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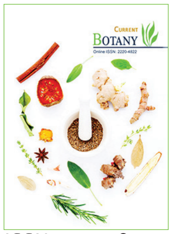

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Geographic variations in vessel and fiber morphology of teak (*Tectona grandis* Linn.) from Kerala: Implications for wood quality and sustainable forestry

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ABSTRACT

Teak (*Tectona grandis* Linn.) is one of the most valuable tropical hardwoods globally, renowned for its exceptional durability, strength, and aesthetic appeal. These attributes make it highly sought after for construction, furniture, and shipbuilding applications. The unique properties of teak are intrinsically tied to its anatomical structure, which influences its physical, mechanical, and hydraulic performance. This study examines the anatomical properties of teak wood collected from seven locations in Kerala, focusing on vessel and fibre morphology to understand how geographic factors influence wood quality. Vessel characteristics such as length, diameter, area, and eco-anatomical indices like mesomorphy and vulnerability reveal significant regional variations, with Nilambur samples demonstrating superior hydraulic efficiency and structural integrity. Fibre traits, including length, width, lumen diameter, and wall thickness, also varied, reflecting environmental and genetic influences. These findings underscore the importance of geographic and ecological factors in shaping wood quality, contributing to sustainable forestry practices and advancements in wood technology.

KEYWORDS: Teak, Wood anatomy, Sustainable forestry, Vessel morphology, Fibre morphology

INTRODUCTION

The characteristics of a tree's wood are influenced by its structural and compositional properties, which encompass strength for mechanical support as well as the composition of xylem and phloem (Chave *et al.*, 2009). The diversity of wood structure is remarkable, arising from differences in the quantity, size, shape, and organisation of cell types, each fulfilling distinct ecological roles (Chave *et al.*, 2009). The capacity and reliability of water transport are significantly affected by the dimensions, frequency, and configuration of vessels, as well as the structure of bordered pit membranes. These elements are essential for tree growth, especially in environments where water is scarce (Tyree & Zimmermann, 2002). Teak (*Tectona grandis* L.f.) stands out as one of the most valued tropical hardwoods, recognised for its light hue, remarkable durability, ease of processing, and inherent strength and stability (Sneha & Ghosh, 2022). This timber is considered one of the strongest in the world (Galeano *et al.*, 2019). The anatomical characteristics of vessels and fibres play a crucial role in comprehending wood quality, as they directly impact physical and mechanical attributes such as permeability, strength, and durability. Vessel characteristics, such as frequency and diameter, significantly determine wood density and moisture content. Specifically, a higher frequency of vessels is associated with increased density, while larger vessel diameters contribute to improved moisture retention (Eloy *et al.*, 2024). In a similar vein, the characteristics of fibres, such as their length, diameter, and wall thickness, play a crucial role in determining mechanical strength. Notably, fibres with thicker walls exhibit enhanced resistance to both compression and tensile forces (Ajuziogu *et al.*, 2014).

Anatomical characteristics, including the vessel-fiber ratio and specific gravity, are associated with wood durability, where an increased vessel-fiber ratio suggests enhanced strength (Antwi-Boasiako & Atta-Obeng, 2009). Statistical analyses indicate that certain anatomical parameters may predict wood strength, facilitating its selection for structural applications (Ajuziogu *et al.*, 2014). Environmental factors and growth conditions, such as soil type, climate, and altitude, are crucial in shaping anatomical features and wood performance. The variations in teak morphology and traits can be attributed to Kerala's diverse soils, climate, and altitudes. In tropical environments, increased rainfall promotes growth, whereas variations in altitude result in phenotypic adaptations observed between highland and lowland areas (Sreekanth *et al.*, 2014; Greeshma & Murugan, 2015). Furthermore, the teak quality is influenced by genetic variation and management practices. Although teak holds significant value in both forestry and commerce, there is a scarcity of studies that examine its anatomical characteristics across various regions in Kerala. Such studies are essential to comprehend the phenotypic and genetic changes impacting teak's mechanical qualities and uses. Addressing this gap can potentially enhance sustainable forestry practices, timber grading, and commercial exploitation. The present study focuses on analysing the differences in vessel and fibre structure among teak samples collected from different regions in Kerala, highlighting how geographical factors influence the quality of the wood. The results will enhance sustainable forestry practices and propel advancements in wood technology research.

MATERIALS AND METHODS

Collection, Preparation and Vessel Morphology Analysis of Specimens

The study was carried out across seven distinct sites in Kerala, namely Nilambur, Konni, Ranni, Illithodu, Thenmala, Waynadu, and Kanjiramkulam. Table 1 and Figure 1 include detailed information regarding the specified sites. The specimens underwent meticulous examination from the esteemed Kerala Forest Research Institute (KFRI) and the Institute of Wood Science and Technology in Bengaluru. To study the anatomical properties of teak, bark samples along with outer xylem and inner phloem (measuring 60 mm × 20 mm × 20 mm) were collected from the main trunks of 40-42-year-old trees growing in different locations. Cross-sections, 15-20 μm thick, were prepared using a sliding microtome, working from the pith to the periphery. Four to five radial positions were examined from the pith to the bark. Digital images of transverse sections were captured using a photonic microscope equipped with a digital camera. ImageJ software (v1.47s) was employed to calculate vessel area, vessel frequency (number of vessels per unit area), and wood porosity (vessel area divided by the total sample area). Additional anatomical features analysed included ring width, vessel diameter, fibre length, fibre wall thickness, and proportions of parenchyma (ray and axial) and vessels. Parameters such as vessel frequency, ray frequency, vulnerability index, vessel composition index, and lumen fraction were also determined. Eco-anatomical properties were calculated using formulas developed by Carlquist (1977).

Fiber Measurement

Characteristics such as fibre length, fibre width, lumen diameter, and wall thickness were measured from macerated samples using Jeffry's method (Jeffry, 1917). Jeffry's solution, consisting of equal volumes of 10% potassium dichromate and 10% nitric acid, was prepared for maceration. Small strips or stem shavings of the wood samples were boiled in this solution for 15-20 minutes to separate the fibres. The macerated material was allowed to settle for 5-10 minutes in test tubes, after which the solution was discarded. The fibres were thoroughly washed with distilled water to remove acid traces, stained with safranine, and mounted on temporary slides using glycerine for microscopic observation. Measurements were performed using an image analyser (Catymage and CatCam500E series).

RESULTS

Vessel Morphology

The morphology of wood vessels plays a crucial role in the physiological and mechanical functions of trees, influencing water transport, structural integrity, and adaptability to environmental conditions. Understanding vessel morphology is essential for comprehending how trees manage water efficiently and respond to various ecological pressures. In the present study, vessel morphology characteristics, including vessel length, diameter, and area were compared among the specimens collected from seven geographically distinct regions (Figure 2). Vessel length varied across the localities, with the highest maximum value observed in Nilambur (246.5 μm) and the lowest in Kanjiramkulam (230 μm). The minimum vessel length followed a similar trend, ranging from 222.8 μm in Nilambur to about 207 μm in Kanjiramkulam. Vessel diameter showed slight variations among the localities, with Nilambur exhibiting the highest value (286 μm) and Kanjiramkulam the lowest (273 μm). The trend indicates a gradual decline in diameter from Nilambur to Kanjiramkulam. In the case of vessel area, the vessel area minimum was highest in Nilambur samples, followed by Konni, Illithodu and Ranni. As seen in the vessel length and diameter, a similar trend was also observed in vessel area max, Nilambur showed the highest vessel area max (92578 μm^2), and Kanjiramkulam was the lowest (90315 μm^2).

Table 1: Details of sample collection

Factor	Site1 Nilambur (Poochappara)	Site2 Konni-(Kaduvappara)	Site3 Ranni	Site4 Illithodu	Site5 Thenmala	Site6 Waynadu (Tholpetty)	Site7 Kanjiramkulam
North latitude	11°28'55"N	9°13'28"N	9°22'48"N	10°11'60"N	8°96'32"N	11°38'45.6"N	8°36'N
East longitude	76°23'86"E	76°50'51"E	76°48'36"E	76°31'59"E	77°06'51"E	76°21'50.4"E	77°05'36"E
Soil type	Alluvial Forestloam	Sandyloam Forestloam	Sandyloam Forestloam	Alluvial Forestloam	Alluvial Forestloam	Sandyloam Alluvial	Sandyloam Alluvial
Rainfall	2580-2632	2560-2613	2530-2603	2510-2599	2545-2589	2562-2602	2540-2594
Range	Karulai	Naduvathamuzhy	Ranni	Malayattoor	Thenmala	Tholpetty	Neyyar
District	Malappuram	Pathanamthitta	Pathanamthitta	Ernakulam	Kollam	Waynadu	Thiruvananthapuram

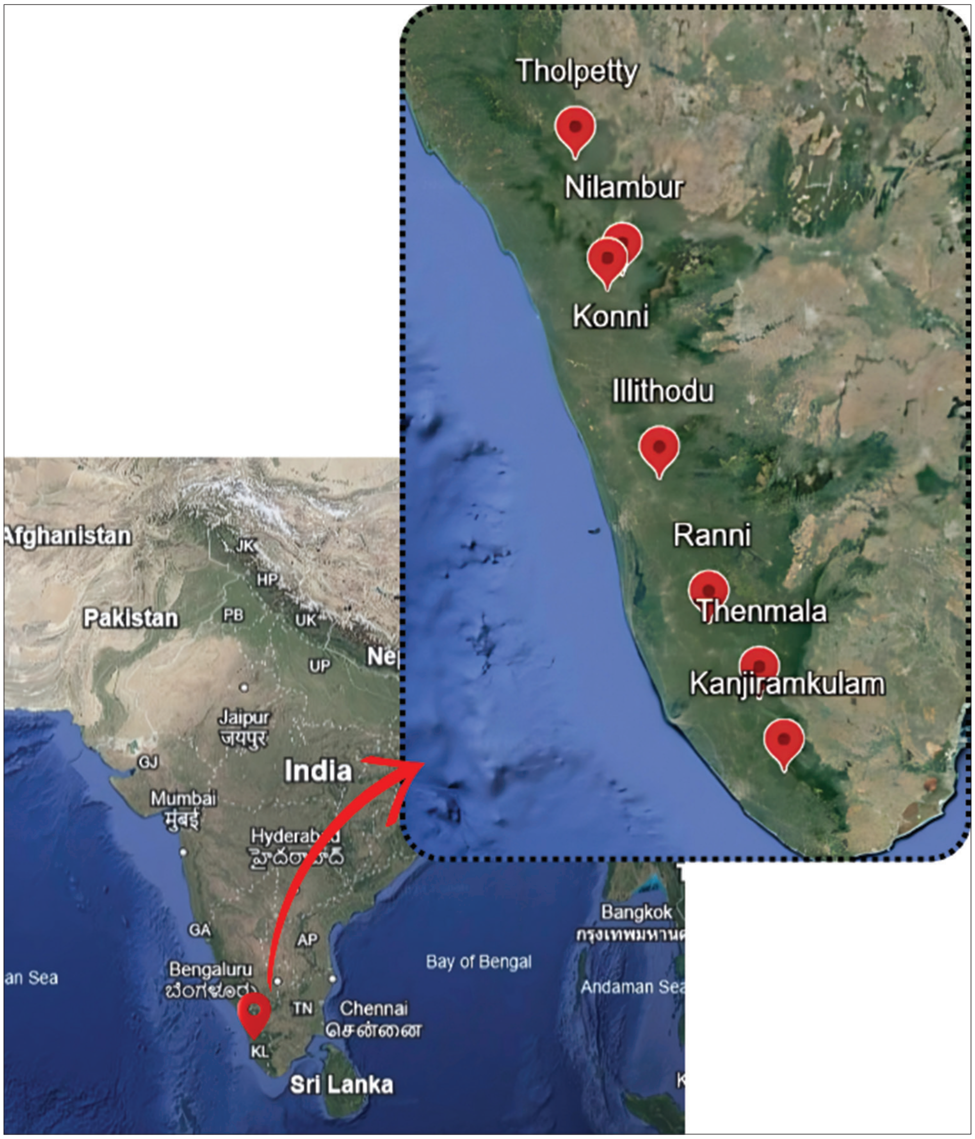

Figure 1: Ecologically distinct localities from where samples were collected

Similarly, the highest vessel area minimum was observed in Nilambur samples (39857 μm^2) compared to the other samples, and the lowest was in Kanjiramkulam samples (38124 μm^2). Eco-anatomical properties such as vessel mesomorphy and vulnerability index were also estimated. Across all localities, vessel mesomorphy values remained relatively consistent, with a slight increase observed in Kanjiramkulam. Nilambur showed a slightly lower vessel mesomorphy compared to other localities. The Vulnerability Index value was lowest in the Konni samples, whereas Kanjiramkulam exhibited the highest vulnerability index. A similar pattern of variation was observed in the case of minimum ray height amongst the samples (Figure 3a, b & c). The maximum ray width slightly varied across localities, decreasing marginally from around 80 μm in Nilambur to 75 μm in Kanjiramkulam. Similarly, the minimum ray width ranged between 25 μm and 30 μm across the localities, showing slight fluctuation. No significant changes in ray frequency were observed among the seven ecologically distinct locations.

Fiber Morphology

The fibre morphological parameters across the studied localities exhibit notable trends. Fibre length (Figure 4a) showed slight variations, with most localities maintaining a relatively stable average between 1.1 mm and 1.3 mm, except for Kanjiramkulam, where a significant reduction was observed, accompanied by higher variability. Fibre width (Figure 4b) showed a gradual decline from Nilambur to Kanjiramkulam, starting around 8.5 μm in Nilambur and decreasing to approximately 6.5 μm in Kanjiramkulam. Fibre width variation was higher in Nilambur and Konni than in other regions. Lumen diameter (Figure 4c) demonstrated a similar declining trend, with values decreasing from approximately 18 μm in Nilambur to around 14 μm in Kanjiramkulam. This parameter exhibited relatively consistent variability across the localities. On the other hand, wall thickness (Figure 4d) showed a subtle increasing trend from Nilambur to Tholpetty, peaking at approximately 5.5 μm, followed by a

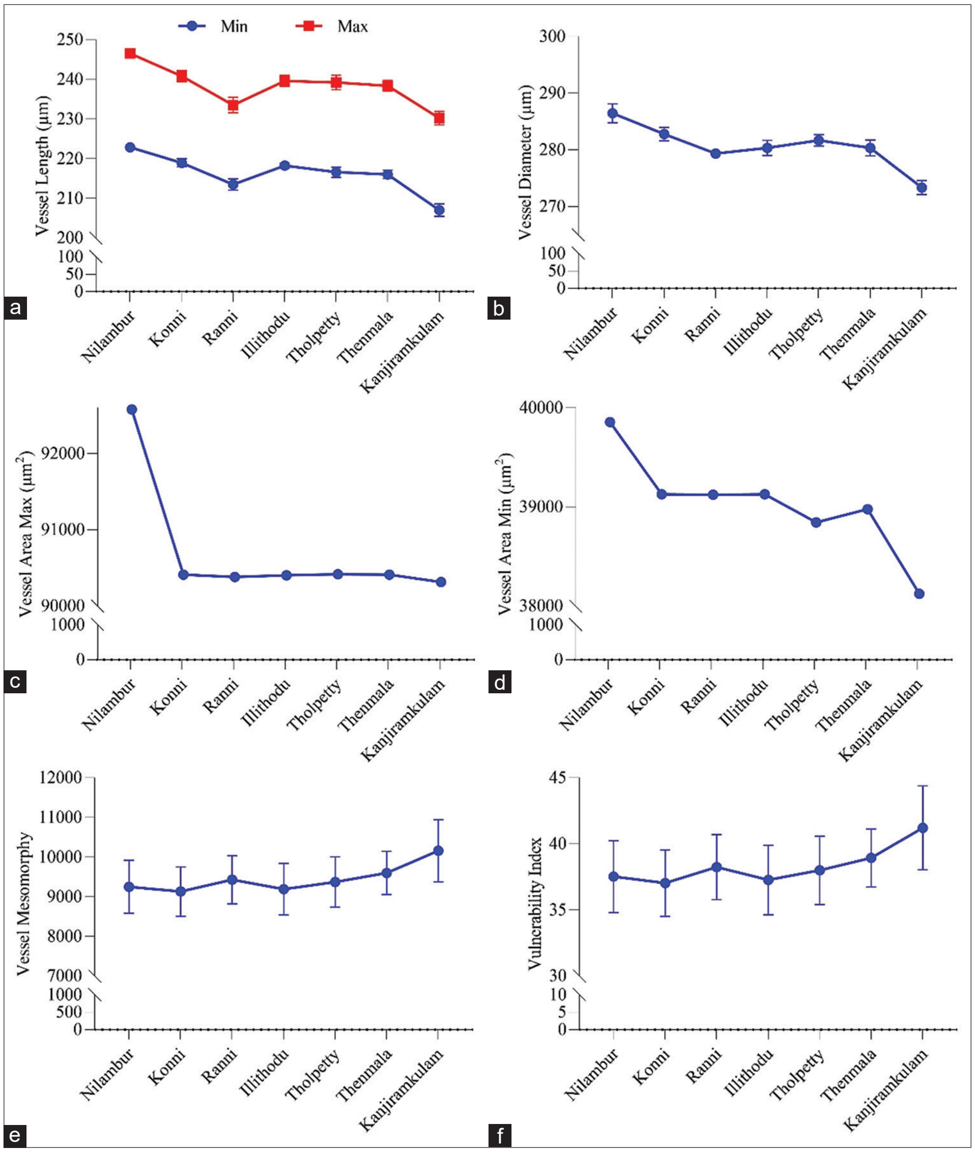

Figure 2: Analysis of Vessel Mophological Characteristics. a) Vessel Length, b) Vessel Diameter, c) Vessel Area Max., d) Vessel Area Min., e) Vessel Mesomorphy and f) Vulnerability Index

decline in Themmala and Kanjiramkulam to around 4.5 µm. These observations suggest that fibre morphological traits are influenced by geographical variations, with a consistent decline in dimensions like fibre width and lumen diameter towards Kanjiramkulam, potentially indicating environmental or genetic factors impacting fibre development.

DISCUSSION

In most flowering plants, vessels serve as the primary channel for water transportation over long distances. The length of vessels is an essential characteristic that influences plants' hydraulic efficiency and safety (Jacobsen *et al.*, 2012). Studies show that the characteristics of vessels, such as their length, are influenced by climatic conditions, with differences observed across various regions (Pumijumnong & Park, 1999). In line with the previous reports, our study shows a significant variation in vessel length amongst the geographically distinct samples (Figure 2a). Similar to vessel length, vessel diameter is influenced by climate, with narrower vessels found in drier environments, indicating the generally smaller size of plants in such conditions (Olson & Rosell, 2013). A countable variation among the samples was observed in our study, indicating the influence of climate over the vessel diameter. Although the research conducted by Rizanti *et al.* (2018) reported a variation in the frequency of vessel elements between long and short rotations of teak, our study did not reveal any significant differences in vessel frequency. Various factors, including growth conditions, management practices, and anatomical differences, shape the wood vessel area in different tree species. A drastic difference in vessel area was observed amongst the studied samples. Nilambur is the sample with the highest vessel area, and Kanjiramkulam is the lowest (Figure 2b & c). The wood vessel mesomorphy and vulnerability index are essential metrics for understanding the hydraulic strategies of plants and their ability to adapt

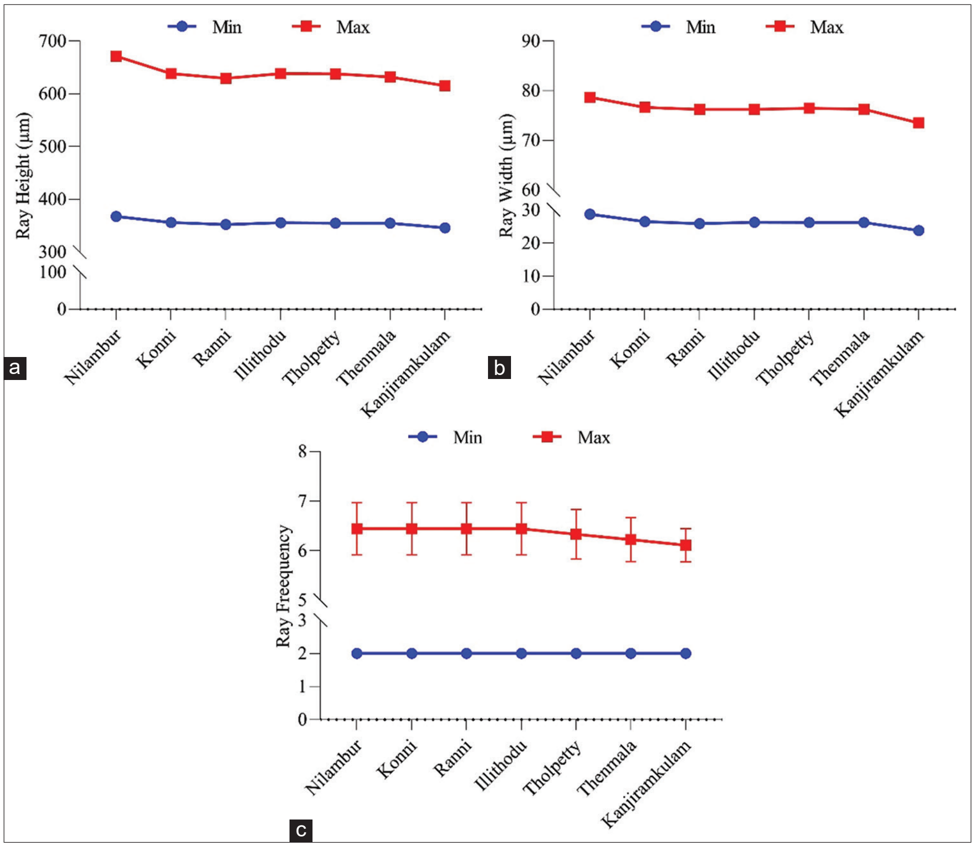

Figure 3: Analysis of Ray Morphology. a) Ray Height, b) Ray width and c) Ray frequency

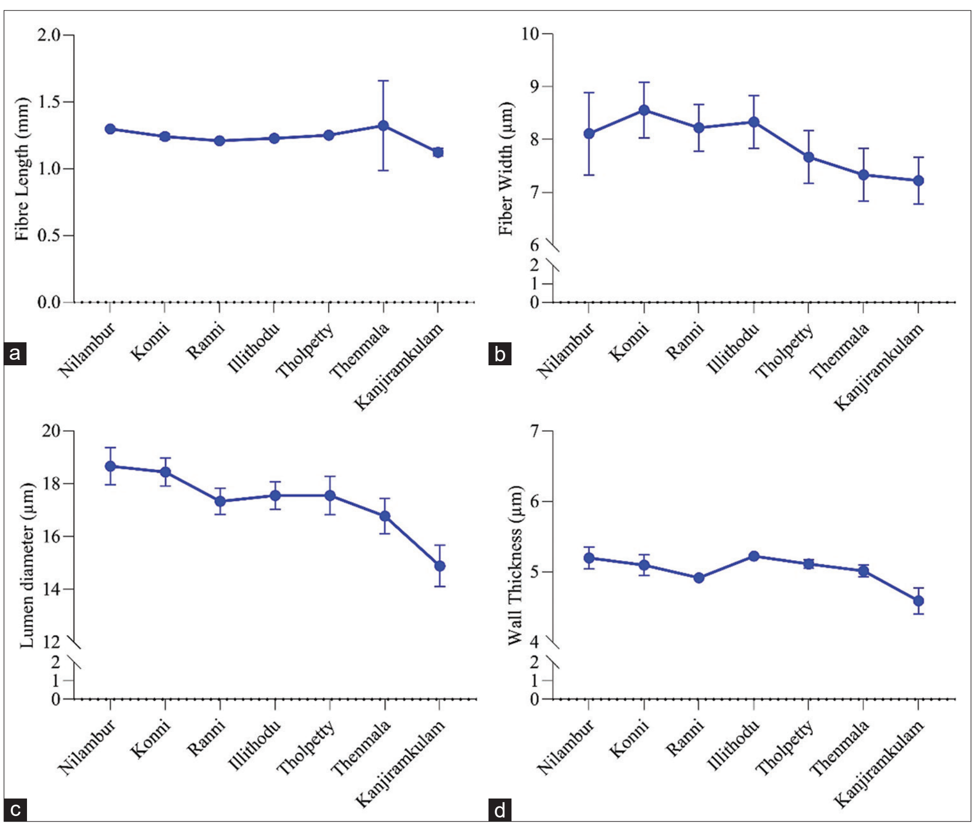

Figure 4: Analysis of Fiber Morphology. a) Fibre Length, b) Fibre width, c) Lumen diameter, and d) Wall thickness

to environmental stressors. These indices, conceptualised by Sherwin Carlquist, provide quantitative insights into how the anatomical characteristics of wood impact its water transport efficiency and resistance to embolism. The vessel mesomorphy index evaluates the balance between vessel size and frequency, reflecting a species' capacity for efficient water conduction while maintaining structural integrity. Meanwhile, the vulnerability index measures the susceptibility of xylem vessels to cavitation under water stress, indicating a plant's drought resilience. Together, these indices play a pivotal role in assessing the trade-offs between hydraulic efficiency and safety, providing valuable information for ecological studies, forestry management, and climate adaptation strategies (Jacobsen & Pratt, 2023). The present study shows that Nilambur samples have the lowest vessel mesomorphy index and vulnerability index, indicating the premium quality of the wood (Figure 2e & f).

Wood ray morphology encompasses the structural attributes of wood rays, which play a critical role in the transport, storage, and radial movement of nutrients, water, and other metabolites in trees. Wood rays comprise parenchyma cells extending radially from the tree's centre, connecting the pith to the outer bark (Chauhan *et al.*, 2017). Research has indicated the differences in ray width and frequency in teak (Cardoso *et al.*, 2015). In accordance with the earlier reports, variations in the ray morphology, including ray width, height, and frequency were observed in our study (Figure 3).

The structural characteristics of wood fibres, known as wood fibre morphology, play a crucial role in determining their mechanical properties and potential applications. Wood fibres, mainly composed of cellulose, display a complex hierarchical structure that includes macro fibrils, microfibrils, and elementary fibrils, which play a significant role in their mechanical strength (Sfiligoj Smole *et al.*, 2019). In the present study, fibre morphological characteristics, including fibre length, width, lumen diameter, and wall thickness, exhibited significant variation among the studied samples, with Nilambur samples having the highest values.

CONCLUSION

This study highlights significant regional variations in teak vessel, ray, and fibre morphology influenced by environmental and ecological factors. Nilambur specimens consistently showed superior vessel dimensions, lower vulnerability index, and higher fibre traits, indicating premium wood quality and better hydraulic efficiency. In contrast, Kanjiramkulam samples exhibited lower values, reflecting environmental stress. These findings underscore the adaptability of teak and its anatomical diversity, providing valuable insights for forestry management and wood quality enhancement.

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