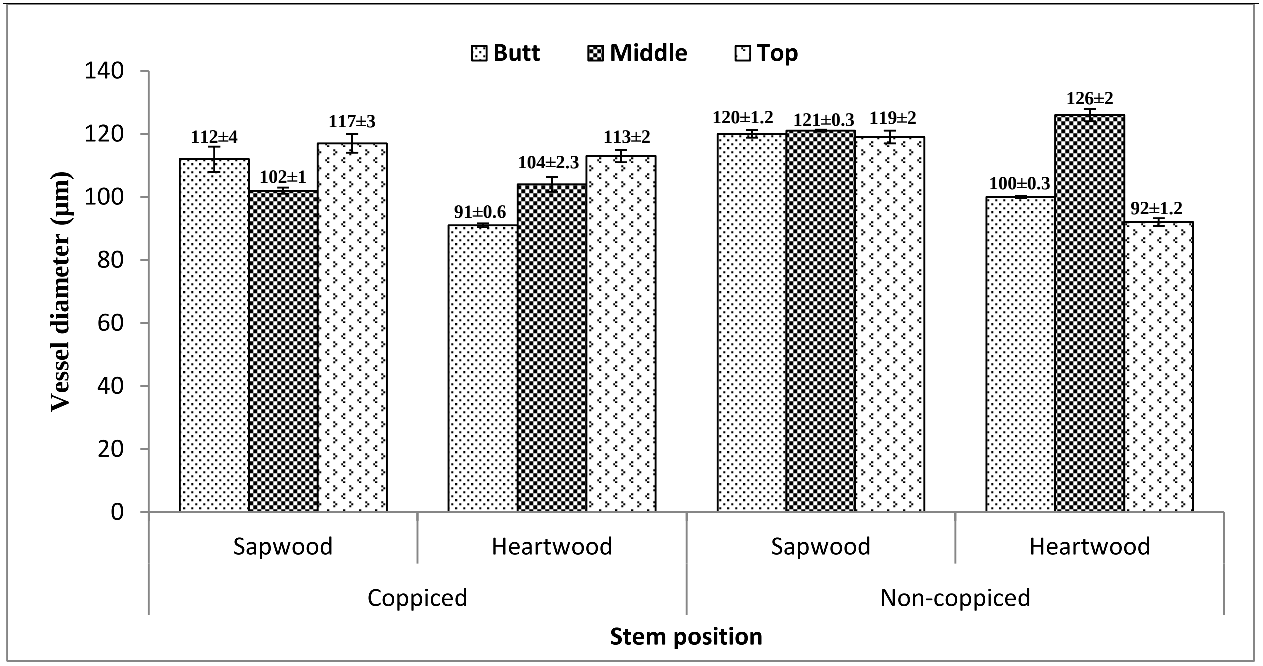

Fig. 1: Vessel diameter within the boles of coppiced and non-coppiced *P. erinaceus*

3.1.3 Tissue proportions

The number of fibres generally decreased up the stem. Thus, the butt for each stem recorded the greatest amount, followed by the middle and the crown. The proportion of fibres radially decreased from the heartwood to the sapwood in both stems. Fibre content for the non-coppiced tree from the respective base to the crown were greater [i.e., 57±1, 55±0.6, 52±0 % (sapwood) and 60±1.2, 57±2, 55±0.3 % (heartwood)] than those from the coppiced [i.e., 52±0.6, 52±0, 50±0.3 % (sapwood) and 57±1, 53±0, 50±0.3 % (heartwood)] (Fig 2). The differences were significant (P<0.05) (Table 2).

In general, the coppiced trees recorded greater Axial Parenchyma (AP) than their non-coppiced counterparts. There was an increase in AP from the butt to the crown from the coppiced [i.e., 29±03, 30±0, 30±0.3 %(sapwood) and 29±0.3, 30±0.3, 30±0.6 % (heartwood)] and the non-coppiced [i.e., 28±0.3, 29±0.3, 30±1.2 % (sapwood) and 27±0.6, 29±1.3, 29±0.2 % (heartwood)]trees respectively (Fig. 2); the differences were significant (P<0.05) (Table 3). An increasing trend of AP towards the periphery of stems was recorded in the radial position although no significant differences(P>0.05) existed between them. There was a general axial increase in Ray Parenchyma (RP) from the base to the crown,and radial increase from theheartwood to the sapwood for the coppiced wood [i.e., 4±0.1,5±0.3 7±1.2% (for the heartwood) and 6±0.3, 7±1.2, 8±0.6 % (for the sapwood)] and the non-coppiced [i.e., 4±0.3, 6±0.2, 7±0 % (for the heartwood) and 7±0.2, 8±0.1, 7±0.3 % (for the sapwood)] respectively (Fig. 2); the amount of RP significantly varied along the axial stem direction (Table 4). No significant differences ($p>0.05$) existed between the proportion of RP from the radial stem direction. Significant difference ($p<0.05$) existed between the amount of RP from the coppiced and non-coppiced trees (Table 4).

The number of vessels generally increased from the butt to the crown/top; the difference was significant ($p<0.05$) (Table 5). The quantity increased from the heartwood to the sapwood [i.e., 4±0.1, 5±0.3, 7±1.2 and 6±0.3, 7±1.2 8±0.6 (for coppiced tree) and 4±0.3, 6±0.2, 7±0 and 7±0.2, 8±0.1, 7±0.3 (the non-coppiced wood) respectively] (Fig. 2); the differences were significant ($p<0.05$). No significant difference ($p>0.05$) existed between the percentage of vessels from the coppiced and non-coppiced trees (Table 5).

Table 2: ANOVA for the amountof fibres within the coppiced and non-coppiced *P. erinaceus*boles

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	130.667	65.333	38.56	<.001***
Radial position	1	32.111	32.111	18.95	<.001***
Tree type	1	106.778	106.778	63.02	<.001***
Axial*Radial position	2	14.889	7.444	4.39	0.024*
Axial*Tree type	2	3.556	1.778	1.05	0.366
Radial*Tree type	1	0.111	0.111	0.07	0.800
Axial*Radial*Tree type	2	8.222	4.111	2.43	0.110
Error	24	40.667	1.694		
Total	35	337.000			

***Significant: P(<0.001) < 0.05; *Significant: P(0.024) < 0.05

Table 3: ANOVA for the amount of Axial Parenchyma within the coppiced and non-coppiced *P. erinaceus*boles

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	21.875	10.937	10.86	<.001***
Radial position	1	1.174	1.174	0.291	0.291
Tree type	1	14.062	14.062	13.97	0.001**
Axial*Radial position	2	1.264	0.632	0.63	0.542
Axial*Tree type	2	0.875	0.438	0.43	0.653
Radial*Tree type	1	0.007	0.007	0.01	0.935
Axial*Radial*Tree type	2	0.264	0.132	0.13	0.878
Error	24	24.167	1.007		
Total	35	63.688			

***Significant: P(<0.001) < 0.05; **Significant: P(0.001) < 0.05

Table 4: ANOVA for theamount of Radial Parenchyma within the coppiced and non-coppiced *P. erinaceus*boles

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	10.0139	5.0069	5.50	0.011*
Radial position	1	2.5069	2.5069	2.76	0.110
Tree types	1	24.1736	24.1736	26.57	<.001***
Axial*Radial position	2	1.7639	0.8819	0.97	0.394
Axial*Tree type	2	1.8472	0.9236	1.02	0.377
Radial*Tree type	1	2.5069	2.5069	2.76	0.110
Axial*Radial*Tree type	2	6.7639	3.3819	3.72	0.039
Error	24	21.8333	0.9097		
Total	35	71.4097			

***Significant: P(<0.001) < 0.05; *Significant: P(0.011) < 0.05

Table 5: ANOVA for the amount of vessels within the coppiced and non-coppiced *P. erinaceus*boles

Source of variation	Df	SS	MS	F-value	P-value
Axial position	2	30.5000	15.2500	16.76	<.001***
Radial position	1	14.1878	14.1878	15.60	<.001***
Tree type	1	0.1878	0.1878	0.21	0.654
Axial*Radial position	2	3.1089	1.5544	1.71	0.202
Axial*Tree type	2	0.9756	0.4878	0.54	0.592
Radial*Tree type	1	0.2500	0.2500	0.27	0.605
Axial*Radial*Tree type	2	1.1667	0.5833	0.64	0.535
Error	24	21.8333	0.9097		
Total	35	72.2100			

***Significant: P(<0.001) < 0.05

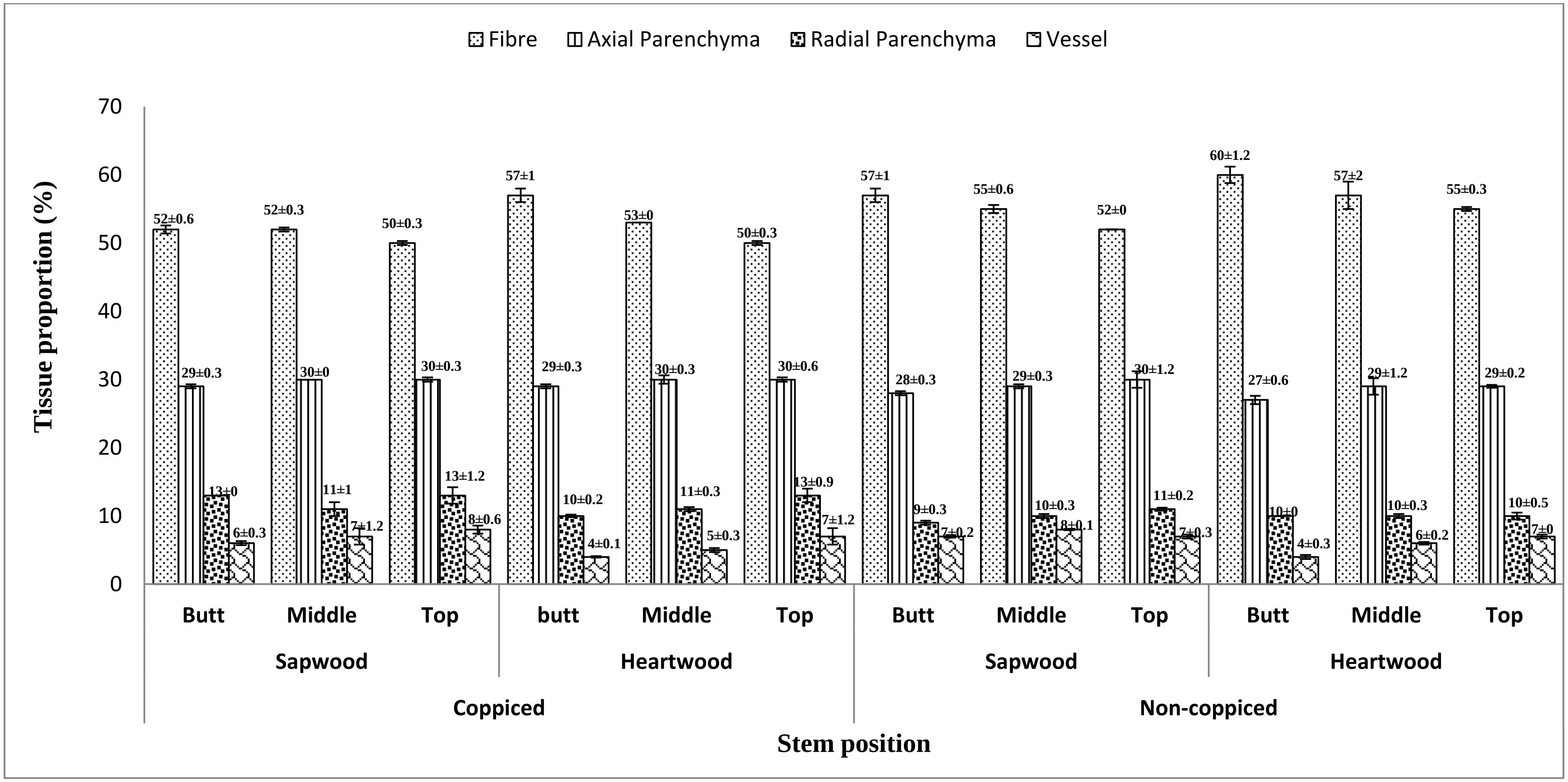

Fig. 2: Tissue proportion within the boles of coppiced and non-coppiced *P. erinaceus*

4. Discussion

4.1 Anatomical characteristics of *Pterocarpus erinaceus*

4.1.1 Anatomical description of *P.erinaceus* wood

*P. erinaceus*wood is diffuse-porous with absent or indistinct growth ring boundary. It has thick-walled fibres with simple to minutely bordered pits, tyloses and prismatic crystals in its vessels and chambered axial parenchyma correspondingly (Plates 1-6). Anatomical description of the wood belonging to theFamily Fabaceae-Papilionoideae is being diffuse-porous[34, 35]. Wood with indistinct or no growth ring boundaries are alsoone of the characteristics of tropical trees[31, 36]. Its thick-walled fibres would make it suitable for wide range of applications from light to heavy construction and enhance its processing, as extremely thick-walled fibresusually pose processing challenges including sawing difficulty. However, the wood would be suitable for veneering, cabinetry, railway sleepers, mine props, flooring, paneling and furniture manufacturing. Besides, the simple to minutely bordered pits together with the thin-thick-walled fibres would ensure efficient application of chemicals (e.g., adhesives), which ensures effective bonding of wooden membersfor furniture and joinery as well as fibre-based products[37]. However, its wood deposits (e.g., crystals, tyloses) may influence the suitability of wood species for particular end-uses such as wood composites (e.g., plywood, veneer), building construction, pulp and paper and furniture[38, 39]. For instance, prismatic crystals pose processing challenges such as blunting effects on saws and cutting tools[40], whiletyloses impede the penetration of chemicals into wood, rendering it impermeable to adhesives and preservatives[41]. [39] and [42] explained that the profusion of tyloses in *G. arborea* made it very resistant to preservative penetration and retarded the setting of cement most, among eight wood species used for wood-cement composites. Moreover, such wood deposits make chip impregnation during pulping very difficult, which leads to poor penetration, drastic cooking and low pulp yield with high reject content, in addition to ultimate bleaching challenges[43]. Nonetheless, their presence (e.g., tyloses) would affect water movement in trees and substantially impede the movement of wood deteriorating organisms by blocking the vessel lumina[44, 45]. Hence, the timber from the coppiced and non-coppiced *P. erinaceus* trees would have the inherent ability to resist the activities of bio-deteriorating organisms due to the presence of tyloses and crystals in them[16, 46]. Moreover, crystals could add a shining appearance on wooden products when profuse, which may partly explain the rich hue of *P. erinaceus*[39].

4.1.2 Vessel lumen diameter of coppiced and non-coppiced *P. erinaceus*

The non-coppiced trees recorded greater vessel diameters (92±1.2-126±2 %) along their boles than those from the coppiced trees (91±0.6-117±3 %). Even so, most diffuse-porous hardwoods have vessels<200 µm(47). Thus, the vessel lumen diameter values recorded for the coppiced and non-coppiced trees conform to this finding for diffuse-porous woods. Wider vessel diameters were recorded generally for the sapwoods [i.e., 112±4, 102±1, 117±3 (from the coppiced tree) and 120±1.2, 121±0.3, 119±2 (from the non-coppiced tree) than for the heartwood [i.e., 91±0.6, 104±2.3, 113±2 (from the coppiced tree) and 100±0.3, 126±2, 92±1.2 (from the non-coppiced tree)] along the boles of both tree types. This is in concurrence with the previous studies by[48]and [49], which acknowledged that vessel lumina increased in size from heartwood (i.e., dead xylem tissue) to sapwood (i.e., active xylem tissue) of trees. Molecular changes (e.g., cell division) and physiological changes (including transpiration and assimilation) that occur in the vascular cambium during cell differentiation could be responsible for the differences in vessel lumen diameter between heartwood and sapwood[50, 51]. Axial variation of vessel lumen diameter did not show any clear trend. Wood could modify their vessel characteristics in order to adjust to the rate of water conduction[52]. Besides, typical requirements for mechanical support[53, 54]and different types of stem construction[55]could lead to varying trends of vessel composition and distribution in timbers. Moreover, the differences between the coppiced and non-coppiced *P. erinaceus* trees could be due to their inherent physiological and genetic properties[56].

The size of vessel lumina influences the water conduction efficiency of timber[57, 58]. *Albizia ferruginea* was observed to have great water uptake capacity owing to its large vessel lumina (300 µm)[59]. However, wider vessels reduce wood density and make timber unsuitable for production of paper and solid-wood products (e.g., railway sleepers, parquet flooring)[60]. As formerly reported by[21] for fibre lumina, wide vessels additionally absorb more moisture into their cavities thereby creating favourable environment for bio-degraders including decay fungi[41]. Thus, coppiced and non-coppiced *P. erinaceus* trees would not be most susceptible to the above-mentioned menace of extremely wide vessel diameters.Large vessel diameters are also unfavourable for paper-making since they present more defects in refining and printing processes and pose problems in the finishing of solid wood products[62]. Nonetheless, large vessels ensure effective penetration of cooking liquor during pulping, which alone is not sufficient to enhance better paper qualities. Thus, coppiced wood is expected to have better paper properties than its respective non-coppiced counterpart[63]. However, their vessel lumen diameters are both ranked small to medium[58, 64].

4.1.3Tissue proportions within the boles of coppiced and non-coppiced *P. erinaceus*

4.1.3.1The percentage of fibres

The respective fibre percentage for non-coppiced*P. erinaceus* from the base to the crown of the trees were greater [i.e., 57±1, 55±0.6, 52±0 % (for sapwood) and 60±1.2, 57±2, 55±0.3 % (for heartwood)] than those from the coppiced [i.e., 52±0.6, 52±0, 50±0.3 % (for sapwood) and 57±1, 53±0, 50±0.3 % (for heartwood)]. The amount of fibres generally decreased up the stem and was greater for heartwood than its corresponding sapwood. (Fig. 2). The differences were significant($p<0.05$).

Usually, coppiced trees grow faster than the non-coppiced[65, 66]. Thus, the differences in growth characteristics exist for such tree types and may cause some variations in their formation, which ultimately affect their wood properties[67, 68]. Moreover, inherent physiological and genetic properties of the two tree types could account for the differences in their fibre proportions[56].

Juvenile wood is often related with shorter fibres, thinner cell walls and greater microfibril angles than its mature wood (69). It is formed under the conditions of apical meristem action on the cambium in the stems of both softwoods and hardwoods[70, 71]. With age, butt ends of stems are away from the crown and are no longer affected by the apical meristem. Thus, away from the juvenile wood zone, wood cells with characteristics of mature wood (e.g., great fibre content), are formed at the butt[12, 71].Similarly, the decrease in fibre content from the butt to the crown of both coppiced and non-coppiced *P. erinaceus*could be attributed to the variation in mature and juvenile wood characteristics along their boles.

Radial variation is the best known and most studied within tree variability, which is normally reflected as radial pattern of change in wood characteristics of juvenile and mature woods[72]. A radial decrease in fibre proportion from the heartwood to the periphery (i.e., the sapwood) was established by our study for *P. erinaceus*timbers. Molecular changes (e.g., cell division) and physiological changes (e.g., transpiration and assimilation),which occur in the vascular cambium during cell differentiation could be responsible for the differences recorded in fibre proportions between the sapwood and the heartwood for both trees[50, 51]. It could also be attributed to the wood's inherent variability.

Fibre content generally decreases from the pith to the periphery and from the butt up the tree height[73].Fibres are, thus, expected to be greater at the butt than at the crown and in the heartwood than the sapwood of a tree. Fibre proportion is related to mechanical properties[74]. These include the compressive strength, Modulus of Rupture (MOE) and Modulus of Elasticity (MOR), shear and tensile strengthsas well as hardness. Great wood density is the result of greatcontent of thick-walled fibres[75]. Coppiced and especially non-coppiced *P. erinaceus* trees are, therefore, expected to have acceptable density since they recorded great amounts of thick-walled fibres and would be suitable for engineering applications such as cabinetry, furniture construction, framing, railway sleepers, mine props, wood composites, and flooring.Similarly,*Carya ovata*, utilized for such applications, has been found to contain great fibre content[58].

4.1.3.2 The percentage of parenchyma

For both Axial and Ray Parenchymacells, coppiced trees recorded greater values than their non-coppiced counterparts with an axial increase from their butt to crown positions (Fig. 2). Both cells radially increased from heartwood to sapwood although the variation was not significant ($p>0.05$).The differences in axial and ray parenchyma cells between the coppiced and non-coppiced *P. erinaceus* trees could be due to their inherent physiological and genetic properties[56], and also changes in juvenile and mature wood properties. In general, butt positions are away from the actions of the apical meristem, which influence juvenile wood production. Thus, away from juvenile wood zones, wood cells with mature characteristics (e.g., less amount of parenchyma cells) are produced[71]. However, environmental and genetic factors could also contribute to the variation in axial and ray parenchyma cells[12, 56].

Both axial and ray parenchyma cells are apparently concerned with physiological functions, which include the storage of nutrients or heartwood formation in trees[76]. Nonetheless, non-fibrous tissues (e.g., parenchyma) pose various problems in paper-making to the extent that greater amounts negatively influence paper quality[71]. Too many parenchyma cells cause "fines" in pulp,which lead to slow machine drainage and effluent difficulties[78]. Moreover, non-fibrous cells cause low timber density[75], which was confirmed for *Liquidambar formosana* and *Turraenthus* *africanus*. Ray and axial parenchyma cells could also cause substantial damage and drying defects to wood including splitting and cracking[79]. Therefore, coppiced and non-coppiced *P. erinaceus* trees are expected to produce high pulp yield and resist problems of "fines" since fibres formed the greatest proportion of all the tissues. Besides, they would have densities of acceptable mechanical properties suitable for applications where strength is a fundamental requirement such as railway sleepers, building construction, flooring, furniture production and mine props, among others. They would also resist problems of dimensional instability in service, as their parenchyma cellsare relatively low. Greater amount of carbohydrates (e.g., starch) could lead to early growth of micro-organisms, which renders wood highly degradable and inferior in quality[39]. The lower amounts of carbohydrates for heartwoods along the coppiced and non-coppiced *P. erinaceus* boles could increase the service-lives of their products by limiting the activities of wood deterioratingorganisms.

4.1.3.3The percentage of vessels

The number of vessels increases with tree height because of increased physiological activities at those portions[23, 81]. The percentage of vessels generally increased from the butt to the top/crown for the two *P. erinaceus*tree types (Fig. 1), which conforms to erstwhile studies[44, 81]. The number of vessels wasgreater in the *P. erinaceus*sapwood than in the heartwood [i.e., 6±0.3, 7±1.2 8±0.6 and 4±0.1, 5±0.3, 7±1.2 respectively (for coppiced tree) and 7±0.2, 8±0.1, 7±0.3 and 4±0.3, 6±0.2, 7±0 respectively (for non-coppiced tree)], which supports the trend similarly observed[80, 82]. Coppiced trees recorded fewer vessels than their non-coppiced counterparts but there were no significant differences ($p>0.05$) between them (Table 5).

Tropical trees modify the distribution of their vessels to acclimatize different stem construction, mechanical strength and their requirement for sufficient water supply[52, 54, 55]. The number of vessels in wood influences its utilization and the occurrence of several vessels together can reduce the density and mechanical properties of timber but ensure efficient water conduction[81]. Besides, the dominance of vessels in wood is not suitable for paper-making. Fewer vessels of coppiced and non-coppiced *P. erinaceus* compares well with *Carya ovata* (6.5%)[58] and, hence, would have considerable mechanical properties for decorative paneling, furniture construction, flooring, mine props, railway sleepers, among others. They would also be suitable for pulp and paper manufacturing, as their fewer vessels are desirable for production[63].

5. Conclusion

- ✓ *P. erinaceus* wood is diffuse-porous with no or indistinct growth ring boundary. It has tyloses and prismatic crystals in its vessel lumina and chambered axial parenchyma respectively, which arethe characteristics typical to tropical hardwoods of the family Fabaceae.
- ✓ Thick-wall fibres constitute the greatest proportion of all *P. erinaceus* wood tissues, which would make it dense, strong and durable against bio-deteriorating organisms.
- ✓ The timber contains deposits (e.g., tyloses and prismatic crystals), which would create problems for liquid movement, chemical preservation, paper making and wood processing.
- ✓ The non-coppiced trees recorded morefibres [i.e., 57±1, 55±0.6, 52±0 % (in the sapwood) and 60±1.2, 57±2, 55±0.3 % (heartwood)] than their respective coppiced counterparts [i.e., 52±0.6, 52±0, 50±0.3 % (sapwood) and 57±1, 53±0, 50±0.3 % (heartwood)].
- ✓ Heartwood fibreswere greater than those in sapwood, and in the butt than in the crown. The differences were significant ($P<0.05$). These wood types would be suitable for both solid wood products where strength is an important requirement andfibre-based products, asthey would have acceptable densities.
- ✓ The coppiced trees recorded greater axial parenchyma than the non-coppiced. Increase in axial parenchymaexisted from the butt to the crown from coppiced [i.e., 29±03, 30±0, 30±0.3 % (sapwood) and 29±0.3, 30±0.3, 30±0.6 % (heartwood)] and non-coppiced [i.e., 28±0.3, 29±0.3, 30±1.2 % (sapwood) and 27±0.6, 29±1.3, 29±0.2 % (heartwood)] trees. Nevertheless, both trees recorded minimum levels, which would resist against biodegraders in service.
- ✓ Ray parenchyma increased axially up the stem,and radially from the heartwood to the sapwood for the coppiced wood [i.e., 4±0.1, 5±0.3 7±1.2 % (for heartwood) and 6±0.3, 7±1.2, 8±0.6 % (for sapwood)] and the non-coppiced [i.e., 4±0.3, 6±0.2, 7±0 % (for heartwood) and 7±0.2, 8±0.1, 7±0.3 % (for

sapwood)].These levels fall within the utilizable limits for various end-uses as far as natural durability is concerned.

- ✓ The number of vessels generally increased up the stem; it was greater for sapwood than heartwood [i.e., 6±0.3, 7±1.2 8±0.6 and 4±0.1, 5±0.3, 7±1.2 (for coppiced) and 7±0.2, 8±0.1, 7±0.3 and 4±0.3, 6±0.2, 7±0 (for non-coppiced) respectively]. No significant difference ($p>0.05$) existed between those in the coppiced and non-coppiced.The vessel proportions recorded for these two wood types are also acceptable for solid-wood and fibre-based products.
- ✓ Vessel diameter was greater for the non-coppiced trees [i.e., 120±1.2, 121±0.3, 119±2 (for sapwood) and 100±0.3, 126±2, 92±1.2 µm (for heartwood)] than the coppiced [i.e., 112±4, 102±1, 117±3 (for sapwood) and 91±0.6, 104±2.3, 113±2 (for heartwood)].Both have small-medium size vessels and are appropriate for solid-wood and fibre-based product manufacturing.
- ✓ Wood anatomical propertiessuch as vessel lumen diameter, percentage fibres, parenchyma cells, and vessels for coppiced and non-coppiced *P. erinaceus*trees are within the utilizable limit for hardwoods famed for furniture, fibre-based products, structural applications and other uses.
- ✓ Xylem anatomy from coppiced and non-coppiced trees are comparable and the former could, thus, supplement the latter in the famed applications for which the non-coppiced trees are known for.
- ✓ Coppicing should be promoted for timbers, which have the capacity to (e.g., *P. erinaceus*) to contribute to the production of enough raw materials to sustain the Timber Industry.

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