VARIATION IN ANATOMICAL PROPERTIES OF FARM GROWN *PTERYGOTA ALATA* IN THE SEMI-ARID REGION OF SOUTHERN INDIA

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Abstract. The study was conducted at the Forest College and Research Institute, Mettupalayam, during 2019-2022, to explore new alternative pulpwood species with good paper-making potential. The samples were collected from seeds origin *Pterygota alata* which were farm grown in Pollachi, India. A total of 12 trees were removed with a specification of four different girth classes (30-45, 45-90, 120-150, 150-180 cm), from that 6 samples were collected from three different radial positions (pith, middle, and periphery) with the dimension of 2×2×2 cm^3. Then samples were subjected to microtomy, maceration, and optical analysis. Fibre, vessel, and ray anatomy were studied in the current investigation. Results revealed that the maximum value of fibre length (1458.96±3.47 µm), fibre diameter (25.50±1.29 µm), vessel diameter (74.94±0.13 µm), vessels area (47723.47±359.67 μm^2), ray height (1731.89±46.89 µm) ray width (165.07±1.41 µm) and ray frequency (5.51±0.02 ray/mm^2) were identified at the peripheral region at the girth of 150-180 and 120-150 cm. The study suggested that *Pterygota alata* could be the prominent alternate species for pulp and paper production.
Keywords: *anatomical features, radial position, girth classes, fibre, vessel, rays*

Introduction

India is one of the major wood consumers in the Asian pacific region, and its raw material demand was met from the natural forests until 1980. However, with the enactment of the Forest Conservation Act, 1980 and the subsequent enunciation of the National Forest Policy in 1988, the country’s forests has been recognized more towards conservation than timber production (FAO, 2009). India has recently experienced rapid economic growth due to economic liberalisation policies that have represented a consistently rising gross domestic product of the country (Ahmed et al., 2016). India is considered among the countries with the highest population growth rate and second fastest-growing economy, making it a significant competitor in the global economy (Montiel, 2016). India is the world's 15th largest paper producer, and it has emerged as

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the consumer market with the fastest rate of growth, with a 10.6% increase in paper consumption per person between 2021 and 2027. Over 16 million tonnes of paper are consumed domestically each year, whereas more than 2 million tonnes are imported. Under the baseline scenario, domestic consumption is expected to reach 23.50 million tonnes per annum by 2025–2026 (MMR, 2022). In 2021, the Indian pulp and paper market was valued at US$ 11.48 billion; by 2029, it is expected to grow to US$ 31.41 billion. The requirement for wood fibre for India's domestic pulp industry has increased due to the country's rising pulp and paper consumption and the required raw material capacity has become around 12.5 million metric tonnes annually (Goyal, 2019; Khare, 2021). Due to increasing demand, India's pulp sector is being forced to rely on increasing amounts of imported hardwood chips to meet its needs for wood fibre (Goyal, 2019). In the struggle to satisfy the high demand for wood products, the wood supply fraction of the market has increased the preference for faster-growing tree species (Sseremba et al., 2016). Challenges perceived by pulp and paper industries post 1988 to arrange their own raw material got converted into an opportunity by encouraging farmers to plant woody fibre on their own land, (through farm forestry and agroforestry) has turned out to be a boon for the industry (Parthiban et al., 2014; Khare, 2021).

Pterygota alata (Roxb.), (Synonyms: *Sterculia alata*) commonly known as "Buddha's Coconut Tree," gets its name from the large and woody fruit that resembles a coconut (Jahan et al., 2014; Mitra et al., 2015; Saudale et al., 2020). *Pterygota alata* is a large deciduous tropical tree species with a high, narrow crown and horizontal branches and it is indigenous to South Asia and Myanmar (Jahan et al., 2014). In India, it occurs in the Sub-Himalayan tract from Nepal eastward to West Bengal, Assam, Maharashtra, Uttar Pradesh, Tamil Nadu, and in the evergreen forests of Karnataka and Kerala (Rao et al., 2002). In an open forest with favourable climatic conditions, this tree can reach a height of 35 metres or more and develop buttresses (Thothathri, 1962). Its clean bole measures around 12 metres in length and has a diameter of one metre. Most often, this species is used as an ornamental tree in gardens (Gamble, 1881). Buddha's Coconut wood is light in weight, milky white to white in colour, and has a limited shelf life (Fatma and Jahan, 2018). This tree recently gained popularity in wood-based industries such as plywood, furniture, toys, sticks, packaging cases, and other handicrafts. Therefore, the overall objective of this study was designed to explore the anatomical variation within a tree and with the girth classes of *Pterygota alata*. The anatomical properties of wood are closely related to many internal and external factors affecting tree growth, such as cambial age, and silvicultural practices. In pulping industry, the pulp quality greatly depends on the anatomical properties of wood (Zbonak et al., 2007). Therefore, understanding the anatomical structure of wood provides fundamental knowledge of wood qualities, which is frequently used to assess the pulp quality of wood. In this study, *Pterygota alata* species are prospectively examined with a focus towards the pulp and paper industry through an early evaluation of wood anatomical characteristics.

Materials and methods

Study site

The study was conducted at Forest College and Research Institute, Mettupalayam from 2019 to 2022. Wood samples were collected from Pollachi, Coimbatore, Tamil

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Nadu, India (10° 39'N; 77° 0'E). The climate of the study area is a tropical type which receives an annual rainfall of 242-369 mm which is chiefly contributing to the southwest monsoon due to the Palghat gap. Summer season starts from March to May with a maximum temperature of 36°C and a minimum of 33°C and winter starts in early October and prolongs up to late January with an average temperature of 20-22°C. Medium to deep red calcareous soil is found in the study area (Sudhalakshmi and Kumaraperumal, 2021).

Sample preparation

The samples were collected from seeds origin of *Pterygota alata*, which were farm grown with a spacing of 5 x 5 m with a specification of four different girth classes (30-45, 45-90, 120-150 and 150-180 cm) (*Figure 1a*). In each girth class, 3 trees were removed for the study from which circular discs of 2 cm height were obtained from each girth class at breast height (1.37 m), and the wood samples each of dimension with a size of 2×2×2 cm^3 were sliced out separately from the disc (*Figure 1b and 2*). For each anatomical characterization, six wooden cubes were taken out from the circular disc in three radial positions (pith, middle and periphery) at the right angle to one another, as illustrated in *Figure 3a and 3b*. Before undergoing through microtome cubes were boiled in water for 20 min. From these wood samples thin microscope sections of 15 to 20 μm size were taken using 'Yorco precision rotary microtome' (Lipshaw Type YSI-115 – Japan). For fibre analysis, wood samples were subjected to maceration.

Figure 1. *a) Pterygota alata tree grown in farm condition b) collection of Pterygota alata wood samples from the farm*

Maceration

Maceration of the wood samples was done by using Jeffrey's method (Sass, 1971). For maceration, Jeffrey's solution 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 radial positions *viz.*, pith, middle and periphery. These shaves were boiled into the maceration fluid for 15 to 20 min so that the fibre individuals were separated. After that these test tubes were held for 5 to 10 minutes,

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allowing the fibres to settle 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 saffranin and mounted on temporary slides using glycerin as the mountant.

***Figure 2.** Round disc was taken from the tree's breast height (1.37 m) for the cutting out samples of the radial positions*

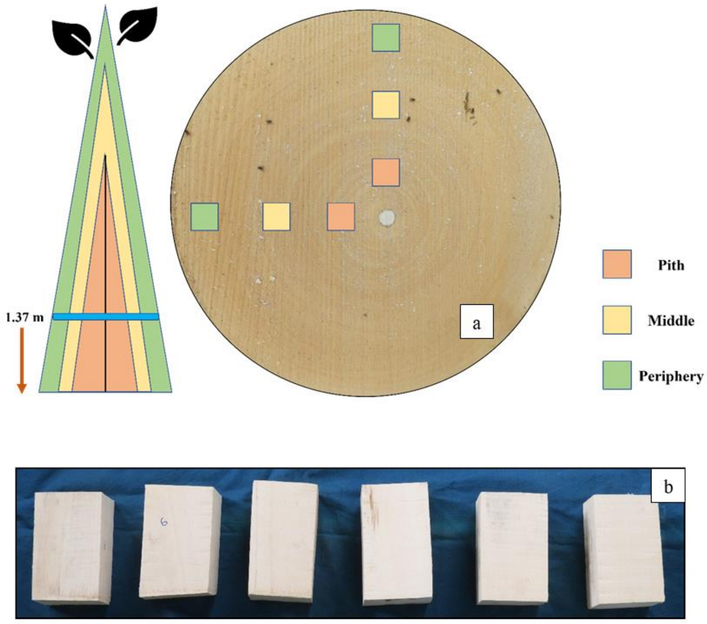

***Figure 3.** a) Pictorial view of samples was collected (Three radial positions) b) 2×2×2 cm^3 sliced out separately from the round disc*

Anatomical observations

Different measurements were taken from the macerated wood samples *viz.,* fibre length (µm), fibre diameter (µm), fibre wall thickness (µm) by measuring the thickness of the wall cross-sectional area and fibre lumen width (µm) by measuring the width of

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the lumen at the cross-sectional area. Vessel length (µm) and vessel diameter (µm) of the vessels were measured on the transverse sections (TS). The vessel arrangement in the heartwood of the species was identified by studying the transverse sections as per Rao and Juneja (1971). Frequency of vessels per square millimetre was calculated by counting the number of vessels in the randomly selected area (per mm^2) and using the formulae given in equation 1. In each field, three count areas were taken.

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

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

$$\text{Ray frequency} = \frac{\text{Number of rays}}{\text{Transect line (1 mm)}} \times 10^6 \qquad \text{(Eq.2)}$$

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

Results

Within tree variation in fibre morphology

In the radial positions, the longest fibre was identified at the peripheral region (1458.96±3.47 µm) at a girth of 150-180 cm and the shortest was observed in the pith region (1214.25 ± 47.07 µm) at 30-45 cm. The interaction effect of girth and radial positions was not significant. Among the girth classes, 150-180 cm girth class had the highest fibre diameter was 25.50± 1.29 µm (periphery region), whereas 30-45 cm girth class had the lowest fibre diameter in pith as 19.09± 0.43 µm. Notably, the girth classes and interaction effect did not exhibit any statistical significance for the fibre diameter, which indicated uniformity at all radial positions. With respect to fibre lumen width, the girth classes, radial positions, and the interaction effect showed statistically significant. The highest fibre lumen width was observed in the pith region of 150-180 cm girth as 17.83 ± 0.46 µm and the lowest value was observed in the peripheral region of 30-45 cm girth class as 13.35 ± 0.86 µm. Fibre wall thickness in the pith of 150-180 cm shows the highest value as 7.57±0.25 µm and the lowest value was found in the

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periphery as 4.94±0.08 µm in 30-45 cm girth class. There was a highly significant (p<0.01) difference between fibre wall thicknesses in different girth classes and radial positions, but it was non-significant in the interaction effect (*Table 1*).

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

Fibre morphology	Girth Classes (cm)	Radial position			Mean
		Pith	Middle	Periphery	
FL (µm)	30-45	1214.25± 47.07	1263.10 ± 17.87	1311.31 ± 10.13	1262.88[b]
	45-90	1230.04 ± 50.25	1324.56 ± 65.61	1362.37 ± 89.37	1305.66[ab]
	120-150	1255.51 ± 4.52	1314.13 ± 30.54	1395.20 ± 17.38	1321.61[a]
	150-180	1250.38 ± 44.16	1370.83 ± 67.91	1458.96 ± 3.47	1360.06[a]
	Mean	1317.67[b]	1304.50[c]	1332.30[a]	**1318.15**
	Factors	SEd	CD (0.05)	CD (0.01)	
	Girth	26.50	54.70	74.54	0.002 **
	Radial position	22.95	47.37	64.55	0.053 *
	GXR	45.90	94.74	129.10	0.717 NS
FD (µm)	30-45	19.09 ± 0.43	19.84 ± 0.21	20.12 ± 0.11	19.68[d]
	45-90	22.97 ± 0.08	22.53 ± 1.54	19.59 ± 0.08	21.69[c]
	120-150	22.94 ± 0.07	23.69 ± 1.70	23.94 ± 0.71	23.53[b]
	150-180	24.73 ± 1.59	24.97 ± 1.70	25.50 ± 1.29	25.07[a]
	Mean	21.59[c]	22.76[b]	23.13[a]	**22.49**
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.61	1.25	1.70	0.058 NS
	Radial position	0.52	1.08	1.47	0.001 **
	GXR	1.05	2.16	2.95	0.551 NS
FLW (µm)	30-45	14.32 ± 0.37	13.62 ± 0.41	13.35 ± 0.86	13.76[c]
	45-90	16.93 ± 0.57	16.23 ± 0.33	15.11 ± 0.14	16.09[b]
	120-150	16.29 ± 0.04	15.89 ± 0.12	17.00 ± 0.47	16.39[b]
	150-180	17.83 ± 0.46	17.18 ± 0.40	16.14 ± 0.31	17.05[a]
	Mean	15.40[b]	15.73[b]	16.34[a]	**15.82**
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.25	0.45	0.61	0.013**
	Radial position	0.22	0.51	0.70	0.000**
	GXR	0.43	0.89	1.22	0.048*
FWT (µm)	30-45	5.77 ± 0.06	5.20 ± 0.07	4.94 ± 0.08	5.31[d]
	45-90	6.57 ± 0.15	6.04 ± 0.13	5.98 ± 0.10	6.19[c]
	120-150	6.43 ± 0.14	6.28 ± 0.13	5.99 ± 0.01	6.23[b]
	150-180	7.57 ± 0.25	7.26 ± 0.08	6.85 ± 0.33	7.23[a]
	Mean	5.94[c]	6.19[b]	6.58[a]	**6.24**
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.09	0.19	0.25	0.001**
	Radial position	0.07	0.16	0.22	0.000**
	GXR	0.16	0.32	0.44	0.407 NS

** = 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

The most common pattern of variation in vessel length was decreased from the pith to the peripheral region. Considering the radial position, the highest vessel length was found in 120-150 cm girth as 318.88±1.19 µm and the lowest vessel length was recorded in 30-45 cm girth class of periphery as 248.44±1.06 µm. The vessel's diameter

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was smaller in the early stage than the later stage, the diameter of the vessels was lower near to the pith as 54.47±0.40 µm in 30-45 cm girth class and the highest was recorded in 120-150 cm girth class of periphery portion as 74.94±0.13 µm. *Table 2* shows that the maximum vessel area was recorded in the peripheral region with a value of 47723.47±359.67 µm^2 in 120-150 cm and the lowest vessel area was recorded in the pith region of 30-45 cm as 23460.93±362.38 µm^2. *Pterygota alata* had the maximum vessel frequency of 5.33±0.01 vessel/mm^2 in the pith region of 30-45 cm girth class. Whereas the minimum vessel frequency was observed as 2.98±0.02 vessel/mm^2 in the middle of 150-180 cm girth class (*Table 2*). In vessel morphology, all the parameters exhibited a significant result with radial positions, girth classes, and its interaction effect, but the vessel length did not show a significant result with an interaction effect.

Table 2. *Within tree vessels anatomical variation with radial position*

Vessel morphology	Girth Classes (cm)	Radial position			Mean
		Pith	Middle	Periphery	
VL (µm)	**30-45**	253.54±0.74	249.25±0.73	248.44±1.06	250.41^d
	45-90	258.88±0.92	257.40±0.94	252.45±2.18	256.25^c
	120-150	318.88±1.19	317.89±1.28	314.99±0.41	317.25^a
	150-180	285.84±0.67	285.73±1.49	282.84±2.41	284.80^b
	Mean	279.29^a	277.57^b	274.68^c	279.29
	Factors	SEd	CD (0.05)	CD (0.01)	P
	Girth	0.75	1.55	2.12	0.001**
	Radial position	0.65	1.34	1.83	0.000**
	GXR	1.30	2.68	3.66	NS
VD (µm)	**30-45**	54.47±0.40	56.59±0.61	57.05±0.52a	56.03^d
	45-90	59.80±0.48	60.27±0.90	64.11±0.63	61.39^c
	120-150	72.25±0.38	74.28±0.35	74.94±0.13	73.82^a
	150-180	68.56±0.53	72.03±0.48	73.32±0.86	71.30^b
	Mean	67.35^a	56.59^b	63.77^c	**62.57**
	Factors	**SEd**	**CD (0.05)**	**CD (0.01)**	**P**
	Girth	0.32	0.67	0.91	0.000**
	Radial position	0.28	0.58	0.79	0.000**
	GXR	0.56	1.15	1.57	0.000**
VA (µm^2)	**30-45**	23460.93±362.38	25326.96±256.26	26418.15±417.84	25068.68^d
	45-90	24113.32±229.78	29117.28±312.32	32283.72±178.81	28504.78^c
	120-150	34786.21±595.23	34809.27±460.02	47723.47±359.67	39106.31^a
	150-180	37083.24±196.11	35502.11±619.43	35378.92±160.57	35988.09^b
	Mean	35451.07^a	31188.91^b	29860.92^c	**32166.97**
	Factors	**SEd**	**CD (0.05)**	**CD (0.01)**	**P**
	Girth	292.34	604.60	823.90	0.000**
	Radial position	253.70	523.60	713.52	0.000**
	GXR	507.39	1047.20	1427.03	0.000**
VF (per mm^2)	**30-45**	5.33±0.01	5.04±0.07	4.44±0.04	4.94^a
	45-90	4.93±0.03	4.61±0.01	5.32±0.01	4.95^a
	120-150	3.59±0.01	3.96±0.01	4.77±0.01	4.11^b
	150-180	4.19±0.00	2.98±0.02	4.95±0.00	4.04^c
	Mean	4.87^a	4.15^c	4.51^b	4.51
	Factors	**SEd**	**CD (0.05)**	**CD (0.01)**	**P**
	Girth	0.015	0.031	0.042	0.000*
	Radial position	0.013	0.026	0.037	0.000*
	GXR	0.026	0.054	0.074	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 highest in the periphery region as 1731.89±46.89 μm of 120-150 cm girth class and the lowest value was recorded from the periphery of 30-45 cm girth as 1121.76± 45.85 μm. The ray height showed a significant result with the girth class alone, but it did not exhibit significant results with radial positions and their combined effect. However, the ray width and ray frequency revealed significant variations with girth classes, radial positions, and their interaction effect. The maximum ray width was recorded in the periphery as 165.07±1.41 μm and the minimum ray width was recorded in the pith region as 138.77±0.54 μm of 30-45 cm girth class. In 150-180 cm girth class the periphery region had the maximum ray frequency of 5.51±0.02 ray/mm^2 and the minimum was recorded in pith as 3.04±0.01 ray/mm^2 in 45-90 cm girth class (*Table 3*).

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

Ray morphology	Girth Classes (cm)	Radial position			Mean
		Pith	Middle	Periphery	
RH (μm)	30-45	1269.64±100.87	1211.90±98.09	1121.76±45.85	1201.10^c
	45-90	1458.33±182.20	1521.14±18.46	1571.00±39.96	1516.82^b
	120-150	1534.23±29.95	1641.63±77.61	1731.89±46.89	1635.92^a
	150-180	1630.72±41.24	1645.32±41.84	1681.43±56.63	1652.49^a
	Mean	1473.23	1505.00	1526.52	**1501.58**
	Factors	**SEd**	**CD (0.05)**	**CD (0.01)**	**P**
	Girth	44.97	92.82	126.48	0.000*
	Radial position	38.95	80.38	109.54	0.439 NS
	GXR	77.89	160.76	219.07	0.247 NS
RW (μm)	30-45	138.77±0.54	140.40±0.46	141.88±1.18	140.35^d
	45-90	143.05±0.75	147.39±1.13	147.41±0.91	145.95^c
	120-150	150.71±0.30	152.27±1.30	153.66±0.41	152.21^b
	150-180	156.64±0.60	157.09±0.84	165.07±1.41	159.60^a
	Mean	147.29b	149.29a	141.88^c	**146.15**
	Factors	**SEd**	**CD (0.05)**	**CD (0.01)**	**P**
	Girth	0.55	1.13	1.54	0.000*
	Radial position	0.47	0.98	1.33	0.000*
	GXR	0.95	1.96	2.67	0.000*
RF (per mm^2)	30-45	3.52±0.01	3.55±0.01	3.95±0.02	3.67^c
	45-90	3.04±0.01	4.01±0.01	4.11±0.02	3.72^c
	120-150	5.00±0.07	4.23±0.03	4.04±0.06	4.42^b
	150-180	5.38±0.01	5.47±0.01	5.51±0.02	5.46^a
	Mean	4.24^b	4.32^a	3.95^c	**4.17**
	Factors	**SEd**	**CD (0.05)**	**CD (0.01)**	**P**
	Girth	0.015	0.033	0.044	0.000*
	Radial position	0.013	0.028	0.038	0.000*
	GXR	0.027	0.056	0.077	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

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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 end-use applications. The diffuse porous wood, dominance of solitary vessels, multiseriate 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 Sotannde, 2007). Measurements from the macerates wood 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 present study, *Pterygota alata* fibre length varied from the pith to periphery which indicated that the species radial positions and girth classes influenced it more significantly towards the fibre length (p<0.05). Conversely, it was not significant in interaction. Fibre length has been reported to play an important role in the processing and mechanical performance of fibre-based products such as paper and fibreboard (Migneault et al., 2008). This might reflect a prominent characteristic of juvenile wood. The progressive increase of fibre length in the pith to periphery direction can be associated with mainly quantitative anatomical differences deriving from the cambium maturation process and consequently of the woody tissue (Larson, 2012); age, site, spacing, nutrition and environmental interactions, which influence the cambium activity responsible for the production of cells that make up the wood (Zobel and Buijtenen, 1989; Larson, 2012).The periodic changes experienced by the cambium due to its ripening produce differences in anatomical structure and wood properties within the growth ring and also between the juvenile and adult wood. The juvenile wood, produced in the first years of growth of the tree, differs from the mature wood, especially in presenting a greater magnitude of variation in its technological properties, notably marked by sudden changes in cellular composition (Zobel and Buijtenen, 1989; Bao et al., 2001; Calonego et al., 2005; de M. Palermo et al., 2015) and this almost always has a negative effect on the wood quality. Results are in consonance with the earlier findings of Saravanan et al. (2013) who reported that the fibre length increases from the pith (615.00 μm) to periphery (670.00 μm) in *Melia dubia* and it was further supported by Kapadi (2020) in an eight-year-old wood sample of *Grewia tiliaefolia* who reported that the lowest fibre length was found in pith (925.70 μm) followed by middle (960.77 μm) and the highest value was in periphery (1055.20 μm). The mean fibre length was greater than 1200 μm across all girth classes which is more than *Eucalyptus grandis* as 780-939 μm (Sseremba et al., 2016), *Melia dubia* as 647-1159 μm (Saravanan et al., 2013); Eucalyptus as 670-810μm (Pirralho et al., 2014) and on par with the outcomes of *Neolamarckia cadamba* as 1509-1854 μm (Gujar, 2017). As well, long fibre can have more fibre joints and thereby build a stronger network (Johansson, 2011).

The variation in fibre diameter increased as the distance from the pith to the periphery changed and all the girth classes consistently showed this pattern, with the exception of the 45-90 cm girth class, which contrasts with other findings. Anoop et al. (2016) stated that the fibre diameter in *Pericopsis mooniana* rises from the inner

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(11.90 µm) towards the bark (14.80 µm). Fibre diameter was found to be 20.26 and 16.10 µm close to the pith and 22.56 and 20.92 µm near the peripheral region in *Gmelina arborea* and *Grewia tiliaefolia*, respectively (Okon, 2014; Kapadi, 2020). As a tree's girth widens, molecular and physiological changes in the vascular cambium and the growth of the wood cell wall cause variations in the fibre diameter in the radial positions (Plomion et al., 2001; Roque et al., 2007). As well, cells close to the pith were young and immature and they quickly divided and grew. When a tree reaches maturity, its growth rate slows down and its cells are comparatively stable. This is the cause of the increase in fibre diameter and length in the periphery (Shen et al., 2021; Wang et al., 2021).

Lumen width was steadily decreasing towards the periphery from the pith. The observed differences in lumen width may also be attributed to the increase in cell size and physiological development of the wood. Roque et al. (2007) reported a positive relationship between variations in lumen width, tree growth and cambium thickness. Oluwafemi and Tunde (2008) found that fibre lumen width in the radial position increased from the annual ring 2 (19.99 µm) to ring 10 (20.88 µm) from the pith and again decreased towards the 13th ring. Tirak Hizal and Erdin (2016) found that the lumen width of *Alnus glutinosa* had a maximum in the inner portion as 17.97 µm followed by the middle portion as 17.42 µm and the lowest value was recorded in the outer portion as 16.58 µm.

Fibre cell wall thickness was highest near the pith and declined from the pith to the bark side of the stem. The fibre walls in the juvenile wood were thicker than in the mature wood. There was a highly significant (p<0.01) difference between fibre wall thicknesses in different radial positions, but it was non-significant in the 150-180 cm girth class. The thickness of the fibre wall is an important indicator of most properties of paper because thick-walled fibres are associated with high tearing strength. The above results are in consonance with the findings of Oluwafemi and Tunde (2008) reported that the fibre wall thickness of *Sterculia setigera* was reduced from the 1st ring near to the pith (3.03 µm) to the 13th ring near to the bark (2.78 µm). Further supported by Emerhi (2012) recorded that the fibre wall thickness of *Rhizophora harrisonii* was decreasing towards bark (8.47 µm) from the pith (8.43 µm). These suggest that fibres from all the positions over all the girth classes are reliable and conducive for pulp production (*Figures 4, 5 and 6*).

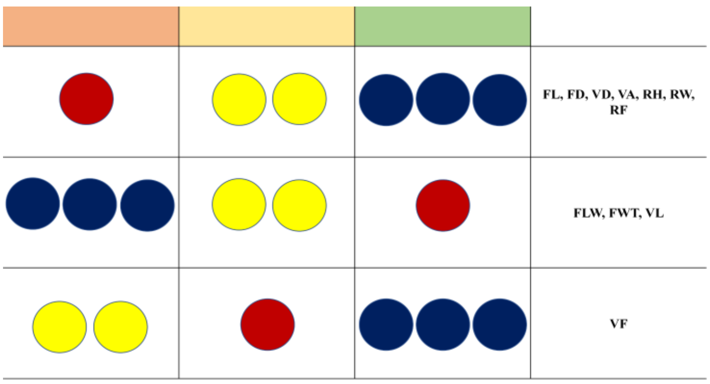

Figure 4. *Anatomical variation at pith, middle and peripheral region of the tree. Overhead light orange represents pith, light gold represents middle and light green represents peripheral region of the wood. Whereas, Dark red denotes low values of anatomical features, while yellow denotes moderate values and dark blue denotes maximum values*

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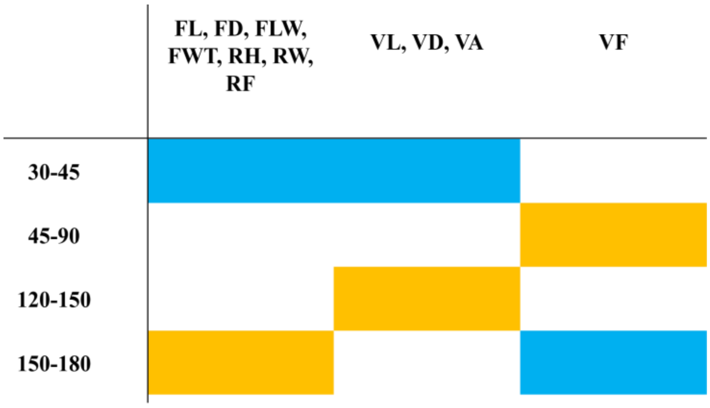

Figure 5. *Girth class wise representation of the maximum and minimum values of anatomical traits. Light blue represents minimum values and orange represents maximum values*

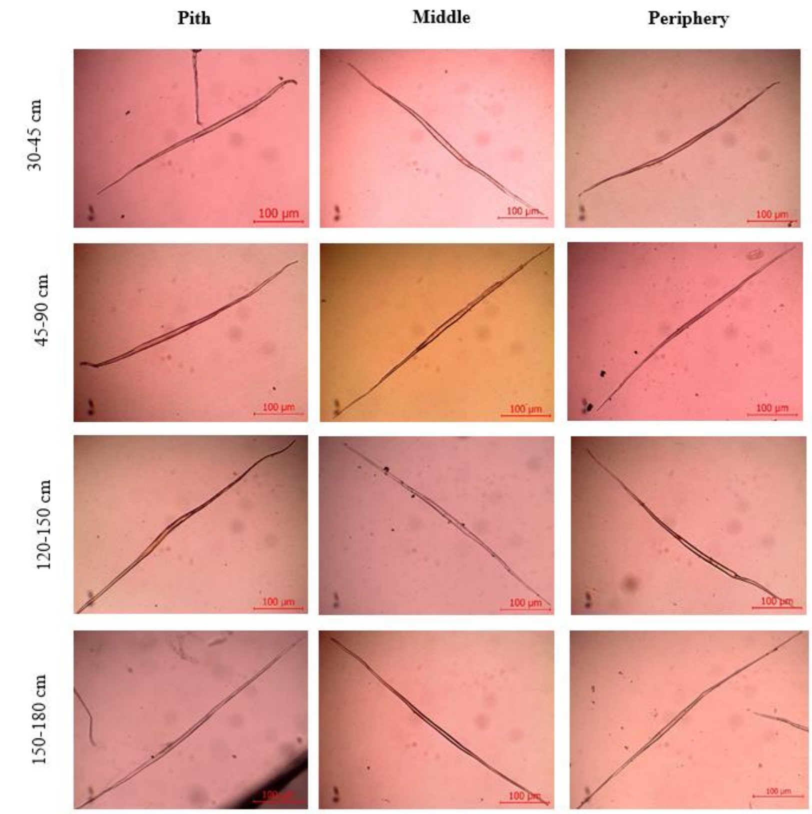

Figure 6. *Microscopic features of the Pterygota alata fibres with pith, middle and periphery section with different girth classes (magnification 10x)*

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 vessel along with wood fibre. So, longitudinal flow will definitely 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

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from vessels. The most common pattern of variation of vessel length was decrease from pith to peripheral region. Regarding the vessels length the contrast findings were found in most of the literature where vessel length is increasing towards the bark from the pith. Cardoso et al. (2015) and de M. Palermo et al. (2015) emphasize that the vessel length was decreased from pith to periphery in *Tectona grandis* (263 to 258 μm); *Eucalyptus grandis* (480.43 to 429.18 μm). In contrast Kapadi (2020) found that the vessel length of *Grewia tiliaefolia* was increased from pith (164.22 μm) to periphery (232.04 μm). Rao et al. (2002) and Giménez et al. (2014) reported that the vessel length and vessel diameter were interrelated in *Eucalyptus tereticornis* and Maytenus.

The radial variation in the vessels diameter was smaller in the early stage than that in the later stage, the diameter of the vessels is lower near the pith region which indicate that the vessel diameter increased with increased radial growth (Pertiwi et al., 2017).The results corroborate with the study conducted by Nugroho et al. (2012) found that the vessel diameter of the *Acacia mangium* was lowest near to the pith (95.60 μm) followed by middle (122.80 μm) and the highest value was found in peripheral region (150.20 μm). All the four different girth classes and three different radial positions of *Pterygota alata* wood showed a diffuse porous type of vessel arrangement in their woods. Similarly, Swaminathan et al. (2012) studied the radial variation of *Melia dubia*, the vessel diameter was increasing from pith (138.60 μm) to the bark (219 μm).

In the current study the mean vessel area increased gradually from pith to bark, whereas the vessel frequency (number of vessels per unit area) decreased outwards from the innermost rings on and levelled off towards the bark. Further out the vessel size was increased and reached its maximum close to the bark. The vessel area also changed significantly from inner to middle-wood. According to Rodrigues et al. (2007) and Rungwattana and Hietz (2015) the vessel area of *Acacia melanoxylon*, *Toona ciliata* and *Melia azedarach* increased from the pith to towards the bark. In the present study the lowest vessel frequency was observed in the middle portion of 150-180 cm girth class as 2.98 ± 0.02 ray/mm^2. The low vessel frequency may also result in relatively lower moisture conductivity in the transition zone of *Pterygota alata* which typically shows more intense internal intraring checks during drying. The number of vessels per unit area generally declined from pith to bark. The vessel frequency started with 20-40 vessels/mm^2 around the pith and it was reduced to around 10-20 vessels/mm^2 within the first half of the radius, then it levelled out with a minimum of 3-5 vessels/mm^2 close to the bark in *Eucalyptus globules* (Leal et al., 2003). This study confirms the findings of Nugroho et al. (2012) who reported that the highest vessels frequency in peripheral region was 9.20 vessels/mm^2 and the lowest value were observed in the middle portion as 7.82 vessels/mm^2 in *Acacia mangium*. Similarly, Prasetyo et al. (2019) recorded that the vessels frequency of three Eucalyptus species was decreasing towards the bark from the pith of *Eucalyptus urophylla* (>15 - <10 vessels/mm^2), *Eucalyptus grandis* (>15 - <10 vessels/mm^2) and *Eucalyptus pellita* (>10 - <10 vessels/mm^2). All the four different girth classes of *Pterygota alata* wood showed a diffuse porous type of vessel arrangement in their woods (*Figures 4, 5 and 7*).

Ray morphology

In hardwoods the changes in the ray volume are small magnitude (Zobel and Buijtenen,1989) with a tendency for wider rays in the outer wood (Carlquist et al., 1988). In the current investigation, the ray morphology of *Pterygota alata* wood varied significantly due to girth. Anatomical studies pertaining to ray morphology revealed

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that the girth has a significant influence on ray height, ray width and ray frequency which has shown an increasing trend due to girth. The increase in ray height with tree girth might be due to transverse division of ray cell initials and fusiform initials of adjacent rays or the addition of segments from fusiform initials. Environment has a greater influence on the dimensions of ray height because environmental stress reduces the rate of cambial growth and ultimately ray height is reduced. The periodic changes in ray width may be due to anticlinal division of initial cells within rays or by merging of rays. Therefore, the ray width increases with girth and stabilizes thereafter. In the current study with respect to ray morphology, peripheral portion recorded the highest ray height followed by the middle portion and the lowest ray height was recorded in the pith portion. Nevertheless, contrast finding was observed in the 30-45 cm girth class where values declined from pith to periphery. This study was in accordance with the findings of Naji et al. (2013) reported that the ray height is increased from the pith to periphery in *Hevea brasiliensis*. The height of the rays in *Hevea brasiliensis* varied from 9.87 to 15.22. However, it was further supported by Saravanan et al. (2013) who found that the ray height was increased from the pith (359.47 μm) to periphery (403.08 μm) in *Melia dubia.* In the present study, the periphery region recorded the maximum ray width followed by middle and the minimum value was recorded in pith. The study was consistent with the findings of Sousa et al. (2009) and Anoop et al. (2016) reported that the ray width was increased from pith to periphery region as 22.30 to 34.90 μm and 1.72 to 9.33 μm in *Quercus suber, Betula pendula* and *Pericopsis mooniana* respectively. Ray frequency was increasing from pith to periphery except 120-150 cm girth class. The lowest value was found in the 45-90 cm girth class with a value of 3.04 ± 0.01 ray/mm^2. The current study is in line with the findings of Naji et al. (2013) reported that the ray frequency of *Hevea brasiliensis* was increased from pith to the bark. Similarly, Longui et al. (2011) found that the ray frequency of the two-source provenance of *Gallesia integrifolia* was varied as 1.70-2.10 ray/mm^2 near to the pith whereas it was increased towards the bark as 2.30-2.50 ray/mm^2.

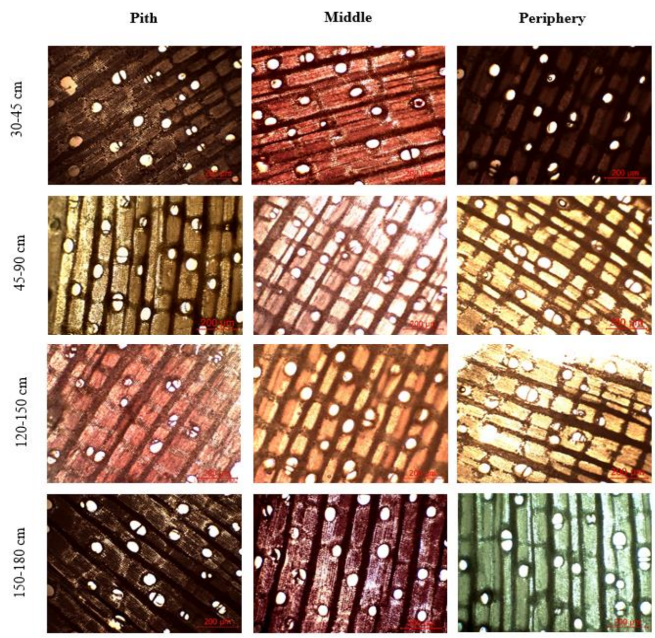

Figure 7. *Microscopic features of the Pterygota alata vessels with pith, middle and periphery section with different girth classes (magnification 4x)*

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As a demonstration of these findings, *Pterygota alata* possesses the finest paper-making qualities in terms of fibre length, diameter, lumen width, and wall thickness. This demonstrated that the conversion of pulp into a marketable product relied on an interaction between the original fibre characteristics and the fibres' reactions to processing variables. The physical characteristics of a piece of paper from one species will frequently differ noticeably from a similar piece from a different species due to the wide variation of wood types, even when processing conditions may have been the same. Many of the characteristics that determine the quality of wood for different end uses, including pulp and paper, are directly influenced by the structure of wood. The qualities of pulp and paper are greatly influenced by various characteristics of fibre morphology among the four types of wood cells. By considering these indicators, and the relative species girth and radial positions, it seems promising to further study *Pterygota alata* for their pulping response as potential new paper-making species in parallel to the prized *Eucalyptus, Cadamba, Subabul, and Melia* (*Figures 4, 5 and 8*).

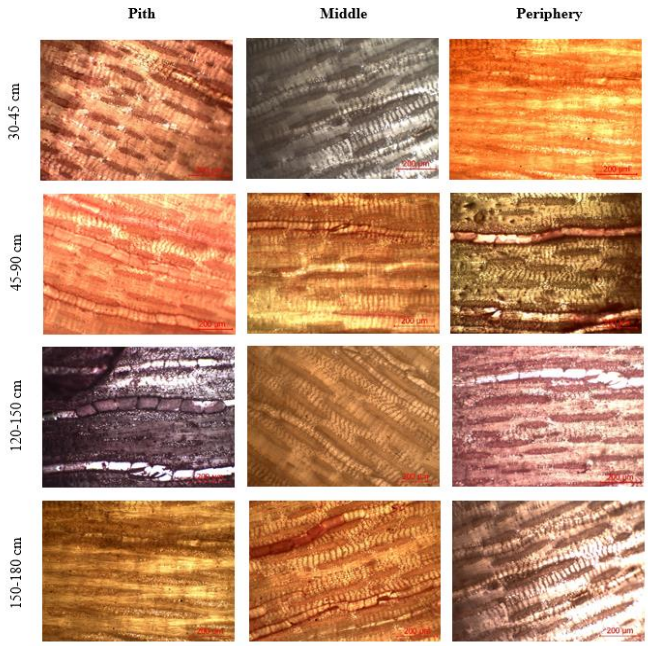

Figure 8. *Microscopic features of the Pterygota alata rays with pith, middle and periphery section with different girth classes (magnification 4x)*

Conclusions

Anatomical studies of *Pterygota alata* are important for the end-use purpose. According to the radial position, fibre length and fibre diameter showed the increasing trend whereas, fibre lumen width and fibre wall thickness were observed a decreasing trend as the distance from the pith is changing. There was a significant difference between the fibre anatomies among the girth classes. Vessel's arrangement in the *Pterygota alata* wood is a diffuse porous type and there was a highly significant difference between the vessel properties. Concerning vessel diameter and area, which are increasing towards the pith and the vessel length was vice versa. An irregular pattern of vessel frequency was noticed between the girth classes. Rays of *Pterygota alata* are a

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multiseriate type. Though, the ray height, ray width and ray frequency showed rising trends towards the periphery. Results of the study indicated that the anatomical build-up of *Pterygota alata* was similar to the species used for pulp and paper production. It can be concluded that *Pterygota alata* might be considered as an ultimate source of fibrous raw material to make pulp and paper. Good quality writing and printing papers could be produced from this type of plant material to minimize the shortfall of pulpable raw material in the country.

Conflicts of Interests. The authors declare no conflict of interests.

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