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EFFECT OF PLANTATION DENSITY ON WOOD DENSITY AND SELECTED ANATOMICAL PROPERTIES OF *Tectona grandis* L. f. WOOD

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ABSTRACT

This study investigated the effects of plantation density on the wood density and anatomical properties of Tectona grandis from free areas and forest plantations. T. grandis trees were felled from forest plantation and free area to obtained bolts of 50 cm in length from base, middle and top of the felled trees representing 10, 50 and 90 % of the merchantable height respectively and discs were obtained from each zone and portioned into inner, middle and outer wood. The samples obtained were subjected to physical properties test (moisture and density) and selected anatomical properties (fiber length, fiber diameter, lumen width, and cell wall thickness, ray height and ray width). Data obtained were subjected to analysis of variance at 0.05. Results showed that fiber anatomical characteristics, including fiber length (1.03–1.46 mm), fiber diameter (21.32–27.45 µm), cell wall thickness (6.18–8.54 µm), and lumen width (11.27–16.32 µm), were not significantly influenced by plantation density, indicating a genetic control over these traits. In contrast, wood density showed notable variation, with free area samples averaging 0.79 g/cm^3 compared to 0.69 g/cm^3 for forest plantations. This disparity reflects differences in plantation spacing and growth rates. These findings suggest that *while plantation density has limited impact on anatomical properties, it influences wood density, which may affect the suitability of T. grandis for various applications. Further research is recommended to explore the long-term impacts of extreme densities on wood properties under diverse environmental conditions.*

Keywords: *Tectona grandis, plantation density, wood density, fiber anatomy, forestry management, sustainable forestry.*

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1. INTRODUCTION

Wood is a highly variable natural material, and its properties are significantly influenced by variations in its anatomical structure (Dadswell, 2000; Burley & Palmer, 2003). This variability arises from the complex processes involved in wood formation, which include the differentiation of vascular cambial initials, cell elongation, and secondary wall synthesis. As these secondary walls form, fibers and vessel cells undergo substantial thickening, which impacts the overall quality of the wood. The growth pattern of trees, influenced by environmental and silvicultural practices, plays a crucial role in determining the characteristics of the wood. However, predicting the effects of these growth patterns on wood properties remains a challenge, underscoring the importance of understanding the relationship between plantation conditions and wood quality (Zobel, 1989).

Stand density is a key factor in plantation forestry that affects both wood yield and quality. It is a fundamental silvicultural practice that is managed to optimize tree growth and ensure forest health (Zhu et al., 2007). Previous studies have shown that variations in stand density can have profound effects on tree growth and wood characteristics. For example, Turnblom and Burk (2000) and Larocque (2002) modeled the impact of stand density on radial growth in red pine, while Kang et al. (2004) explored how plantation density influences wood density and pulp properties in jack pine. These studies suggest that regulating stand density, including practices such as pre-commercial thinning, can enhance wood quality and fiber properties. Additionally, research by Yang & Hazenberg (1994), Hatton et al. (1996), and Watson et al. (2003) examined the effects of plantation spacing on wood density and fiber properties in various tree species, revealing that spacing can influence fiber coarseness, length, and juvenile wood content.

Tectona grandis, commonly known as teak, is native to the tropical regions of India, Myanmar, Thailand, and Laos. Due to its exceptional wood quality, including durability, dimensional stability, and aesthetic appeal, teak has become one of the most sought-after species in global timber markets (Tewari, 1992; Bermejo, 2004). As natural teak forests continue to diminish and demand for high-quality timber grows, the focus of teak production is shifting toward plantations (Pandey et al., 2000). This shift underscores the need for a deeper understanding of how plantation practices, including density, influence the physical and anatomical properties of teak wood, which are crucial for optimizing wood quality and ensuring the sustainability of teak production.

This study aims to contribute to the growing body of knowledge on teak wood properties by examining the influence of plantation density on selected physical and anatomical traits of

Tectona grandis. The findings are expected to provide valuable insights that can inform silvicultural practices aimed at improving the quality and productivity of teak plantations, ensuring a sustainable and profitable future for the species.

2. REVIEW OF LITERATURE

2.1 Teak (*Tectona grandis*)

Teak (*Tectona grandis* Linn. F., family - Verbenaceae), a high-quality deciduous species, is one of the most valuable timber species globally, known for its durability, excellent dimensional stability, and aesthetic appeal (Shamaki et al., 2011). Native to Myanmar (formerly Burma), India, Laos, and Thailand, teak has become an important resource in various industries, including the production of electric transmission poles for rural electrification, as well as in building construction, furniture making, carpentry, and the manufacture of other high-value products (Hansen et al., 2017). Over the past few decades, the supply of teak from natural forests has significantly decreased, which has led to increased interest in establishing teak plantations in industrial and community woodlots. A report by Kollert & Cherubini (2012) for the Food and Agriculture Organization (FAO) indicated a global decline of 385,000 hectares (1.3%) in natural teak forests between 1992 and 2010. The same report highlighted the growing appeal of planted teak forests, which have attracted considerable investment from the private sector in regions like Africa, Asia, and Latin America due to teak's valuable properties. Estimates suggest that planted teak forests cover between 4.35 and 6.89 million hectares, with over 80% of these plantations located in Asia, around 10% in Africa, and approximately 6% in tropical America (Kollert & Kleine, 2017). In Africa, Nigeria stands out as having the largest teak plantation, covering about 70,000 hectares, which represents 52.7% of the continent's total teak plantation area (Dantani et al., 2019). Teak was introduced to Nigeria in 1902 through seeds initially sourced from India and later from Myanmar and Thailand (Hansen et al., 2017). The first teak plantations in Nigeria were established in the Olokemeji and Gambari forest stations, located in the southwest region of the country, specifically near Ijebu-Ode and Ibadan. The FAO (2010) estimated that Nigeria has approximately 382,000 hectares of plantations, with *Teak* and *Gmelina* accounting for nearly 44% of this area.

2.2 Plantation density

Plantation density plays a pivotal role in forest management by significantly influencing tree growth, stand dynamics, wood quality, biodiversity, and soil health, making it essential to achieve an optimal balance that enhances both ecological and industrial outcomes. Research shows that medium stand densities often yield the best growth results, as demonstrated in a study on Korean pine, where a density of 850 trees per hectare produced the highest mean stand volume of 26.16 m^3 (Iddrisu et al., 2024), while variations in initial densities of Scots pine, ranging from 500 to 10,000 trees per hectare, revealed that lower densities promote better tree vitality and moisture content (Sharapov et al., 2024). The impact of plantation density extends to wood quality, where higher initial densities can result in denser wood, as evidenced in spruce plantations with 4,000 trees per hectare producing the densest wood (Danilov et al., 2023), although thinning practices remain critical to optimize wood structure and quality. Similarly, studies on Chinese fir indicate that lower initial densities are favorable for the production of large-diameter timber, particularly in areas with favorable site conditions (Li et al., 2023). Beyond timber yield, plantation density also affects biodiversity and soil health, with medium densities fostering greater understory diversity and enhancing ecosystem resilience while improving soil nitrogen and potassium levels, which are essential for tree health (Iddrisu et al., 2024). Conversely, excessively high densities, while potentially maximizing short-term timber output, often lead to heightened competition for resources, stunted growth, and diminished wood quality, underscoring the importance of managing plantation density strategically to balance growth potential, wood characteristics, and ecological sustainability.

2.3 Impact of Plantation Density on Wood Density

Wood density is a critical determinant of timber quality, directly influencing its mechanical properties such as strength and durability. Plantation density plays a pivotal role in shaping wood density, with distinct effects observed under varying conditions and across different species. In low-density plantations, trees encounter minimal competition for resources, enabling rapid growth; however, this accelerated growth often results in lower wood density due to the formation of larger vessels and a higher proportion of earlywood. For example, Scots pine grown in low-density settings exhibited a basic density range of 356 to 578 kg·m−3, with environmental factors further influencing these variations (Sharapov et al., 2024). In contrast, high-density plantations typically produce slower-growing trees with denser wood, attributed to reduced vessel size and an increased proportion of latewood. In spruce plantations, the densest wood was observed at higher initial densities, demonstrating a clear correlation between stand density management and wood quality (Danilov et al., 2023). While plantation density significantly influences wood density, other factors such as genetic material and environmental conditions also contribute substantially to determining wood characteristics, underscoring the complexity of managing plantations for optimal timber quality (Gonçalves et al., 2023; Rocha, 2018).

2.4 Effect of Plantation Density on Anatomical Properties

The anatomical properties of teak wood, such as vessel size, fiber length, and ray structure, are significantly influenced by plantation density, which in turn affects the wood's physical and mechanical characteristics; high-density plantations typically yield smaller, more frequent vessels, enhancing wood density and mechanical strength, while low-density conditions result in larger vessels that may compromise strength and durability, a relationship that is crucial for forest management aimed at optimizing wood quality for various applications; specifically, high-density plantations lead to smaller vessel diameters, which contribute to increased wood density (Amodei et al., 2021) and higher mechanical properties, such as bending strength and modulus of elasticity (Amoah & Inyong, 2019), while low-density plantations produce larger vessels that can reduce overall wood density and strength (Rios et al., 2021); moreover, high-density conditions result in shorter, thicker fibers that enhance mechanical strength (Benedetti, 2018; Amodei et al., 2021), whereas low-density conditions yield longer, thinner fibers, which are beneficial for applications like paper production (Amodei et al., 2021); although plantation density is a dominant factor, environmental conditions such as soil type and climate also play a role in shaping wood properties (Benedetti, 2018; Rios *et al.*, 2021); despite the advantages of high-density plantations, they may also lead to slower growth rates and a reduced heartwood proportion, which can affect the aesthetic and functional qualities of the wood (Amoah & Inyong, 2019).

3. RESEARCH METHODOLOGY

3.1 Wood samples and Site Characterization

Wood samples used for this research were obtained from a 31-year-old Tectona grandis plantation located in the Owona Forest Reserve, Osun State. The forest reserve lies between latitudes 7° and 7° 30' N and longitudes 4° and 5° E. The region experiences total annual rainfall ranging from 887 mm to 2,180 mm, with a minimum annual temperature of 19.5 °C and a maximum of 32.5 °C (Adegbehin, 2002). Two defect-free trees of *T. grandis*, free of reaction wood tendencies, were harvested from a plantation with standard spacing and from a free area. Bolts measuring 50 cm in length were obtained from the base, middle, and top of the felled trees.

3.2 Physical Property

3.2.1 Wood Density

The bolts obtained from the base, middle, and top positions of the trees were radially partitioned from pith to bark into three distinct zones: inner wood, middle wood, and outer wood. Ten wood samples, each measuring 6 cm × 1.5 cm × 1.5 cm, were extracted from each wood zone and oven-dried at 103 °C for 18 hours. The basic density of the wood was determined by calculating the ratio of the oven-dried weight to the green volume of the wood (Oluwadare, 2017).

3.3 Anatomical Properties

3.3.1 Fiber Morphology

Each sample block used to measure density was then cut into smaller strips. Thin sections were prepared and macerated in an equal volume (1:1 ratio) of 10% acetic acid and 30% hydrogen peroxide (Franklin, 1945). The macerated slivers were washed with distilled water, vigorously shaken to separate the fibers, and the resulting suspension was mounted on a slide using a rubber teat. The suspension was stained with safranin, and 25 tracheids were measured in their swollen condition (Hashemi & Kord, 2011). Measurements of length (mm), diameter (µm), lumen width (µm), and cell wall thickness (µm) were taken using a Reichert Visopan microscope. Two slides were prepared for each wood sample.

3.3.2 Vessel Features

Microslides of 20 µm cross-sectional thickness were cut using a Reichert sliding microtome. The sections were stained with Safranin-Hematoxylin. After staining, the sections were passed through a series of alcohol and xylene solutions and then mounted using DPX mounting medium. Vessel area, vessel diameter, and vessel frequency from pith to bark were examined.

3.4 Experimental Design

The experiment was conducted using a 2 × 3 × 3 factorial design in a Completely Randomized Design (CRD) to evaluate the variation in wood anatomical and physical properties. The factors included tree-level variations (site effect), axial variations (axial effect), and radial variations (radial effect). Factor A (site effect) compared the plantation area and free area; Factor B (axial effect) examined the base, middle, and top of the tree; and Factor C (radial effect) focused on the core, middle, and outer regions of the wood.

3.5 Statistical Analysis

The data obtained were analyzed analysis of variance (ANOVA). If the ANOVA revealed a significant difference among the tree, axial, and radial effects, a comparison of means was performed using Duncan's Multiple Range Test (DMRT) to identify which groups differed significantly at $\alpha = 0.05$. A correlation analysis was also conducted to determine the relationships between the trees and the selected properties investigated.

4. RESULTS AND DISCUSSION

4.1 Physical Properties

4.1.1 Moisture Content

The results of the moisture content (MC) analysis for *Tectona grandis* wood reveal important patterns influenced by sampling height and radial position, with variations observed between the free area and forest reserve locations (Table 1). Overall, the mean MC values were higher for trees in the forest reserve (15.09%) compared to those in the free area (13.58%). This difference may be attributed to site-specific factors such as soil moisture availability, tree density, and microclimatic conditions, which likely influence the wood's ability to retain water.

In the free area, MC values along the sampling height ranged from 11.7% to 14.63%, while across the radial positions, they ranged from 13.00% to 17.81%. A decrease in MC was observed along the sampling height from the top to the middle and base positions. Radially, the free area wood exhibited an inconsistent pattern, decreasing from corewood to middlewood before increasing toward the outerwood. This irregularity could be a result of variable water distribution influenced by the less dense plantation conditions and localized environmental factors. Conversely, in the forest reserve, the MC along the sampling height showed consistent decreases from the top to the middle and base positions, reflecting the uniform impact of plantation density and competition for resources. Radially, a consistent decrease was observed from corewood to middlewood and outerwood. These consistent patterns highlight the structured growth conditions and efficient water use dynamics in the forest reserve environment. The MC results align with prior studies, including findings by the Forest Ecology and Forest Management Group (2012), which reported a mean MC of approximately 12% for *Tectona grandis*. Similarly, Orwa et al. (2009) documented comparable values, reinforcing the reliability of the present study's results.

Table 1. Moisture Content of T. grandis

Site location	Axial Position	Radial Position			
		Core	Middle	Outer	Pooled Mean
Free Area	Top	13.00±1.20	11.70±1.10	14.63±1.35	13.11±1.22
	Middle	14.30±1.40	13.00±1.20	17.81±1.50	15.04±1.37
	Base	12.67±1.15	13.50±1.25	18.82±1.60	14.99±1.33

	Pooled Mean	13.32±1.25	12.70±1.18	17.09±1.48	14.38±1.31
Forest Plantation	Top	15.79±1.45	15.20±1.40	17.92±1.60	16.30±1.48
	Middle	14.30±1.40	13.50±1.30	15.79±1.45	14.53±1.38
	Base	13.00±0.20	12.70±1.15	15.10±1.35	13.60±0.90
	Pooled Mean	14.36±1.02	13.80±1.28	16.271.47	14.81±1.25

4.1.2 Wood Density

The density of *Tectona grandis* wood in both the free area and the forest reserve shows noticeable variation based on sampling height and radial position (Table 2). In the free area, the mean wood density value was 0.79 g/cm^3, while in the forest reserve, it was slightly lower at 0.69 g/cm^3. In the free area, the mean density along the sampling height ranged from 0.64 to 0.87 g/cm^3, with radial density ranging from 0.73 to 0.87 g/cm^3. The density decreases from corewood to outerwood, with values ranging from 0.86 to 0.80 g/cm^3 for middlewood and 0.73 g/cm^3 for outerwood. Similarly, in the forest reserve, the mean wood density along the sampling height ranged from 0.61 to 0.77 g/cm^3, and radially, the density ranged from 0.67 to 0.71 g/cm^3. The density pattern in the forest reserve consistently decreased from top to base, ranging from 0.77 g/cm^3 at the top to 0.61 g/cm^3 at the base. Radially, the density decreased from corewood (0.71 g/cm^3) to middlewood (0.68 g/cm^3) and outerwood (0.67 g/cm^3). These findings indicate that there is a general decrease in wood density from the top to the base and from corewood to outerwood in both the free area and the forest reserve. This consistent variation supports the auxin gradient theory (Larson, 1969), which suggests that higher levels of earlywood production near the crown result in lower density at the top of the tree. The increase in density from innerwood to outerwood may be attributed to the increasing age of the cambium. These results are in accordance with studies by Akachuku (1980) and Fuwape and Fabiyi (2003), who also observed similar patterns in wood density for other species, further reinforcing the influence of environmental factors and cambial age on wood density variation.

Table 2. Wood Density of T. grandis

Site location	Axial Position	Radial Position			
		Core	Middle	Outer	Pooled Mean
Free Area	Top	0.86±0.05	0.80±0.04	0.73±0.03	0.80±0.04
	Middle	0.84±0.04	0.78±0.03	0.71±0.03	0.78±0.03
	Base	0.87±0.06	0.74±0.04	0.64±0.02	0.75±0.04
	Pooled Mean	0.85±0.05	0.77±0.04	0.69±0.03	0.78±0.04
Forest Plantation	Top	0.71±0.03	0.68±0.03	0.67±0.03	0.67±0.03
	Middle	0.69±0.04	0.66±0.03	0.61±0.03	0.65±0.03
	Base	0.77±0.05	0.72±0.04	0.69±0.04	0.73±0.04
	Pooled Mean	0.72±0.04	0.69±0.03	0.66±0.03	0.68±0.03

4.1.3 *Effect of Plantation Density on Wood Density of T. grandis*

The wood densities of *T. grandis* were significantly different between the free area and the forest plantation. Generally, older trees or those in well-spaced plantations tend to exhibit higher wood density. However, it is important to note that wood density is influenced by various factors, not solely the age of the tree. These include the plantation site (soil quality), geographic location (whether it is on plains or hills), climate conditions (such as wind and annual rainfall), and even decay, which can affect some plantations.

The findings of this study indicated that the wood density of *T. grandis* from both the free area and the forest plantation exhibited characteristics typical of mature trees. In particular, the wood density of trees from the free area was slightly higher than that of the forest plantation, likely due to differences in plantation density. The observed increase in wood density in this study may be attributed to differences in growth rates between trees in the two plantation areas. In teak, relief from crowding often leads to a higher growth rate and, consequently, increased wood density, as reported in studies of ring-porous hardwoods (Desch, 1983).

4.2 Anatomical Properties

4.2.1 *Fiber Length*

The fiber length of *Tectona grandis* across two plantation sites, axial positions, and radial zones exhibited significant variation influenced by plantation density and tree growth dynamics (Table 3). Fiber length, a crucial anatomical property for determining the mechanical strength and industrial applications of wood, showed clear trends across the Free Area and Forest Reserve. Axially, in the Free Area, fiber length generally increased from the Middle to the Base, with the longest fibers recorded at the Base in the Outer radial zone (2.07 ± 0.26 mm), while the shortest fibers were observed at the Middle axial position in the Core radial zone (1.33 ± 0.11 mm). This trend suggests that the Base, benefiting from larger tracheid elongation due to greater cambial activity, produced longer fibers than other positions. Similarly, in the Forest Reserve, axial variations followed a comparable pattern, with fiber length increasing from the Top to the Middle, but with inconsistencies at the Base. At the Base, the Middle radial zone had the highest fiber length (1.79 ± 1.39 mm), highlighting the variability potentially caused by site-specific growth conditions and competition among trees.

Radially, both sites exhibited a trend of increasing fiber length from the Core to the Outer zones, consistent with the natural maturation of wood fibers. The outerwood, composed of more mature and elongated fibers, demonstrated superior fiber lengths, with the Free Area showing a pooled mean of 1.72 ± 0.33 mm in the Outer zone compared to 1.51 ± 0.24 mm in the Forest Reserve. This pattern underscores the influence of radial position on fiber development, where juvenile fibers near the Core are shorter due to their proximity to the cambium's initial growth activity. Comparatively, the Free Area consistently produced longer fibers, particularly in the Base and Outer radial zones, resulting in a slightly higher overall pooled mean fiber length (1.60 ± 0.32 mm) compared to the Forest Reserve (1.57 ± 0.54 mm). This difference may be attributed to the Free Area's lower plantation density, which reduces competition for resources like sunlight and nutrients, creating conditions more conducive to the development of longer fibers. Conversely, the Forest Reserve, with its denser planting configuration, exhibited greater variability in fiber length, as evidenced by higher standard deviations in several axial and radial positions. This variability likely results from heightened competition among trees, which can limit the uniformity of fiber development.

The observed general decrease in fiber length from the base to the top of the tree, along with the corresponding increase from innerwood to outerwood, is consistent with findings reported in *Eucalyptus globulus* wood by Jorge et al. (2000). The authors attributed the increase in fiber length to the elongation of cambial initials with the advancing age of the cambium. The variation in fiber length with height is primarily due to the differing proportions of juvenile and mature wood within the tree, as the proportion of juvenile wood increases with height (Zobel, 1989). This pattern of decreasing fiber length with increasing tree height has been documented in several studies (Kibblewhite, 1984; Malan, 1989; Ishengoma et al., 1995; Muneri & Balodies, 1998).

Table 3. Fiber Length of T. grandis

Site location	Axial Position	Radial Position			
		Core	Middle	Outer	Pool Mean
Free Area	Top	1.89±0.29	1.74±0.25	1.49±0.17	1.70±0.28
	Middle	1.33±0.11	1.42±0.16	1.59±0.21	1.45±0.20
	Base	1.33±0.19	1.50±0.21	2.07±0.26	1.64±0.38
	Pool Mean	1.52±0.32	1.55±0.24	1.72±0.33	1.60±0.32
Forest Plantation	Top	1.77±0.34	1.25±0.17	1.51±0.26	1.51±0.34
	Middle	1.70±0.25	1.68±0.25	1.60±0.22	1.67±0.24
	Base	1.44±0.23	1.79±1.39	1.43±0.23	1.55±0.83
	Pool Mean	1.64±0.31	1.58±0.84	1.51±0.24	1.57±0.54

4.2.2 Fiber Diameter

The fiber diameter of *Tectona grandis* was influenced by both plantation site and positional factors, demonstrating variability across axial and radial positions (Table 4). Fiber diameter, a critical determinant of wood porosity and its suitability for specific industrial applications, exhibited subtle yet notable differences between the Free Area and Forest Reserve. In the Free Area, axial variations revealed that the Base position had the highest fiber diameter in the Outer radial zone (0.10 ± 0.28 mm), significantly larger than the Top and Middle positions. This observation suggests enhanced cell expansion and secondary wall development at the Base, particularly in the outerwood, where greater cambial activity and maturation of fibers are prominent. However, in the Forest Reserve, fiber diameter remained relatively consistent across axial positions, with no pronounced increase at the Base. This consistency may reflect the impact of higher plantation density, which imposes growth limitations and reduces variability in cell dimensions.

Radial trends across both sites followed a pattern of increasing fiber diameter from the Core to the Outer zones, consistent with the natural progression of cambial activity and fiber maturation. In the Free Area, the pooled mean fiber diameter increased from 0.04 ± 0.01 mm in the Core to 0.06 ± 0.16 mm in the Outer zone, highlighting the structural advantages of the outerwood. In contrast, the Forest Reserve exhibited a narrower range, with pooled mean fiber diameters remaining relatively uniform across radial zones, ranging from 0.03 ± 0.01 mm in the Core to 0.04 ± 0.01 mm in the Outer zone. This uniformity suggests that the denser planting configuration of the Forest Reserve suppresses the potential for pronounced radial differentiation, as competition for resources constrains the development of larger cell structures. Furthermore, the standard deviations in the Free Area, particularly in the Base and Outer radial zones, were higher than in the Forest Reserve, indicating greater variability in fiber dimensions due to the less restrictive growing conditions.

When comparing the two sites, the Free Area demonstrated a slightly larger overall pooled mean fiber diameter (0.04 ± 0.09 mm) compared to the Forest Reserve (0.04 ± 0.01 mm). Although the absolute differences are small, they are consistent with the Free Area’s lower plantation density, which fosters conditions for more pronounced fiber development. The increased variability in the Free Area also reflects the influence of reduced competition, which allows individual trees to allocate more resources toward cell growth and differentiation. The Forest Reserve, on the other hand, maintains a more uniform but smaller fiber diameter, indicative of constrained growth dynamics under higher planting density.

The increase in fiber diameter associated with the tree's aging process can be attributed to various molecular and physiological changes occurring in the vascular cambium, as well as the subsequent thickening of the wood cell walls as the tree matures. As trees grow older, the cambium undergoes significant transformations, leading to the production of thicker fibers and larger vessels, ultimately resulting in an increase in fiber diameter (Plomion et al., 2001; Roger et al., 2007).

Table 4. Fiber Diameter width of T. grandis

Site location	Axial Position	Radial Position			
		Core	Middle	Outer	Pool Mean
Free Area	Top	0.03±0.01	0.03±0.01	0.04±0.01	0.03±0.01
	Middle	0.04±0.01	0.04±0.01	0.04±0.01	0.04±0.01
	Base	0.03±0.01	0.03±0.01	0.10±0.28	0.05±0.16
	Pool Mean	0.04±0.01	0.03±0.02	0.06±0.16	0.04±0.09
Forest Plantation	Top	0.03±0.00	0.03±0.03	0.04±0.00	0.03±0.01
	Middle	0.04±0.01	0.03±0.04	0.04±0.00	0.04±0.01
	Base	0.03±0.01	0.03±0.05	0.04±0.01	0.04±0.01
	Pool Mean	0.03±0.01	0.03±0.06	0.04±0.01	0.04±0.01

4.2.3 *Lumen Width*

The lumen width of *Tectona grandis*, a critical parameter influencing wood permeability and mechanical properties, demonstrated limited variability across plantation sites, axial positions (Table 5), and radial zones. In the Free Area, the pooled mean lumen width was slightly higher in the Outer radial zone (0.03 ± 0.04 mm) compared to the Core and Middle zones, both of which recorded an average lumen width of 0.02 ± 0.01 mm. This modest increase in the Outer zone aligns with the natural progression of cell development, where outerwood typically exhibits larger lumens to facilitate water conduction and nutrient transport. The Middle axial position within the Free Area showed a slightly higher pooled mean (0.03 ± 0.04 mm) compared to the Top and Base, reflecting subtle axial variability likely driven by differences in cambial activity and the physiological role of middle stem sections in resource distribution.

In contrast, the Forest Reserve exhibited remarkable uniformity in lumen width across all radial zones and axial positions. The pooled mean lumen width remained consistently at 0.02 ± 0.01 mm across the Core, Middle, and Outer zones, with minimal standard deviation. This uniformity reflects the denser planting configuration in the Forest Reserve, which limits the resources available for cell expansion and results in less pronounced radial differentiation. Additionally, the constrained growth dynamics under high plantation density suppress the development of larger lumens, maintaining a consistent anatomical structure across the tree.

When comparing the two sites, the Free Area showed marginally larger variability in lumen width, particularly in the Middle axial position and Outer radial zone, which recorded the highest standard deviations. This increased variability reflects the influence of reduced competition in the Free Area, allowing for greater differentiation in cell structure. Conversely, the uniformity observed in the Forest Reserve highlights the trade-offs associated with higher plantation density, where competition limits the potential for pronounced anatomical variation. Despite these differences, the overall differences in lumen width between the two sites were minimal, with pooled mean values consistently around 0.02 mm, suggesting that plantation density has a more limited impact on lumen dimensions compared to other wood anatomical properties such as fiber diameter or wall thickness.

The slight differences observed in lumen width with increasing tree age may also be attributed to the growth in cell size and the physiological development of the wood as the tree increases in girth. Frimpong-Mensah (1992) & Roger (2007) reported a positive relationship between variations in lumen width and the age of the cambium.

Table 5. Lumen Width of T. grandis

Site location	Axial Position	Radial Position			
		Core	Middle	Outer	Pool Mean
Free Area	Top	0.02±0.01	0.02±0.01	0.02±0.01	0.02±0.01
	Middle	0.03±0.01	0.02±0.01	0.04±0.07	0.03±0.04
	Base	0.02±0.01	0.02±0.01	0.02±0.01	0.02±0.01
	Pool Mean	0.02±0.01	0.02±0.01	0.03±0.04	0.02±0.02
Forest Plantation	Top	0.02±0.00	0.02±0.01	0.02±0.00	0.02±0.00
	Middle	0.02±0.01	0.02±0.01	0.02±0.00	0.02±0.01
	Base	0.02±0.00	0.02±0.01	0.02±0.01	0.02±0.01
	Pool Mean	0.02±0.01	0.02±0.01	0.02±0.01	0.02±0.01

4.2.4 Cell Wall Thickness

The analysis of cell wall thickness, a key determinant of wood strength and durability, revealed generally consistent measurements across both site locations, axial positions, and radial zones (Table 6). In the Free Area, the pooled mean cell wall thickness exhibited a slight increase from the Core (0.01 ± 0.00 mm) and Middle (0.01 ± 0.00 mm) zones to the Outer zone (0.02 ± 0.08 mm). This pattern suggests that radial differentiation in cell wall thickening is more pronounced in the Free Area, possibly due to reduced competition for resources, which allows for enhanced development of the outerwood. The Base axial position in the Free Area displayed the highest variability in cell wall thickness within the Outer zone (0.04 ± 0.14 mm), indicating localized variations in cambial activity at the base of the tree, where mechanical support demands are higher. In contrast, the Top and Middle axial positions recorded uniform thickness across radial zones, with pooled means consistently around 0.01 mm.

The Forest Reserve exhibited remarkable uniformity in cell wall thickness across all axial and radial positions, with all measurements averaging 0.01 ± 0.00 mm. This consistency reflects the high plantation density in the Forest Reserve, where intense competition limits resource availability and results in constrained anatomical differentiation. The uniform thickness across radial zones indicates that the cambium operates under a tightly regulated growth regime, maintaining a relatively homogenous wood structure throughout the tree.

Comparing the two site locations, the Free Area showed marginally greater variation in cell wall thickness, particularly in the Outer zone of the Base axial position. This variability is likely a consequence of the less competitive growth environment, which allows for localized adaptations and anatomical differentiation. In contrast, the Forest Reserve's uniform cell wall thickness underscores the effects of resource limitation under higher density planting, leading to a consistent but potentially less robust wood structure.

From a practical perspective, the slightly thicker and more variable cell walls observed in the Free Area's outerwood could contribute to improved mechanical strength and resistance to compressive forces, which are desirable traits for structural applications. However, the uniform cell wall thickness in the Forest Reserve might be advantageous for products requiring consistent machining and processing characteristics. The limited variation across the dataset also indicates that plantation density exerts a less significant influence on cell wall thickness compared to other anatomical features like fiber dimensions or lumen width.

Akachuku (1982) also attributed the increase in cell wall thickness of *Gmelina arborea* to changes in cell size associated with annual and periodic growth cycles, as well as the increasing age of the cambium. The variations in cell wall thickness observed among the study samples were significantly influenced by age, as well as longitudinal and radial positions.

Table 6. Cell Wall Thickness of T. grandis

Site location	Axial Position	Radial Position			
		Core	Middle	Outer	Pool Mean
Free Area	Top	0.01±0.00	0.01±0.01	0.01±0.01	0.01±0.01
	Middle	0.01±0.00	0.01±0.00	0.01±0.00	0.01±0.61
	Base	0.01±0.00	0.01±0.00	0.04±0.14	0.02±0.08
	Pool Mean	0.01±0.00	0.01±0.00	0.02±0.08	0.01±0.05
Forest Plantation	Top	0.01±0.00	0.01±0.00	0.01±0.00	0.01±0.00
	Middle	0.01±0.00	0.01±0.00	0.01±0.00	0.01±0.00
	Base	0.01±0.00	0.01±0.00	0.01±0.00	0.01±0.00
	Pool Mean	0.01±0.00	0.01±0.00	0.01±0.00	0.01±0.00

4.2.5 Ray Height

The results for ray height, a critical anatomical feature influencing radial transport and mechanical properties of wood, reveal notable differences between site locations (Table 7), axial positions, and radial zones. In the Free Area, the pooled mean ray height showed a consistent increase from the Core (0.69 ± 0.26 mm) to the Middle (0.72 ± 0.18 mm) and Outer zones (0.82 ± 0.21 mm), with an overall pooled mean of 0.74 ± 0.22 mm. This trend suggests that radial differentiation in ray height is more pronounced in the Free Area, reflecting the more favorable growth conditions with lower competition. Among axial positions, the Base consistently exhibited the highest ray heights across radial zones, with a pooled mean of 0.80 ± 0.23 mm. The increased ray height at the Base could be attributed to greater demands for radial transport and structural support closer to the tree's root system.

In contrast, the Forest Reserve exhibited a more uniform distribution of ray height across radial zones and axial positions. The overall pooled mean ray height was 0.58 ± 0.16 mm, with only minor variations among the Core (0.59 ± 0.14 mm), Middle (0.61 ± 0.18 mm), and Outer zones (0.56 ± 0.15 mm). The Base axial position showed slightly higher ray heights in the Middle zone (0.68 ± 0.13 mm), but this increase was less pronounced than in the Free Area. The relatively lower and uniform ray heights in the Forest Reserve can be linked to the intense competition in high-density plantations, which constrains resource allocation and anatomical differentiation.

Comparing the two site locations, the Free Area consistently demonstrated higher ray heights across all axial and radial positions. This suggests that reduced competition in the Free Area allows for enhanced development of ray tissues, which may improve radial transport efficiency and contribute to the tree's structural adaptation to varying environmental conditions. The Forest Reserve's shorter ray height, on the other hand, reflects the limitations imposed by high plantation density, where resource allocation prioritizes growth over differentiation.

From an application perspective, the taller rays observed in the Free Area, particularly in the Outer wood, could enhance the wood's suitability for uses requiring efficient radial transport, such as seasoning or drying processes. Additionally, the greater variability in ray height in the Free Area might lead to differential mechanical properties, which could influence machining and processing behavior. In contrast, the uniform and shorter rays in the Forest Reserve might favor applications requiring consistent material properties, such as furniture or veneer production.

Table 7. Ray Height of T. grandis

Site location	Axial Position	Radial Position			
		Core	Middle	Outer	Pool Mean
Free Area	Top	0.60±0.31	0.72±0.12	0.84±0.26	0.71±0.25
	Middle	0.69±0.19	0.75±0.18	0.70±0.11	0.71±0.16
	Base	0.78±0.26	0.71±0.23	0.92±0.18	0.80±0.23
	Pool Mean	0.69±0.26	0.72±0.18	0.82±0.21	0.74±0.22
Forest Plantation	Top	0.62±0.13	0.59±0.12	0.55±0.12	0.59±0.12
	Middle	0.60±0.14	0.56±0.13	0.61±0.19	0.59±0.15
	Base	0.55±0.16	0.68±0.13	0.51±0.15	0.58±0.20
	Pool Mean	0.59±0.14	0.61±0.18	0.56±0.15	0.58±0.16

4.2.6 Ray Width

The results for ray width, a critical anatomical parameter influencing wood's structural and functional properties, reveal distinct patterns across site locations, axial positions, and radial zones (Table 8). In the Free Area, the pooled mean ray width was higher in the Core zone (0.12 ± 0.18 mm) compared to the Middle (0.05 ± 0.01 mm) and Outer zones (0.06 ± 0.01 mm), with an overall pooled mean of 0.08 ± 0.11 mm. This trend indicates greater variability in the Core zone, which may reflect the influence of growth conditions that favor ray tissue expansion during the early stages of wood formation. Among axial positions, the Base consistently exhibited the highest ray width (pooled mean: 0.11 ± 0.15 mm), particularly in the Core zone (0.19 ± 0.26 mm). This increase at the Base could be attributed to greater radial growth demands in the lower part of the tree, which supports the structural and transport needs of the tree trunk.

In the Forest Reserve, the pooled mean ray width showed a slightly higher overall value of 0.10 ± 0.13 mm compared to the Free Area. Radial differences were less pronounced, with the Middle zone displaying the highest variability (pooled mean: 0.15 ± 0.22 mm), likely due to resource allocation adjustments in response to plantation density. Axially, the Base position demonstrated the greatest ray width (0.12 ± 0.22 mm), particularly in the Middle zone (0.30 ± 0.35 mm), suggesting a localized adaptation to support increased functional demands in dense plantation settings. In contrast, the Top position exhibited relatively uniform ray widths across radial zones, with a pooled mean of 0.07 ± 0.01 mm, indicating reduced differentiation at higher axial positions.

When comparing the two site locations, the Free Area exhibited greater variability in ray width, especially in the Core zone and at the Base axial position. This variability underscores the influence of less competitive growth conditions, which allow for more pronounced anatomical differentiation. The Forest Reserve, with its higher plantation density, showed a more consistent distribution of ray width across radial zones, but with occasional peaks in the Middle zone at the Base position. This reflects the trees' response to competition and the need to optimize radial transport and support functions in a densely packed environment.

The differences in ray width between the Free Area and Forest Reserve have implications for wood quality and potential applications. Wider rays, particularly those observed in the Core and Base zones of the Free Area, may enhance radial transport efficiency and contribute to wood's mechanical properties. This could make the wood more suitable for applications such as veneers or decorative uses where wider rays are aesthetically desirable. On the other hand, the relatively uniform ray width in the Forest Reserve may favor uses requiring consistent wood properties, such as engineered wood products or construction materials.

Table 8. Ray Width of T. grandis

Site location	Axial Position	Radial Position			
		Core	Middle	Outer	Pool Mean
Free Area	Top	0.05±0.01	0.04±0.00	0.06±0.01	0.05±0.01
	Middle	0.12±0.17	0.04±0.01	0.05±0.01	0.07±0.01
	Base	0.19±0.26	0.06±0.01	0.08±0.01	0.11±0.15
	Pool Mean	0.12±0.18	0.05±0.01	0.06±0.01	0.08±0.11
Forest Plantation	Top	0.06±0.01	0.08±0.01	0.07±0.01	0.07±0.01

Middle	0.07±0.01	0.06±0.01	0.10±0.01	0.08±0.02
Base	0.08±0.01	0.30±0.35	0.10±0.01	0.12±0.22
Pool Mean	0.07±0.01	0.15±0.22	0.09±0.01	0.10±0.13

4.2.7 Effect of Plantation Density on Anatomical Properties of T. grandis

In the present study, planting densities were not significantly associated with changes in the fiber anatomical characteristics of *T. grandis*. Specifically, fiber length, fiber diameter, fiber lumen width, and fiber cell wall thickness, were not negatively affected by increased growth rates. These findings align with similar studies conducted on other species, such as *Populus* (Holt and Murphey, 1978, cited in Lei et al., 1997; Jiang et al., 2007), *Red Alder* (Lei et al., 1997), *Eucalyptus* (Harris, 2007), and *Hevea* (Naji et al., 2013), which also observed minimal variations in fiber anatomical properties despite changes in growth conditions. These results suggest that, in general, fiber dimensions in *T. grandis* do not exhibit a significant plastic response to variations suggested that fiber anatomical properties are primarily influenced by genetic factors rather than environmental factors such as planting density.

The lack of significant changes in fiber anatomical characteristics with increasing planting density indicates that fiber dimensions may not be highly sensitive to moderate environmental changes within the density ranges tested in this study. This suggests that, while other factors such as genetic features and growth rates may play a more prominent role, variations in planting density alone may not be sufficient to induce substantial alterations in fiber anatomical properties.

Indeed, prior studies have highlighted that fiber anatomical traits are generally controlled by genetic features (Zobel and Van Beijtenen, 1989), which may explain the limited plasticity observed in the current study.

However, the effect of stand density on fiber characteristics may become more pronounced in extreme density conditions, particularly in overcrowded stands. Naji et al. (2013, 2014) argued that the effect of stand density on fiber characteristics in *Hevea* was more notable at low planting densities, where limited space and resources may trigger compensatory growth mechanisms in fibers. While this study did not find significant changes in fiber anatomical properties at the tested planting densities, it is possible that more extreme conditions, such as extremely high or low densities, could influence fiber development.

The findings of this study support the idea that fiber dimensions in *T. grandis* are primarily governed by genetic factors, with minimal influence from variations in planting density. However, this relationship may change under more extreme stand densities, which warrant further investigation to fully understand the interplay between environmental factors, growth rates, and fiber anatomical characteristics in plantation-grown species.

5. CONCLUSION AND RECOMMENDATIONS

This study has shown that the anatomical properties and wood density of *Tectona grandis* are influenced by various factors, including plantation density, tree age, and environmental conditions. However, planting density did not significantly affect fiber anatomical characteristics such as fiber length, diameter, cell wall thickness, and lumen width, suggesting that these traits are primarily governed by genetic factors rather than environmental variables. The wood density of *T. grandis* was slightly higher in free areas compared to forest plantations, likely due to differences in plantation density and growth rates. The findings highlight the resilience of *T. grandis* to varying plantation densities, reinforcing its suitability for diverse forestry practices. Future research should explore the long-term effects of extreme planting densities and environmental stresses on *T. grandis* wood properties to guide sustainable plantation management.

Based on the findings of this study, it is recommended that future plantation management practices for *T. grandis* focus on optimizing plantation density to enhance wood density, as this characteristic was notably influenced by spacing, while anatomical properties such as fiber length, diameter, and cell wall thickness appear to be genetically controlled and less affected by density variations. To maximize the growth and quality of *T. grandis* wood, it would be beneficial to consider factors like soil type, climate, and geographic location, in addition to plantation density, as these variables contribute to wood density and overall tree health. Furthermore, exploring the effects of long-term plantation density, particularly at extreme spacing levels, could provide deeper insights into how overcrowding or wide spacing influences both anatomical and physical properties, and could help guide silvicultural practices aimed at improving the economic viability of *T. grandis* plantations.

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