ANATOMICAL PROPERTIES OF *PTERYGOTA ALATA*: AN ALTERNATE TREE SPECIES FOR SUSTAINABLE PRODUCTION OF WOOD

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(Received 3rd Dec 2022; accepted 27th Feb 2023)

Abstract. Current investigation was conducted to comprehend the girth increment and axial variation impact on the anatomical behavior of wood. To determine the intended uses, it is important to investigate the anatomical features of the wood. For this study, wood was removed from seeds origin *Pterygota alata* which were farm grown in Pollachi, Tamil Nadu, India. And from that 2×2×2 cm dimension samples were collected from four different girth classes (30-45, 45-90, 120-150, and 150-180 cm) and three axial positions (25%, 50% and 75% of the tree height). The samples were then subjected to microtomy, maceration, and optical measurements. The vessel, fibre, and ray anatomy were studied in this investigation. A log-linear model was used to examine the combined impact of girth increment, axial positions and their interaction. Fibre length, fibre diameter, fibre wall thickness, vessel length, ray height, ray width, and ray frequency were decreased towards the top, whereas fibre lumen width, vessel diameter, and vessel area were significantly increased towards the top. Growth of the girth had a positive influence on fibre length, fibre diameter, fibre lumen width, fibre wall thickness, vessel length, ray height, ray width and ray frequency. In contrast, vessel frequency decreased with the girth increment. Fibre and ray of the *Pterygota alata* were more than or near 1000 µm and vessels were diffuse porous among all the axial positions and girth classes. The anatomical characteristics of the *Pterygota alata* are similar to those of wood species used to make pulp and paper, so it could be a potential species to use in pulp production.
Keywords: *anatomical features, axial position, girth classes, fibre, vessel, ray*

Introduction

Pterygota alata (Roxb.), commonly known as "Buddha's Coconut tree" (Jahan et al., 2014; Mitra et al., 2015; Saudale et al., 2020) is large tropical tree species native to South Asia and Myanmar. It has a high, narrow crown with horizontal branches (Jahan et al., 2014). In India, it is in the Sub-Himalayan region from Nepal eastward to West Bengal, Assam, and Maharashtra, as well as in Uttar Pradesh, Tamil Nadu, and the evergreen forests of Karnataka and Kerala. This tree can grow up to a height of at least 35 metres and produce buttresses in an open forest with favourable climatic conditions (Thothathri, 1962). Its smooth bole is one metre in diameter and almost 12 metres long. This species is most frequently utilized as a decorative tree in gardens (Gamble, 1881). Buddha's Coconut Wood has a short shelf life, is light in weight, and ranges in colour from milky white to white (Fatma et al., 2018). The wood-based sectors, including plywood, furniture, toys, sticks, packaging, and other handicrafts, have recently seen a rise in demand for this tree.

For the sustainable management of tree resources and their use, studies that increase knowledge about the anatomy of wood are crucial (Naji et al., 2011). Wood anatomical characteristics act as the structural foundation for other wood attributes and are frequently used to assess wood quality (Quilho et al., 2000; Miranda and Pereira, 2002; Huang et al., 2003; Zhang et al., 2020). Many internal and external factors that govern tree growth, such as genetic origin, cambial age, and silvicultural methods, are strongly tied to the anatomical features of wood e.g., *Populus* (Doungpet, 2005; Šefc et al., 2009), *Eucalypts* (Zobel and Buijtenen, 1989; Ramírez et al., 2009) and *Cunninghamias* (Guo, 2014; Li et al., 2014), all exhibit considerable genetic control over their wood anatomical characteristics. Furthermore, Pande and Singh (2005) reported significant inter-clonal variation in wood anatomical properties in *Dalbergia sissoo*. Luostarinen et al. (2017) found that clones of Finnish Norway spruce significantly differed from each other in anatomical characteristics. The spatial patterns of wood anatomical properties within trees, as well as the differences across trees, are important for plant structure, mechanical support and other cross-disciplinary purposes in addition to the production of wood (Li et al., 2019). In broadleaf trees, fibres and vessels make up the majority of the wood anatomical structure (De Mil et al., 2018), and their size, quantity and shape are important indicators. The radial and axial growth of trees have a remarkable impact on the microstructure of wood. According to studies, radial and axial growth cause changes in the vessel diameter, fibre length, fibre diameter, cell wall thickness, and vessel frequency (Liu et al., 2020). Vertically, a decline in fibre length with axial height has been reported in a few hardwood species (Webb, 1964; Saucier and Thras, 1966) as well as according to some contrary findings, in a few tree species, vessel lumen diameter was found to decrease with axial height (Anfodillo et al., 2006; Petit et al., 2007), although it did not apply universally.

The demand for short- and long-rotation wood species has dramatically risen as a result of population exponential growth, fast urbanisation, and industrialisation (Parthiban et al., 2017). To meet the rising demand for wood products, the wood supply segment has expanded its preference for fast-growing tree species (Zziwa et al., 2006; Sseremba et al., 2016). Due to the rising demand for wood and fibre and the dwindling supply of wood, agroforestry and farm forestry have been used to investigate possible fast-growing tree species appropriate for different wood-based industries (Parthiban et al., 2014). Among the various fast-growing species, the potential of *Pterygota alata* is also promising. The anatomical characteristics of Eucalyptus (Pirralho et al., 2014), *Pterygota macrocarpa*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_20112029

and *Pterygota brasiliensis* (Gottwald and Richter, 1984), are similar to those of *Pterygota alata*. In the case of comparable functioning, it is expected that *Pterygota alata* wood will be able to perform the same tasks as the aforementioned species of wood. Compared to other fast-growing trees, *Pterygota alata* has not undergone any systematic research. Keeping this view in mind, the study was carried out to explore the significant effects of girth increment and axial height on the anatomical traits of *Pterygota alata* as an alternate species for the sustainable production of wood.

Materials and methods

Study area description

The study was carried out between 2019 and 2022. Samples of wood were removed from the agroforestry farm in Pollachi, Coimbatore, Tamil Nadu, India (10° 39'N; 77° 0'E). The study region has a tropical climate with an annual rainfall of 650 mm it is primarily caused by the southwest monsoon because of the Palghat gap. The 36°C is the maximum temperature and 33°C is the minimum temperature of the summer season, which lasts from March through May. The winter, with average temperatures of 20 to 22°C, begins in early October and lasts until late January. Generally Medium to deep red calcareous soil found in the study area.

Wood sampling

The samples were removed from seeds origin *Pterygota alata* which were grown on a farm with a spacing of 5 × 5 m with a specification of four different girth classes (30-45, 45-90, 120-150 and 150-180 cm) (*Fig. 1a*). In each girth class, 3 trees were removed for the study from which circular discs of 2 cm height were obtained from three different axial positions (25%, 50% and 75% of the tree height), and the wood samples each of dimension with a size of 2×2×2 cm were sliced out separately (*Fig. 1d*)). For each anatomical characterization, six wooden cubes were taken at the radial direction (pith to periphery) from the round disc (*Fig. 1b and 1c*). Before going to slice in microtome the wooden cubes were boiled in water for 20 min and then these samples thin microscopic sections of size 15 to 20 µm were taken using ‘Yorco precision rotary microtome’ (Lipshaw Type YSI-115– Japan). For fibre and vessel length analysis, wood samples were subjected to maceration.

Maceration

Maceration of the wood samples was done by using Jeffrey’s method (Sass, 1971). For maceration, Jeffrey’s solution was used which was prepared by mixing equal volumes of 10% potassium dichromate and 10% nitric acid. Wood shavings were taken from the 2 cm^3 wood blocks separately from the three axial positions *viz.*, 25%, 50% and 75% of the tree height. These shaves were boiled in the maceration fluid for 15 to 20 min so that the fibre individuals were separated. Then these test tubes were kept for 5 to 10 min so that the fibres settled at the bottom. Then the solution was discarded and the resultant material was thoroughly washed in distilled water until traces of acid were removed. The fibre samples were stained using safranin and mounted on temporary slides using glycerin as the mountant.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
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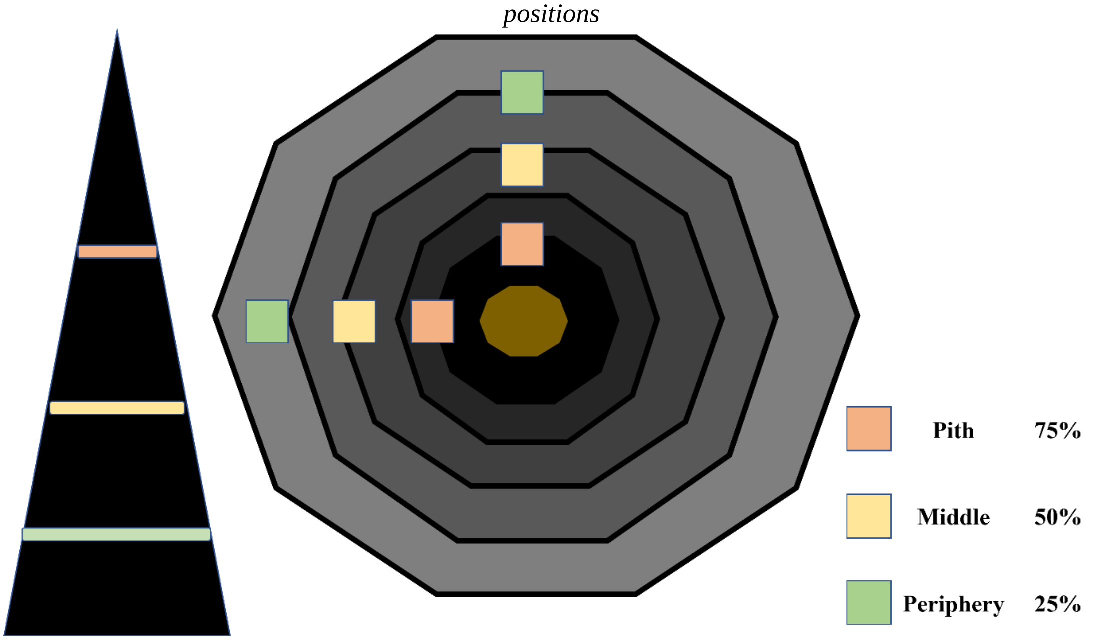
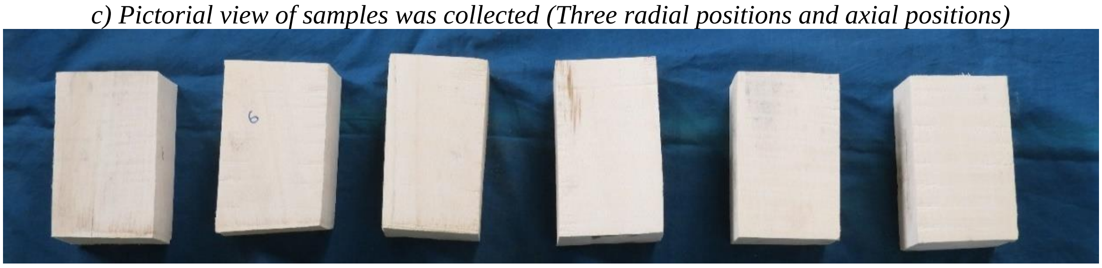
a) Pterygota alata tree grown in farm condition b) Round disc collected from three different axial positions



c) Pictorial view of samples was collected (Three radial positions and axial positions)



d) 2x2x2 cm^3 samples were taken out from round disk

Figure 1. *Anatomical features of Pterygota alata*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
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Measurements of anatomical features

Different measurements were taken from the macerated wood samples *viz.,* fibre length (µm), fibre diameter (µm), fibre lumen width (µm) by measuring the width of the lumen at the cross-sectional area and fibre wall thickness (µm) by measuring the thickness of the wall cross-sectional area. Also, vessel length (µm) measurements were taken from the macerated samples of the wood, whereas vessel diameter (µm), vessel area (μm^2) was measured on the transverse sections (TS) of microscopic slice, as well as vessel arrangement in the heartwood of the species was identified as per Rao and Juneja (1971). Frequency of vessels per squared millimetre was calculated by counting the number of vessels in randomly selected areas per field and using the formulae given below (*Equation 1*). In each field, three count areas were taken.

$$\text{Vessel frequency} = \frac{\text{Number of Vessels}}{\text{Area in } \mu^2}\ x\ 10^6 \qquad \text{(Eq.1)}$$

Ray height and width (µm) were measured on the tangential longitudinal sections (TLS) for each tissue type. Frequency of rays per squared millimetre was calculated by counting the number of rays intersecting with a transect line drawn randomly in each field (*Equation 2*). Observations were recorded by counting the rays at three different lines.

$$\text{Ray frequency} = \frac{\text{Number of rays}}{\text{Area in } \mu^2}\ x\ 10^6 \qquad \text{(Eq.2)}$$

All the observations were carried out by using Optika Digital Microscope (Italy) and measurements of the anatomical sample were done by Optika Image Analyser software on the 100 and 200 µm scale bar. The 10× magnificent was used to measure the fibre and vessel morphology, while the 4× magnificent was used to measure the rays.

Statistical analysis

Measurements of the anatomical properties were analysed by Statistical Package for Social Science data (SPSS) IBM software version 20. Variation among the trees for each anatomical trait was analysed by a two-way ANOVA test. To compare the treatment means, the Tukey’s test was performed using the Statistical Package for Social Science data (SPSS) software. A log-linear model was used to examine the combined impact of girth increment, axial positions and their interaction (*Equation 3*).

$$y = a + b * \ln(x) \qquad \text{(Eq.3)}$$

Results

Within tree variation in fibre morphology

Regarding the anatomical properties of *Pterygota alata* the highest fibre length (FL) of 1757±32.23 µm was found in 45-90 cm girth at 25% of tree height in the axial position and the lowest was 919.00±19.59 µm in 30-45 cm girth class at 75% tree height and it was decreased from 25 to 75 % of tree height (*Fig. 2 and Table 1*). Generally, longer fibres are identified at 25% tree height compared to 75% tree height. The maximum fibre diameter (FD) of 27.20±0.46 µm was noticed in the 150-180 cm girth class at 50% of tree

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
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height and the minimum fibre diameter of 18.00±0.82 µm was in 30-45 cm at 75% tree height. The fibre lumen width (FLW) of 18.42±0.87 µm was found to be highest in the 150-180 cm girth class at 75% tree height whereas, the lowest was in the 30-45 cm girth class with 25% tree height as 13.25±0.37 µm. The maximum fibre wall thickness (FWT) of 7.91±0.10 µm was seen in 150-180 cm girth classes with 50% tree height while the minimum of 4.18±0.19 µm was found in 30-45 cm girth class with 75% tree height (*Fig. 3*). This pattern was significant among the different girth classes and axial positions (p<0.01, p<0.05).

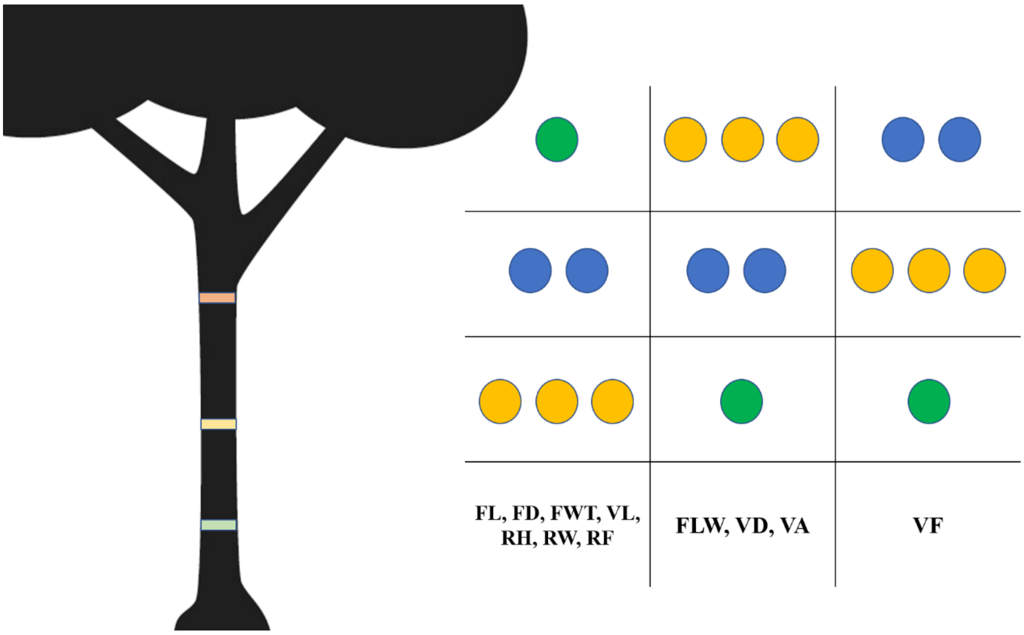

Figure 2. *Anatomical variation at base, middle and top region of the tree. Green represents low, blue represents moderate and yellow represents maximum values of the anatomical traits*

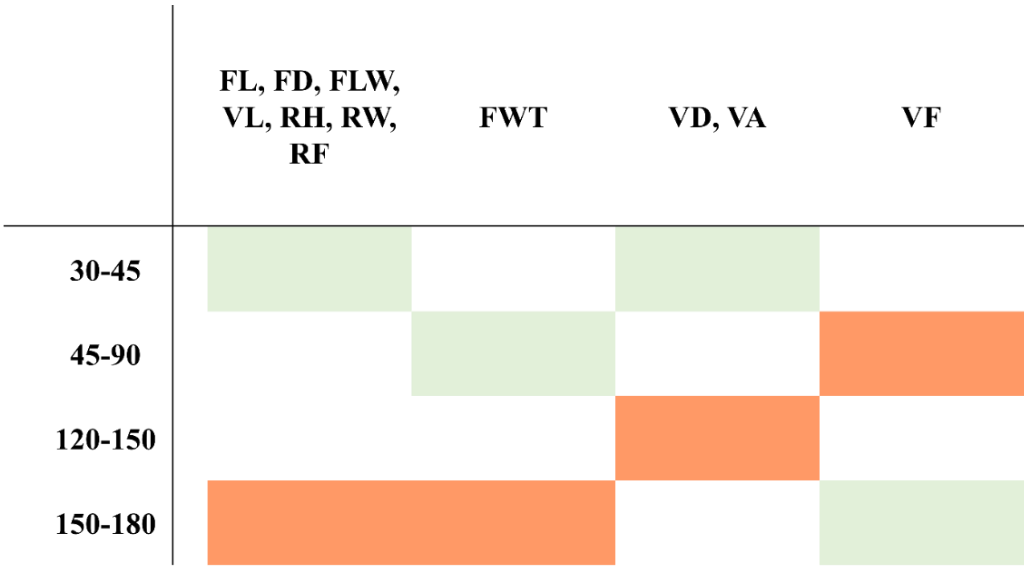

Figure 3. *Girth class wise representation of the maximum and minimum values of anatomical traits. Olive green represents minimum and orange represents maximum value*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_20112029

Table 1. *Within tree fibre anatomical variation with axial position*

Fibre morphology	Girth classes (cm)	Axial Position			Mean
		25%	50%	75%	
FL (µm)	30-45	1601.50 ± 8.87	1308.15 ± 12.05	919.00 ± 19.59	1276.22[c]
	45-90	1757.06 ± 32.23	1421.58 ± 20.03	971.67 ± 10.59	1383.44[a]
	120-150	1733.50 ± 27.40	1355.67 ± 9.53	959.00 ± 12.17	1349.39[b]
	150-180	1731.50 ± 26.60	1418.67 ± 23.69	1016.67 ± 37.59	1388.94[a]
	Mean	1705.89[a]	1376.02[b]	966.58[c]	1349.50
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	12.73	22.75	31.00	0.000 **
	Axial position	11.02	26.27	35.79	0.000 **
	G×A	22.04	45.50	62.00	0.099 NS
FD (µm)	30-45	21.00 ± 0.55	19.25 ± 0.82	18.00 ± 0.82	19.42[c]
	45-90	22.96 ± 0.15	22.77 ± 0.63	21.01 ± 0.69	22.25[b]
	120-150	24.17 ± 0.37	23.10 ± 0.18	21.41 ± 1.04	22.89[b]
	150-180	26.33 ± 0.16	27.20 ± 0.46	23.77 ± 0.63	25.77[a]
	Mean	23.61[a]	23.08[a]	21.05[b]	22.58
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.35	0.72	0.99	0.000 **
	Axial position	0.30	0.63	0.85	0.000 **
	G×A	0.61	1.25	1.71	0.185 NS
FLW (µm)	30-45	13.25 ± 0.37	13.49 ± 0.50	14.37 ± 0.15	13.70[c]
	45-90	14.97 ± 0.34	15.33 ± 0.65	16.83 ± 0.04	15.71[b]
	120-150	15.28 ± 0.32	15.22 ± 0.25	17.07 ± 0.06	15.86[b]
	150-180	16.09 ± 0.40	17.22 ± 0.23	18.42 ± 0.87	17.24[a]
	Mean	14.90[b]	15.31[b]	16.67[a]	15.63
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.24	0.50	0.68	0.000 **
	Axial position	0.20	0.43	0.59	0.000 **
	G×A	0.42	0.86	1.17	0.376NS
FWT (µm)	30-45	7.31 ± 0.45	6.67 ± 0.11	4.18 ± 0.19	6.05[b]
	45-90	6.26 ± 0.24	5.58 ± 0.24	3.63 ± 0.22	5.16[c]
	120-150	7.15 ± 0.23	7.31 ± 0.50	4.24 ± 0.24	6.23[b]
	150-180	7.86 ± 0.18	7.91 ± 0.10	5.92 ± 0.33	7.23[a]
	Mean	7.14[a]	6.88[a]	4.49[b]	6.17
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.16	0.33	0.45	0.000 **
	Axial position	0.14	0.29	0.39	0.000 **
	G×A	0.28	0.57	0.78	0.090NS

**= Significant at the 0.01 level; * = Significant at the 0.05 level; NS = Non-significant; FL = fibre length, FD = fibre diameter, FLW = fibre lumen width, FWT = fibre wall thickness

Within tree variation in vessel morphology

Results revealed that among the different girth classes, the highest vessel length of 319.70±0.69 µm was recorded in the 120-150 cm girth class at 25% tree height and the lowest vessel length of 174.68±0.53 µm was reported in 45-90 cm girth class with 75% tree height. The axial variation of the vessel diameter of *Pterygota alata* shows a consistent pattern, which was increased with the height with a value ranging from 50.57±1.03 to 83.80±0.83 µm in 45-90 cm girth class with 25% tree height and 120-150 cm with 75% tree height respectively (*Fig. 2*). The area of vessels did not show a conspicuous pattern, but there is a general observation that the 75 percent portion of the

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_20112029

tree had vessels with a larger area in the 120-150 cm girth class estimates as 38905.93±1183.83 µm^2 and the 25% tree height had vessels with a smaller area of 12852.25±496.64 µm^2 in 30-45 cm girth class. The highest vessel frequency of 5.98±0.03/mm^2 was observed in the 45-90 cm girth class with 25% tree height and the lowest 2.48 ± 0.46 /mm^2 was in the 150-180 cm girth class with 25% tree height. Uniquely, the vessel area of the 120-150 cm and 150-180 cm girth classes did not show statistical significance depicting uniform vessel area at all the tree height levels else the recordings of the vessels highly significantly differed among the axial position (*Fig. 3 and Table 2*).

Table 2. *Within tree vessel anatomical variation with axial position*

Vessel morphology	Girth Classes (cm)	Axial Position			Mean
		25%	50%	75%	
VL (µm)	30-45	214.30 ± 0.37	206.66 ± 1.16	196.94 ± 1.45	205.97^d
	45-90	263.95 ± 0.56	219.11 ± 0.54	174.68 ± 0.53	219.25^c
	120-150	319.70 ± 0.69	185.00 ± 1.92	176.72 ± 1.29	227.14^b
	150-180	267.05 ± 0.56	238.22 ± 1.36	203.13 ± 1.41	236.14^a
	Mean	266.25^a	212.25^b	187.87^c	222.12
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.63	1.13	1.54	0.000 **
	Axial position	0.55	1.31	1.78	0.000 **
	G×A	1.09	2.67	3.08	0.000**
VD (µm)	30-45	51.00 ± 0.07	52.18 ± 0.82	56.92 ± 0.90	53.37^b
	45-90	50.57 ± 1.03	53.01 ± 0.42	61.60 ± 1.02	55.06^b
	120-150	66.26 ± 0.49	73.74 ± 0.85	83.80 ± 0.83	74.60^a
	150-180	66.58 ± 1.15	74.37 ± 2.91	78.95 ± 0.50	73.30^a
	Mean	58.60c	63.33b	70.32a	64.08
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.65	1.35	1.84	0.000 **
	Axial position	0.57	1.17	1.60	0.000 **
	G×A	1.13	2.34	3.19	0.005**
VA (µm^2)	30-45	12852.25 ± 496.64	24043.96 ± 128.96	27043.16 ± 368.17	21313.12^c
	45-90	22952.69 ± 1161.77	24702.60 ± 1633.06	35059.05 ± 1038.00	27571.44^b
	120-150	37515.93 ± 1955.93	35797.08 ± 2408.66	38905.93 ± 1183.83	37406.31^a
	150-180	35850.94 ± 772.53	35788.75 ± 456.07	35991.26 ± 1163.39	35876.98^a
	Mean	27292.95^c	30083.10^b	34249.85^a	30541.97
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	720.34	1486.71	2025.95	0.000 **
	Axial position	623.83	1287.53	1754.52	0.000 **
	G×A	1247.66	2575.05	3509.05	0.001**
VF (per mm^2)	30-45	4.96 ± 0.04	5.47 ± 0.02	5.11 ± 0.15	5.18^a
	45-90	5.98 ± 0.03	5.33 ± 0.00	4.61 ± 0.01	5.31^a
	120-150	3.97 ± 0.02	4.56 ± 0.03	3.96 ± 0.03	4.16^b
	150-180	2.48 ± 0.46	4.51 ± 0.46	4.50 ± 0.00	3.83^c
	Mean	4.35^c	4.97^a	4.55^b	4.62
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.11	0.23	0.31	0.000 **
	Axial position	0.10	0.20	0.27	0.000 **
	G×A	1.92	0.40	0.54	0.000**

**= Significant at the 0.01 level; * = Significant at the 0.05 level; NS = Non-significant, VL = vessel length, VD = vessel diameter, VA = vessel area, VF = vessel frequency

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Within tree variation in ray morphology

Ray height was inconsistent with all the girth classes and axial positions with estimates in the range of 896.09±3.39 µm (30-45 cm) to 1657.93±0.88 µm (150-180 cm) in 75% and 25% tree height respectively (*Fig. 2*). The maximum ray width of 155.28±1.40 µm was recorded in the 150-160 cm girth class with 25% tree height whereas the minimum of 83.09±1.55 µm was in 30-45 cm at 75% tree height. With respect to the ray frequency highest was noted in 150-180 cm at 25% tree height with a value of 5.32±0.01 /mm^2 and the lowest of 2.98±0.02 /mm^2 was seen in 30-45 cm at 75% tree height (*Fig. 3 and Table 3*).

Table 3. *Within tree ray anatomical variation with axial position*

Ray morphology	Girth Classes (cm)	Axial position			Mean
		25%	50%	75%	
RH (µm)	30-45	1488.63 ± 1.62	1074.92 ± 2.16	896.09 ± 3.39	1153.21
	45-90	1577.60 ± 1.42	1218.82 ± 1.44	965.06 ± 0.93	1253.82
	120-150	1611.52 ± 8.31	1256.52 ± 2.06	996.39 ± 1.72	1288.14
	150-180	1657.93 ± 0.88	1301.74 ± 3.07	1063.80 ± 2.70	1341.16
	Mean	1583.92	1213.00	980.33	1259.08
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	1.80	3.73	5.08	0.000 **
	Axial position	1.56	3.22	4.40	0.000 **
	G×R	3.12	6.46	8.80	0.000**
RW (µm)	30-45	140.19 ± 0.96	122.10 ± 0.81	83.09 ± 1.55	115.13^d
	45-90	143.32 ± 1.01	126.28 ± 0.85	110.58 ± 1.63	126.73^c
	120-150	152.90 ± 0.77	131.40 ± 1.21	113.00 ± 1.41	132.43^b
	150-180	155.28 ± 1.40	136.05 ± 0.78	118.46 ± 1.18	136.60^a
	Mean	147.92^a	128.96^b	106.28^c	127.72
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.67	1.39	1.90	0.000 **
	Axial position	0.58	1.21	1.64	0.000 **
	G×A	1.19	2.41	3.28	0.000 **
RF (per mm^2)	30-45	4.55 ± 0.03	3.52 ± 0.01	2.98 ± 0.02	3.69
	45-90	4.75 ± 0.01	4.11 ± 0.01	3.08 ± 0.00	3.98
	120-150	5.00 ± 0.00	4.34 ± 0.01	3.22 ± 0.00	4.19
	150-180	5.32 ± 0.01	4.50 ± 0.00	3.48 ± 0.02	4.44
	Mean	4.90	4.11	3.19	4.07
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.007	0.015	0.020	0.000 **
	Axial position	0.006	0.013	0.018	0.000 **
	G×A	0.012	0.026	0.035	0.000 **

**= Significant at the 0.01 level; * = Significant at the 0.05 level; NS = Non-significant, RH=Ray height; RW=Ray width; RF=Ray frequency

Discussion

Fibre morphology

Wood anatomical characters are known to have diverse applications in plant systematics and evolution; such data have been employed in the identification and classification of flowering plants (Herendeen and Miller, 2000). Evidence from the present study also suggests that in addition to morphological features, wood anatomical features are useful in identifying and delimiting the *Pterygota alata* wood for different

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end-use applications. The diffuse porous wood, dominance of solitary vessels, axial parenchyma, rays and fibres are unifying characteristics of the *Pterygota alata* wood. The increasing demand for pulp and paper can only be met by sourcing woody plant species with substantial fibre characteristics (Oluwadare and Ashimiyu, 2007). Measurements from the wood macerates of individual samples of *Pterygota alata* were used to obtain the fibre morphological features *viz.*, fibre length, fibre diameter, lumen width and wall thickness. In the current study 45-90 cm girth at 25% of tree height had the longest fibre while the 30-45 cm girth class at 75% tree height had the lowest fibre length (*Figs. 2 and 3*). Fibre length has been reported to play important role in the processing and mechanical performance of fibre-based products such as paper and fibreboard (Migneault et al., 2008). Considering that the estimates of fibre length in all axial positions of all the trees at all the girth are above the critical length of 250 μm, as noted by Pirralho et al. (2014), they are all desirable for pulping and paper making. The current study was consistent with the findings of Cardoso et al. (2015) who reported that the fibre length of *Tectona grandis* varied from 1070 μm to 1220 μm. In general, there is an overall increase in fibre length due to the length increase of cambial initials with increasing cambial age in the *Neolamarckia cadamba* and *Grewia tiliifolia* (Gujar, 2017; Kapadi, 2020). Although there is no dominant and conspicuous pattern in axial variation of fibre diameter, it is commonly decreased from 25 to 75 percent of the tree height, an observation an agreement with the earlier study of Sseremba et al. (2016). In the present inspection, the fibre diameter was a maximum at 50% tree height whereas, it was a minimum at 25% and 75% tree height. This increment could be explained by the increase in the proportion of juvenile wood in the sections that are 50 percent of tree height, which often have larger lumens that in effect provide wider diameters of the fibres. The result shows that the fibre lumen width was smaller and lower for the region of the base to top. The results corroborate with the study conducted by Sharma et al. (2005) who stated that the fibre diameter of two clones of *Eucalypt urograndis* hybrid (*Eucalyptus grandis* x *Eucalyptus urophylla*) was 15.2 μm and 15.7 μm, respectively. Oluwadare and Ashimiyu (2007) reported that the fibre diameter of *Leucaena leucocephala* was 15.67 μm. Further, it was supported by Gujar (2017) who reported that the fibre diameter of *Neolamarckia cadamba* was 41.97 μm at the base and 38.63 μm at top of the tree height. With respect to the fibre lumen wall thickness of *Pterygota alata*, the highest FLWT and FWT were observed in the 150-180 cm girth class at 75% tree height while the lowest was in 30-45 cm girth class at 25% tree height. The pattern of variations observed from the results also shows some form of inconsistency as the value increase from 25% to 75% of tree height. This pattern was significant among the different girth classes and axial positions. The reported values were supporting the earlier reports of Cardoso et al. (2015) who stated that the highest FLWT and FWT were 16.90 μm and 6.4 μm in *Tectona grandis*, respectively (*Figs. 4 and 5*).

Vessel morphology

Vessels are connected by intervessel pits on the tangential wall of radial multiples, which allow the radial flow of sap (Fujii et al., 2001). Longitudinal penetration is mainly conducted by vessels along with wood fibre. So, the longitudinal flow will be related to vessel diameter and length and intervessel pit size and number. However, their permeability may have a decisive influence on the subsequent spread of liquid from vessels. The typical pattern of variation in vessel length was decreased from the 25 percent portion of the tree to the 75 percent portion (*Fig. 2* and *Fig. 3*).

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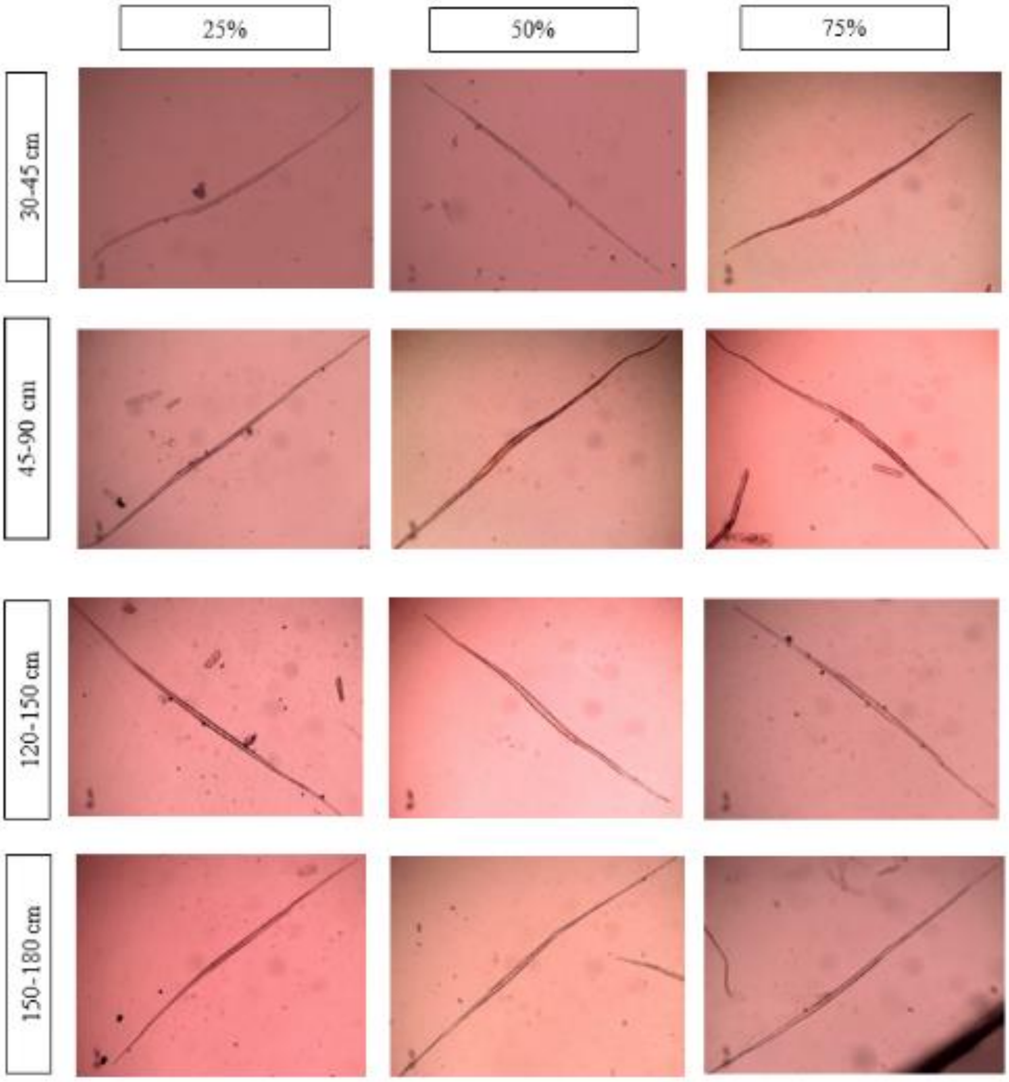

Figure 4. *Microscopic features of the Pterygota alata fibres at 25%, 50% and 75% height with different girth classes. (Magnificent 10x: Scale bar 100 µm)*

Greater vessel length at 25% of the tree height is consistent with the findings of Ohshima et al. (2005). This might be attributed due to the more porosity and have an impact on dimension stability during processing. The higher porosity could be a result of more surface area offered by the greater lengths and thus the presence of more pits. This study confirms the findings of Ahmed and Chun (2011) who reported the vessel length of *Tectona grandis* and *Gmelina arborea* as 305.12 µm and 296.85 µm, respectively. Wide vessels are the most efficient water conductors (Baas et al., 1983) since the water conductivity increases with the fourth power of vessel diameter and only with the first power of vessel frequency (Tyree and Zimmermann, 2002). The diameter of vessels does not show a consistent pattern from 25 to 75 percent of tree height, similar to the findings of Rao et al. (2002) and Owolabi et al. (2021) in *Eucalyptus tereticornis* was found to be 127±1.1 µm to 152±1.2 µm and 105.6±46.1 to 179.2±62.2 µm in Acacia species, respectively. The area of vessels did not show a conspicuous pattern, but there is a general observation that the 75 percent portion of the tree had vessels with larger areas with 120-

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150 cm girth class and the 25% tree height had vessels with a smaller area. A similar result was reported by Cardoso et al. (2015) in *Tectona grandis* as 16,683 to 19,339 µm^2. In the present study, the highest vessel frequency was observed in 45-90 cm at 25% tree height and the lowest was in 150-180 cm at 25% tree height. Similar reports are given by Ahmed and Chun (2011) who reported the vessel frequency of *Tectona grandis* and *Gmelina arborea* as 6.08 /mm^2 and 6.13 /mm^2, respectively (*Figs. 6 and 7*).

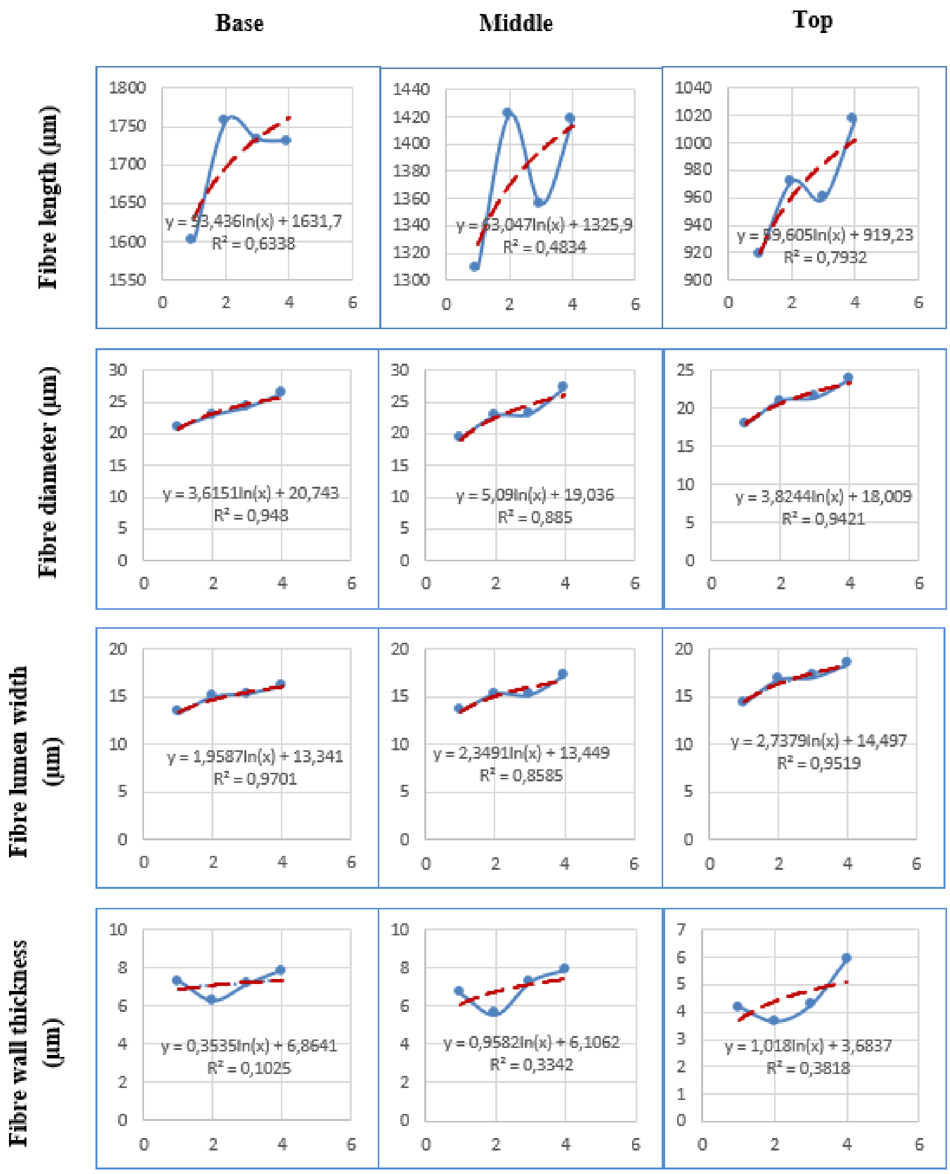

Figure 5. **The R^2 value of fibre properties of Pterygota alata in base, middle and top portions at four different girth classes were varied from 0.10 to 0.80 in log-linear regression which indicates that the fibre properties varied 10 to 80% among the girth classes. Among the fibre properties, fibre wall thickness showed 10% variation at 45-90 cm girth class in base portion and 33% variation in middle portion which indicates that 45-90 cm girth class does not change any variation whereas, 150-180 cm girth class showed 97% variation in fibre lumen width. Overall, the fibre properties had R^2 value above 0.80 which is good fit for studying the fibre properties except fibre length and fibre wall thickness*

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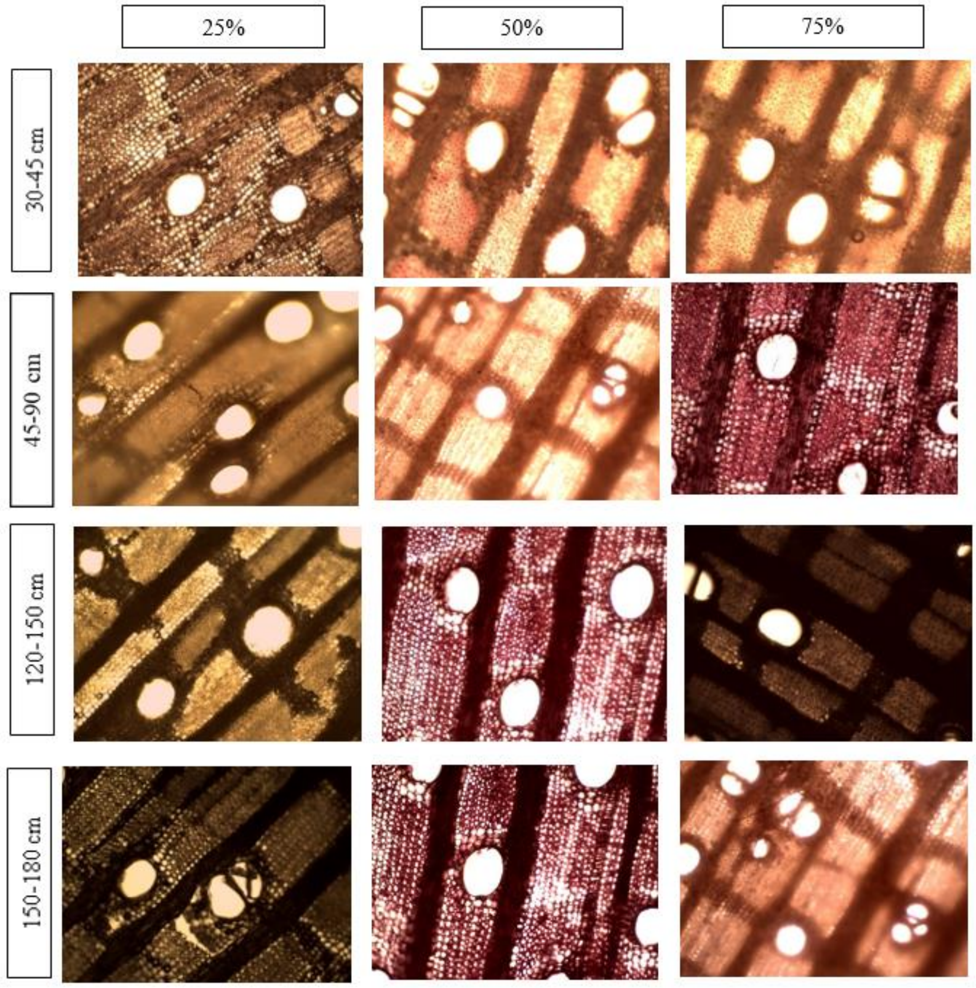

Figure 6. *Microscopic features of the Pterygota alata vessels at 25%, 50% and 75% height with different girth classes. (Magnificent 10x: Scale bar 100 µm)*

Ray morphology

Ray cells are connected end to end and form a capillary. Even the presence of an abundance of ray cells, is often a hindrance to penetration in hardwood (Behr et al., 1969; Siau, 1995). This was because of the variation of ray cell structures. Ray cell constitutes on average about 17% of the heartwood xylem, but sometimes the proportion of rays can be more than 30% (Bowyer et al., 2007). Even in the same wood species, the ray parenchyma height and width varied from juvenile wood to matured wood and earlywood to latewood. In the current study, the maximum ray height was observed in 150-180 cm at 25% tree height and the minimum was in 30-45 cm at 75% tree height (*Fig. 2 and Fig. 3*). The range of the ray height studied is in harmony with the findings of Baar et al. (2013) who reported that the ray height varied from 4659 µm (*Afzelia africana*) to 5296 (*Intsia palembanica*). Considering that three of the four girth groups showed absolute figures that depict a decrease in ray height at 75 percent of the tree, a generalized weak pattern can be deduced that ray height increases from 25 to 75 percent of tree height. With respect to ray frequency, the highest was noted in 150-180 cm at 25% tree height and the lowest was seen in 30-45 cm at 75% tree height. The lower value of ray frequency contributes to a lower volume of parenchyma and better pulp yield (Sseremba et al.,

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2016). The reduced number of rays as the tree grows older could be explained by the decreased physiological requirements of trees at higher proportions of tree height and the presence of fewer portions of juvenile wood. Smaller diameter trees have lower growth rates and hence a reduced need for rays that transport nutrients in the radial direction, as opposed to higher juvenile wood proportions with higher physiological requirements at small tree height that would demand the presence of larger rays. Consequently, such lower values of ray frequency give low movement during processing and seasoning, especially in the axial dimension of wood among the smaller-diameter trees. The ray frequency was found to be lower compared to the earlier reports given by Sseremba et al. (2016); Cardoso et al. (2015); Emmerich et al. (2019) in *Eucalyptus grandis* (8.92 to 10.20 /mm^2 in 25% tree height); *Tectona grandis* (9.00 to 11.00 /mm^2) and in *Pinus sylvestris* (3.70 /mm^2) to *Larix deciduas* (5.90 /mm^2), respectively (*Figs. 8 and 9*).

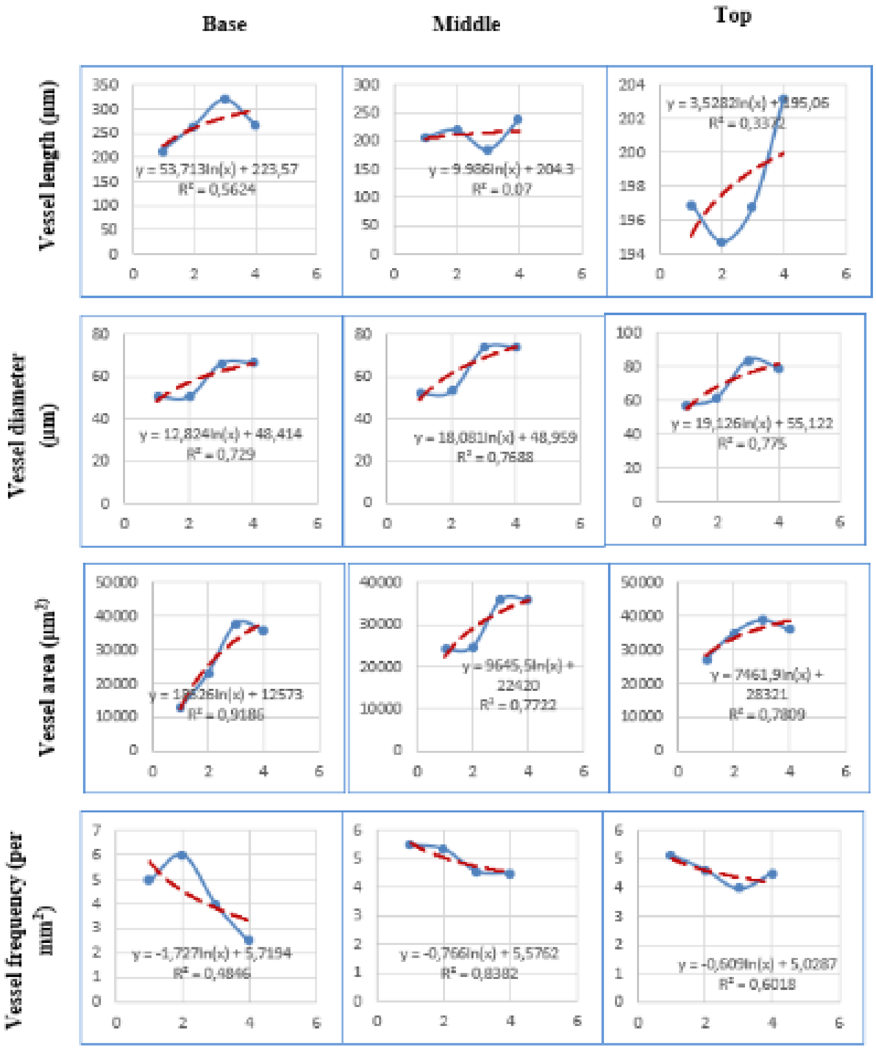

Figure 7. **The R^2 value of vessel properties of Pterygota alata in base, middle and top portions at four different girth classes were varied from 0.07 to 0.91 in log-linear regression which indicates that the fibre properties varied 7% to 91% among the girth classes. Among the vessel properties, vessel length showed 7% variation at 30-45 cm girth class in middle portion and 33% variation in top portion which indicates that 30-45 cm girth class do not change any variation whereas, vessel area showed R^2 as 0.91 for a regression model considered to be reliable and good fit for studying the vessel area in base portion*

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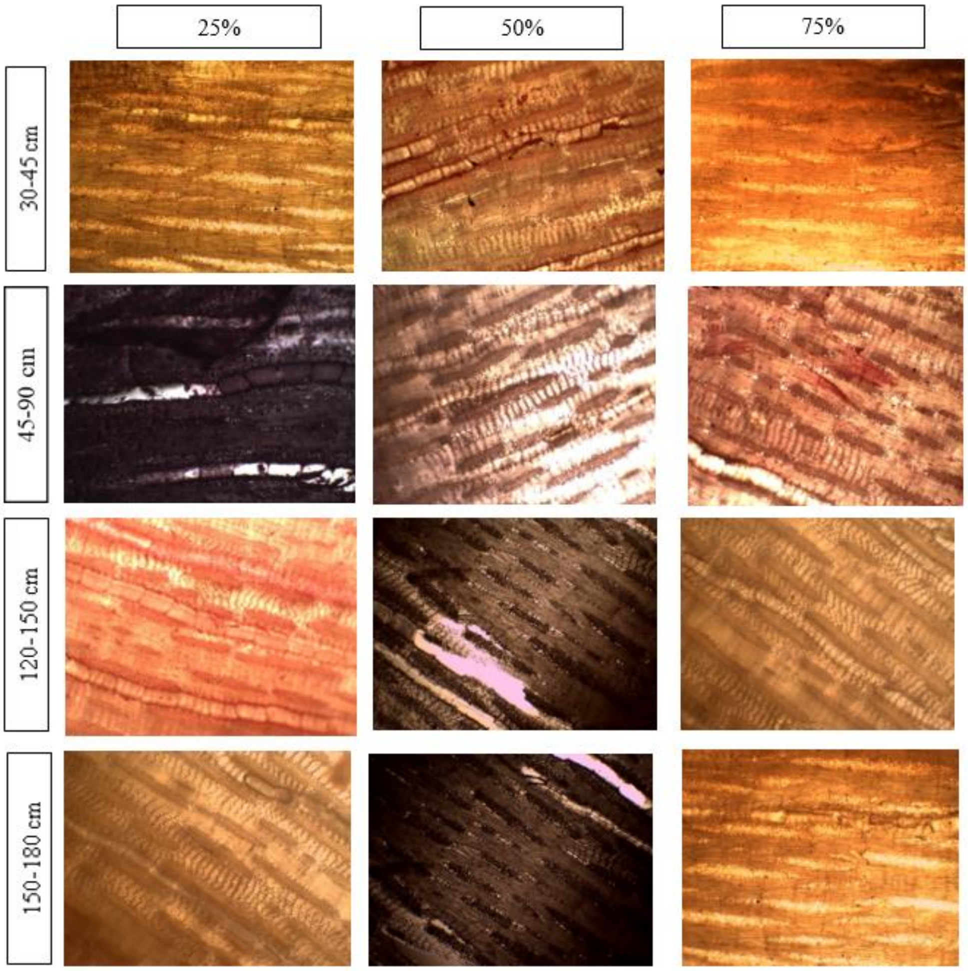

***Figure 8.** Microscopic features of the Pterygota alata rays at 25%, 50% and 75% height with different girth classes. (Magnificent 4x: Scale bar 200 µm)*

As evidence of these results, *Pterygota alata* has the highest paper-making quality as fibre length, fibre diameter, fibre lumen wall thickness and fibre wall thickness are well matched with the criteria of pulp and paper mentioned by Pirralho et al. (2014) and Sseremba et al. (2016). This indicates that the successful conversion of pulp into a marketable product depends on a combination of original fibre characters and the response of the fibres to processing variables. Because of the great variety of wood types, the physical properties of a piece of paper from one species will often vary markedly from a similar piece from another species, although processing conditions may have been identical. The structure of wood is directly responsible for many of the properties which in turn decide the quality of wood for specific end uses, pulp and paper being one of them. Among the four cell types of wood, various aspects of fibre morphology play a significant role in determining pulp and paper characteristics. Considering these indicators, as well as the relative species girth and axial positions, it seems promising to additional study *Pterygota alata* for its pulping response as a potential new paper-making species in parallel to the prized *Eucalyptus, Cadamba, Subabul, and Melia*.

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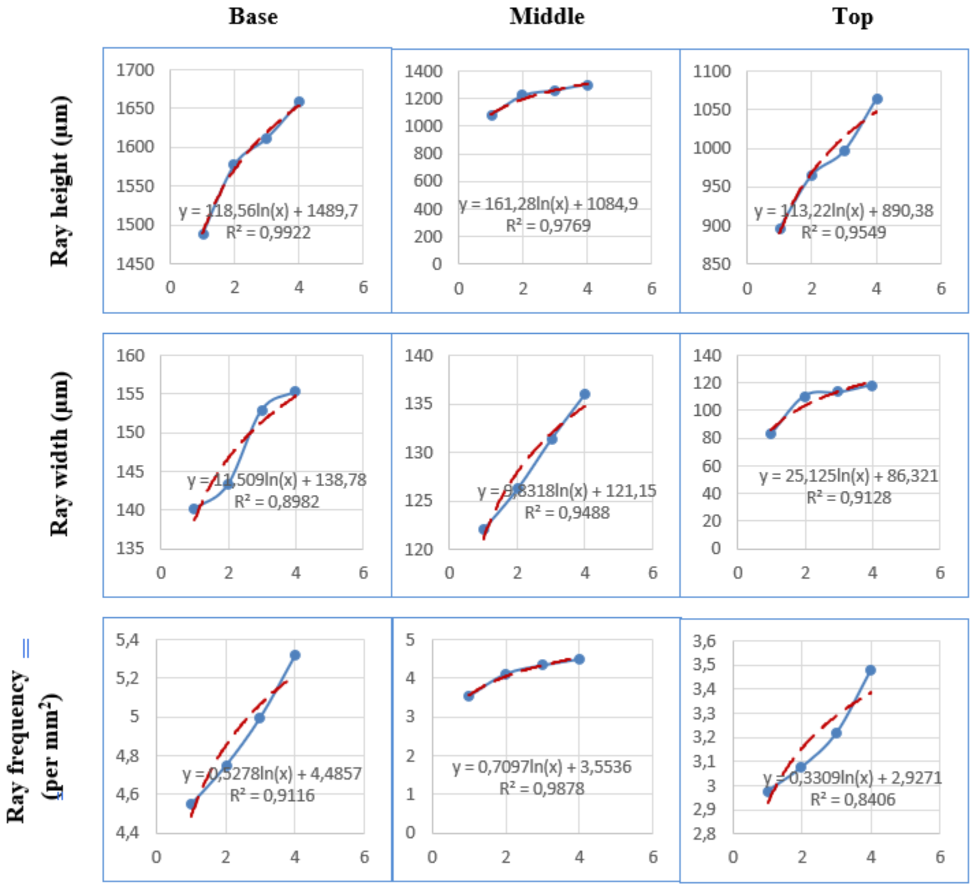

Figure 9. **The R^2 value of ray properties of Pterygota alata in base, middle and top portions at four different girth classes were above 0.80 from log linear regression which indicates that the model is a good fit*

Conclusion

According to the axial position of the *Pterygota alata*, fibre length, fibre diameter, fibre wall thickness, vessel length, ray height, ray width and ray frequency showed a decreasing trend whereas, fibre lumen width, vessel diameter and vessel area were observed the increasing trend as changing the distance from base to top. The middle portion of the tree recorded the maximum vessel frequency. Except vessel for frequency, other anatomical properties of the *Pterygota alata* were increased with the girth class and there was a significant difference between the fibre, vessel and ray anatomy among the girth classes. The vessel arrangement in the *Pterygota alata* wood is diffuse-porous type and the rays of *Pterygota alata* are multiseriate type. The fibre length of this wood is more or near 1000 µm among all the axial positions and girth classes. Results of the study indicated that the anatomical build-up of *Pterygota alata* was similar to the species used for pulp and paper production. Based on the anatomical features, the entire tree of *Pterygota alata* from the girth of 30 to 180 cm is capable of producing good-strength pulp. Hence, the study suggested that *Pterygota alata* will be the alternate prominent species for pulp and paper production.

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