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# Evaluation Of Axial And Radial Variations Of Selected Mechanical Properties Of *Terminalia catappa* (Linn) As A Lesser-Known Wood Species

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## ABSTRACT

The increasing demand for sustainable and alternative wood species necessitates the evaluation of lesser-known species for structural applications. This study investigates the mechanical properties of *Terminalia catappa* wood from three trees sourced from Rivers State University, Port Harcourt. The trees were analyzed axially (top, middle, and base) and radially (inner, core, and outer wood) to assess modulus of rupture (MOR), modulus of elasticity (MOE), compressive strength parallel to grain (CS//G), shear strength (SS), and impact strength (IS). Specimens were prepared in accordance with standard mechanical testing dimensions, and data were analyzed using ANOVA at a 5% significance level. Results indicated that MOR (2.99–3.09 N/mm<sup>2</sup>), MOE (680.35–753.00 N/mm<sup>2</sup>), CS//G (17.56–21.16 N/mm<sup>2</sup>), and IS (3.20–4.12 N/mm<sup>2</sup>) exhibited an increasing trend from base to top and from inner to outer wood. SS (12.69–19.47 N/mm<sup>2</sup>) also increased axially but fluctuated radially. Statistical analysis showed no significant differences ( $P > 0.05$ ) across both planes. The findings position *Terminalia catappa* as a medium-density wood, suitable for non-structural applications such as furniture and plywood manufacturing. Further research is recommended to explore the commercial viability and sustainability of this lesser-known species.

**Keywords:** Modulus of Elasticity, Compressive, Parallel, Shear, Impact Strength Test

## INTRODUCTION

Wood remains an essential and adaptable construction material in the building industry due to its distinctive mechanical properties, sustainability, and ease to processing. Historically, wood has been used for a wide range of applications, from basic structural frameworks to complex architectural designs due to its flexibility and aesthetic appeal. Among the various wood species, *Terminalia catappa*, commonly referred to as Indian almond or tropical almond, has received recognition for its impressive qualities. This rapidly growing, deciduous hardwood species flourishes in tropical and subtropical regions, including Nigeria, making it a readily available resource in these areas. The increasing interest in *Terminalia*

*catappa* arises from its potential to act as an eco-friendly and economical alternative to traditional wood species, especially in regions where sustainable practices are progressively emphasized (Aleru et al., 2023).

*Terminalia catappa* are reported and grown for its multipurpose uses. However, it remains an untapped as underutilized (lesser known) tree (Weerasekara et al., 2015; Aina et al., 2019). A sizeable amount of the worldwide timber industry is made up of lesser-known wood species, also known as minor or underutilized species. Despite their abundance and potential for various applications, these species are frequently overlooked in favor of more popular and commercially established woods (Tomar et al., 2016). Oduro et al. (2021) noted that while *Terminalia catappa* is commonly found in Ghana and utilized for various purposes, it is classified as a lesser-known species due to its full potential not being fully realized in commercial applications. The authors emphasize that many species, including *Terminalia catappa*, have not been extensively studied or utilized despite their availability and potential benefits, indicating that increased awareness and research could enhance their use in forestry and other industries.

The mechanical properties of wood are paramount in determining its suitability for structural and non-structural applications. Key properties such as compressive strength, bending strength, modulus of elasticity, and shear strength play vital roles in defining the performance and durability of wood in construction (Cai and Ross, 2010). These properties, however, are not uniform across all wood species; they are influenced by a myriad of intrinsic factors, including the wood's density, fiber structure, and grain orientation. Additionally, extrinsic factors like environmental conditions, moisture content, and processing techniques further contribute to variations in mechanical performance (Aleru and David-Sarogoro, 2016; David-Sarogoro and Aleru, 2016; Kommentare, 2017; Glass and Zelinka, 2021; Kherais et al., 2024;). Such variability underscores the importance of conducting localized studies to understand the mechanical behavior of specific wood species under particular conditions.

*Terminalia catappa*, in particular, holds significant promise for structural applications in regions where it is abundant. The species' fast growth rate and adaptability to diverse climatic conditions (ACIAR, 2013; Santos et al., 2022), make it a sustainable choice for both small-scale and large-scale utilization. However, its widespread adoption requires a thorough understanding of its mechanical properties to ensure safety, reliability, and efficiency in construction and other uses. In Rivers State, Nigeria, where *Terminalia catappa* is naturally abundant, leveraging this resource aligns with the region's goals of promoting self-reliance and reducing dependence on imported materials. Studies focused on evaluating the mechanical properties of *Terminalia catappa*, therefore, are not only scientifically relevant but also economically and environmentally significant. Rivers State University, Port Harcourt has increasingly prioritised the utilisation of local materials for construction and engineering purposes. As such, this study contributed and supported this initiative by providing an assessment of the mechanical properties of *Terminalia catappa* wood species grown within the university community in Rivers State, Nigeria.

The research investigated important properties like modulus of rupture, modulus of elasticity, compressive strength parallel to grain, shear strength, and impact resistance by putting the wood through a series of standardised mechanical tests. These properties are crucial for assessing the wood's structural integrity and ability to tolerate different loads and stresses. Furthermore, the study investigated the effects of age, processing techniques, and exposure to the environment on the wood's mechanical properties, offering a thorough dataset for well-informed decision-making. By incorporating locally accessible materials into contemporary engineering solutions, this article contributed to a larger initiative to promote sustainable construction methods.

The results of this study established *Terminalia catappa* as a competitive alternative for structural applications in Nigeria and the world, as global building trends move towards sustainability. Thus, improved the economic and environmental viability of construction techniques in Rivers State and comparable areas by bridging the gap between engineering needs and local resource availability.

## **MATERIALS AND METHOD**

### **Study Area**

The tree samples of *Terminalia catappa* wood used in this research were sourced from the Rivers State University campus, situated at latitude 4.80040 N and longitude 6.9841° E. This study area is located within the capital city of Rivers State, which serves as an industrial hub in the heart of the Niger Delta—a region renowned as one of the largest wetlands in the world, covering an area of approximately 2,900 km<sup>2</sup> (NDES, 1997). The elevation of the study area ranges from 10 to 15 meters above sea level (Ubong *et al.*, 2015).

Characterized primarily by tropical lowland forests and mangrove swamps, this ecosystem is influenced by both saltwater and freshwater inundations. However, human activities have contributed to the degradation of certain forested regions. The meteorological conditions in Port Harcourt exhibit a humid, semi-hot equatorial climate, marked by heavy rainfall (Papadiki, 1961; NEDECO, 1980).



**Modulus of Rupture (MOR)/ Bending Strength**

The Modulus of Rupture (MOR) test was conducted following the British standard BS 373, utilizing a universal testing machine. Standard test specimens measuring 20 mm x 20 mm x 300 mm were prepared, with the load applied at a rate of 0.1 mm/sec and the grain oriented parallel to the direction of loading, specifically on the radial face of the specimens. The bending strength of the wood, commonly referred to as the MOR, was determined by recording the load at failure and monitoring the corresponding values directly from the machine. Consequently, the MOR was calculated as follows:

$$MOR = \frac{3PL}{2bd^2} \dots\dots\dots \text{Equation 4}$$

Where:

MOR is the Modulus of Rupture

P is the Load (N)

L is the Length of Sample (mm)

B is the width of the sample (mm)

H is the thickness of the sample (mm)

**Modulus of Elasticity (MOE) in Bending**

The modulus of elasticity (MOE) was determined in accordance with the British standard BS 373, using standard test specimens measuring 20 mm x 20 mm x 300 mm, which were derived from the MOR test. The corresponding MOE values were recorded, and the MOE was calculated using the following formula:

$$MOE = \frac{PL^3}{\Delta bd^3} \dots\dots\dots \text{Equation 5}$$

Where:

MOE = Modulus of Elasticity

P is the Load (N)

L is the Length of sample (mm)

B is the width of the sample (mm)

D is the thickness of the sample (mm)

Δ Is the slope of the graph

**Compressive Strength Parallel to Grain**

This measurement represents the maximum stress endured by a compression specimen parallel to the grain, with a length-to-least-dimension ratio of less than 11. Specimens measuring 20 mm x 20 mm x 60 mm were prepared for testing. Each specimen was positioned in the testing machine with its length aligned parallel to the direction of the load, ensuring that the load was applied concentrically. The load was gradually increased until failure occurred, with the load at failure designated as the maximum compressive load (Pmax). The compressive strength parallel to the grain was calculated by dividing the maximum compressive load by the cross-sectional area of the specimen (A). The ultimate compressive strength was determined using Equation 6.

$$CS//G = \frac{P_{max}}{ab} \dots\dots\dots \text{Equation 6}$$

Where ;

CS//G is Compress strength Parallel to grain

Pmax is the Maximum load (N)

a is the length of sample

b is the width of sample

**Shear Strength**

The shear strength test was conducted in accordance with the ASTM (2009) guidelines, featuring a setup designed to ensure that the test piece fails exclusively along the designated shear zone.

$$T = \frac{F}{A} \dots \dots \dots \text{Equation 7}$$

T is the Shear Strength

F is the applied force

A is the cross-sectional area of wood with area parallel to the applied force.

**Impact Strength Test**

The impact test was conducted using the Hatt-Turner impact testing machine, following the British standard BS 373. Test samples measuring 20 mm x 20 mm x 300 mm were supported over a span of 24 cm, with a support radius of 15 mm. Spring-restricted yokes were fitted to prevent rebound. The samples were subjected to repeated blows from a 1.5 kg weight, starting at a height of 50.8 mm and increasing in increments of 25.4 mm until complete failure occurs. At that point, the height of the maximum hammer drop was recorded in meters.

**Experimental Design and Statistical Analysis**

A completely randomized design (CRD) was employed for this study. Treatments were replicated three times, and the data were analyzed using the Statistical Package for the Social Sciences (SPSS) Version 20, utilizing a one-way analysis of variance (ANOVA) at a 5% significance level.

**RESULTS AND DISCUSSION**

**Modulus of Rupture (MOR) of *Terminalia catappa***

The Modulus of Rupture (MOR) of *Terminalia catappa* wood species, as illustrated in Figure 2, indicates a range between 2.99 N/mm<sup>2</sup> and 3.09 N/mm<sup>2</sup> along the axial length of the tree. The MOR increases from the base to the top of the tree, with the highest value of 3.09 N/mm<sup>2</sup> observed at the top and the lowest value of 2.99 N/mm<sup>2</sup> recorded at the middle section. Radially, the MOR demonstrates an increase from the inner to the outer wood across the tree’s bole. Interestingly, a fluctuation is observed at the core of the tree, where the MOR values range from 2.90 N/mm<sup>2</sup> to 3.18 N/mm<sup>2</sup>, with the core exhibiting the highest value of 3.18 N/mm<sup>2</sup>. Statistical analysis reveals no significant differences (P>0.05) in MOR values along both the radial and axial directions.

These findings are consistent with earlier studies on the mechanical properties of hardwood species. For instance, Izekor and Fuwape (2010) reported a similar trend of increasing MOR from the inner to outer regions and along the height of the tree for *Tectona grandis*. Additionally, Githiomi and Kariuki (2010) found that wood density and mechanical strength, including MOR, often vary radially and axially due to differences in growth conditions and anatomical properties. This trend is also observed in hardwood species like *Larix sibirica* in Tumenjargal *et al.*, (2020). Panshin and de Zeeuw (1980) asserted that the increased stress and decreased weight in the upper parts, the top portion of tree often has greater mechanical characteristics. In Scots pine wood, Büyüksarı, *et al* (2017) also found that tree height and section (top, middle, or bottom) significantly affect the MOR, with the top often showing higher values.

The observation of increased MOR from the inner to outer wood is consistent with studies on growth ring patterns and wood formation. Wang *et al.*, (2012) suggested that the outer wood of trees generally experiences more tension due to the mechanical stresses of the growing tree, leading to stronger and denser wood.

The higher MOR at the core of the tree noted in the results (highest value of 3.18 N/mm<sup>2</sup>) may be attributed to the unique structure of the earlywood and latewood growth patterns. Zobel and van Buijtenen, (1989) explain that corewood (or earlywood) tends to have higher structural strength in certain species due to its denser fiber composition. However, contrasting evidence exists in the literature. For example, Desch and Dinwoodie (1996) argue that variations in MOR do not always follow a predictable pattern radially or axially, as factors such as environmental stress, genetic variability, and age can lead to

irregular trends. Similarly, a study by Agarana, *et al.*, (2019) statistical analysis of mechanical properties of wood showed significant radial and axial variations in MOR, with statistical differences at  $P < 0.05$ , challenging the notion of uniformity in mechanical properties across the bole. The study's finding of no significant difference may also be attributed to the variability in mechanical properties like MOR which can be more pronounced in species with more heterogeneous growth patterns, but *T. catappa* may have relatively uniform properties. This could also point to the homogeneity of wood strength within this species, which might not always be the case in others (Senalik and Farber, 2021; Arriaga *et al.*, 2023). These differences underscore the complexity of wood mechanical properties, suggesting that while *Terminalia catappa* exhibits specific trends in MOR, other wood species may display distinct patterns influenced by a combination of intrinsic and extrinsic factors. When compared to other hardwood species, the woods (i.e., *T. catappa*) MOR values are somewhat low, which could limit its use in structural applications that call for stronger materials. But given that the tree's mechanical properties are consistent, it would be a viable choice for making plywood or other non-structural wood products where great mechanical strength is not as important.

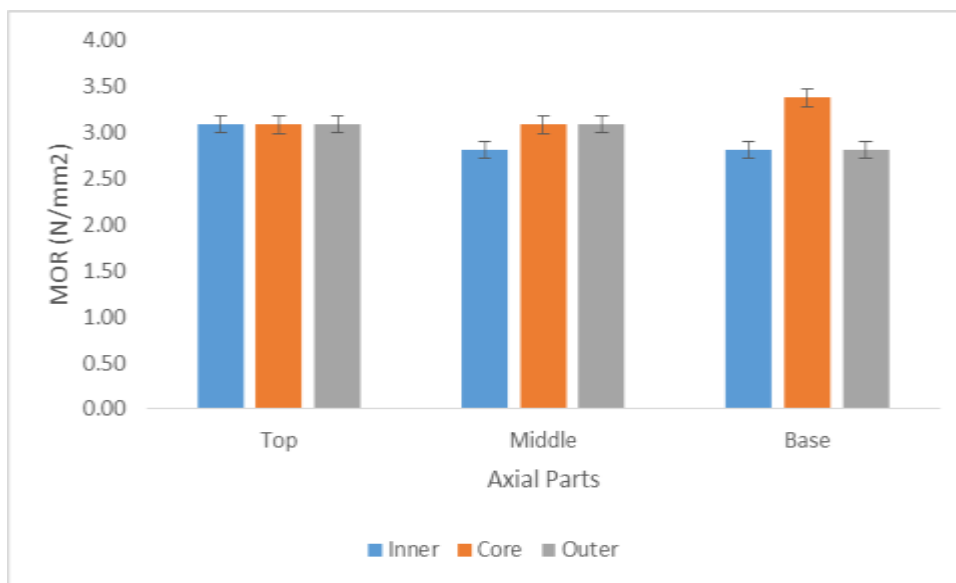


Figure 2: Modulus of Rupture of *Terminalia catappa*

#### Modulus of Elasticity of *Terminalia catappa*

The result on the Modulus of Elasticity (MOE) of *Terminalia catappa* wood species presented in figure 3 below shows a range from  $680.35\text{N/mm}^2$  to  $753.00\text{N/mm}^2$  with an increase from base to top with the middle having a highest value of  $753.00\text{N/mm}^2$  and base having the lowest value of  $680.35\text{N/mm}^2$  along the axial length and with an increase from inner to outer wood across the bole of the tree radially with mean values ranging from  $687.83\text{N/mm}^2$  to  $730.66\text{N/mm}^2$  respectively with the core having the highest value of  $730.66\text{N/mm}^2$ . There was no significance difference ( $P > 0.05$ ) at both radial and axial

These findings align with earlier studies on wood MOE properties. A gradient of increasing stiffness up the tree's axial length is a frequent pattern seen in the MOE of many tree species.

A common trend seen in the stiffness (MOE) of many tree species is that it tends to increase as you move up the tree. For example, Baar *et al.* (2015) discovered that the middle part of several wood species usually has higher stiffness compared to the base or top, likely because this section is under more structural pressure to support the tree's growth. In a similar study, Appiah-Kubi *et al.* (2016) also found higher stiffness in the middle of plantation-grown *Khaya ivorensis* hardwood species, suggesting this might be linked to how the tree grows and how mechanical stress is spread throughout its structure. This will help fight against environmental stresses such as wind and weight from snow or foliage.

Several studies have shown that MOE tends to rise as one ascends the tree from the base to the middle area. For example, measurements showed that dynamic MOE increased as one climbed the trunk, with notable increases observed between parts of varying height (Papandrea *et al.*, 2022). According to this pattern, the centre portion is designed for maximum rigidity and resistance to bending forces, both of which are essential for holding branches and foliage (Green *et al.*, 1999).

The overall trend of increased MOE in the outer wood relative to the inner wood is consistent with other wood science research. Hein *et al.*, (2016) posited that due to its denser fibre composition and the mechanical pressures placed on the tree's surface as it grows, outerwood typically has a stiffer texture than innerwood. Additionally, Izekor and Fuwape (2010) observed similar findings in *Tectona grandis*, and Li *et al.* (2021) reported the same for *Pinus radiata*, where the outerwood layers demonstrated stronger MOE than the softer corewood. It is interesting to note that the corewood of *T. catappa* had a higher mean MOE (730.66 N/mm<sup>2</sup>) than other parts of the tree, which goes against the usual pattern where the outerwood typically has better MOE.

However, Davies *et al.* (2016) observed similar findings in *Pinus radiata*, suggesting that some species may have denser or more structured corewood, particularly in earlywood or certain environmental conditions. Also, Finto *et al.* (2011) corroborated this in their work carried out on *Pinus taeda L.* (loblolly pine) wherein core wood exhibited a higher mean MOE than other parts of the tree. This suggests that corewood maintains its stiffness better than outer sections at certain heights. The lack of statistical significance ( $P > 0.05$ ) in both the axial and radial directions could suggest that *T. catappa* has a fairly uniform structure, with little variation in the modulus of elasticity (MOE) across different sections of the wood. This means that the wood might not have highly specialized mechanical properties, such as stiffness, when compared to other species that show more noticeable differences in their MOE. Because of this, *T. catappa* might not be the best choice for structural uses where high stiffness or more variability is required. However, its relatively high MOE in the middle and outer sections of the tree indicates that it could still work well for applications like furniture making or plywood, which need moderate levels of stiffness.

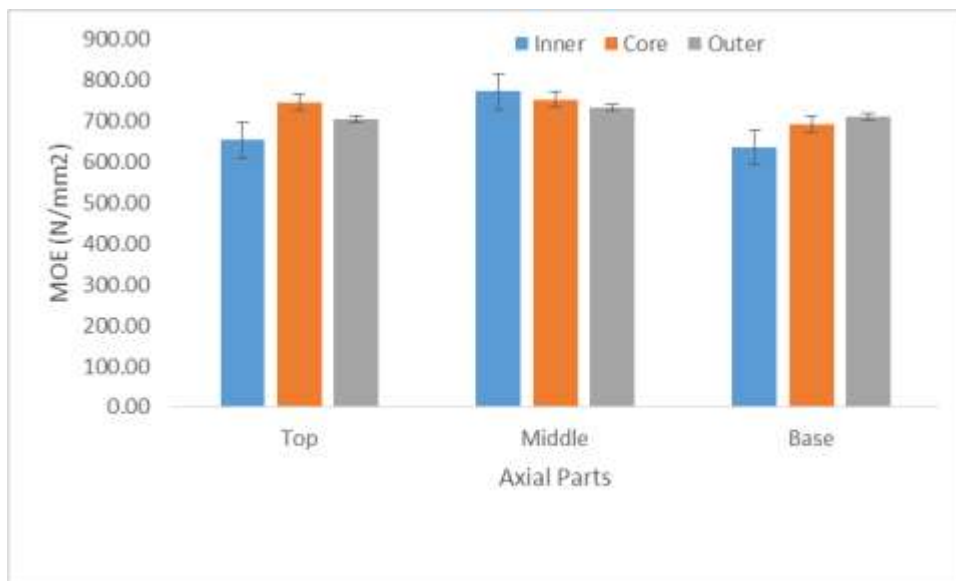


Figure 3: Modulus of Elasticity of *Terminalia catappa*

**Compressive strength parallel to grain of *Terminalia catappa***

The result on the Compressive strength parallel to grain of *Terminalia catappa* wood species presented in figure 4 below shows a range from 17.56N/mm<sup>2</sup> to 21.16N/mm<sup>2</sup> with an increase from base to top with

the middle having a highest value of 21.16N/mm<sup>2</sup> and base having the lowest value of 17.56N/mm<sup>2</sup> along the axial length and with an increase from inner to outer wood across the bole of the tree radially with mean values ranging from 18.35N/mm<sup>2</sup> to 22.13N/mm<sup>2</sup> respectively with the core having the highest value of 22.13N/mm<sup>2</sup>. There was no significance difference ( $P > 0.05$ ) at both radial and axial

Wood's compressive strength frequently varies within tree height, with the middle section usually showing higher values. According to Mattheck and Tesari (2004) and Gril *et al.* (2017), the central portion of the tree frequently exhibits higher compressive strength in response to the increased stress load that is placed on it throughout growth. The trend of increased compressive strength from the inner to the outer wood is also consistent with findings from other studies. Perez-Pena *et al.* (2020) reported that compressive strength generally increases from the pith (core) to the bark (outerwood) due to the increase in basic density from innerwood to outerwood. This high density is attributed to the higher lignin content and fiber orientation in the outer growth rings (Hoadley, 2000 and Chung, 2004).

Similarly, Lachenbruch and Roberts (2021). found that radial variations in mechanical properties are largely due to the denser structure of the outer wood as it supports the growing tree and withstands environmental stresses. The observation of higher compressive strength in the core wood of *T. catappa* (mean value of 22.13 N/mm<sup>2</sup>) is noteworthy, as corewood typically exhibits lower stiffness compared to outerwood in most tree species. This finding suggests that *T. catappa* may possess distinct structural or compositional characteristics that differentiate it from other species where outerwood generally demonstrates greater mechanical strength. Similar results have been observed in some tropical hardwoods, where the corewood can show strong mechanical properties. This is often due to the denser latewood rings or a unique fiber structure that enhances its strength. Mankowski and Laskowska (2021) reported certain hardwood species, including some species may have higher mechanical strength, in this case compressive strength in corewood due to the characteristics of their earlywood and latewood layers.

The absence of significant differences ( $P > 0.05$ ) in compressive strength across both the radial and axial directions suggests that any variations observed may fall within the natural variability of the species. This indicates that the compressive strength of the wood is relatively uniform, and fluctuations in strength are likely a typical characteristic of this species. Some researchers, such as Adetayo and Dahunsi (2017) argue that species with more consistent density throughout the tree would exhibit less variation and/or homogeneous structure in compressive strength. Studies carried out by Green *et al.* (1999) on some wood species have demonstrated that the compressive strength of clear wood specimens is relatively uniform throughout the tree, attributed to the consistent anatomical structure and growth patterns of the species. Similarly, research on parallel strand lumber (PSL) indicates that the compressive strength of specimens with a uniform mesostructure remains consistent, with limited variation observed across different sections of the material (Weng and Zhang, 2008). Growth conditions, such as soil type, moisture availability, and climate, can significantly influence wood strength. Eilmann *et al.* (2011) and Yu *et al.* (2021) posited that environmental stress can lead to structural changes in wood that may either enhance or compromise its strength, depending on the specific conditions and adaptations of the tree species involved.

The absence of significant differences might indicate that *T. catappa* has a more consistent grain structure, or that environmental factors such as growth rate or soil fertility lead to uniformity in wood properties. In cases where trees grow in favorable conditions, wood properties might not show significant variation.

The compressive strength of *T. catappa*, ranging between 18.35 N/mm<sup>2</sup> and 22.13 N/mm<sup>2</sup>, positions this wood as suitable for non-structural applications, such as furniture making, plywood, and joinery. The radial and axial consistency of the material further suggests that its strength remains relatively uniform, minimizing concerns about variability during processing. This characteristic simplifies the selection and handling of the wood. However, for structural applications that demand greater compressive strength-such as in construction materials or heavy-duty furniture-*T. catappa* may not be the optimal choice, especially when compared to stronger wood species like oak or teak.

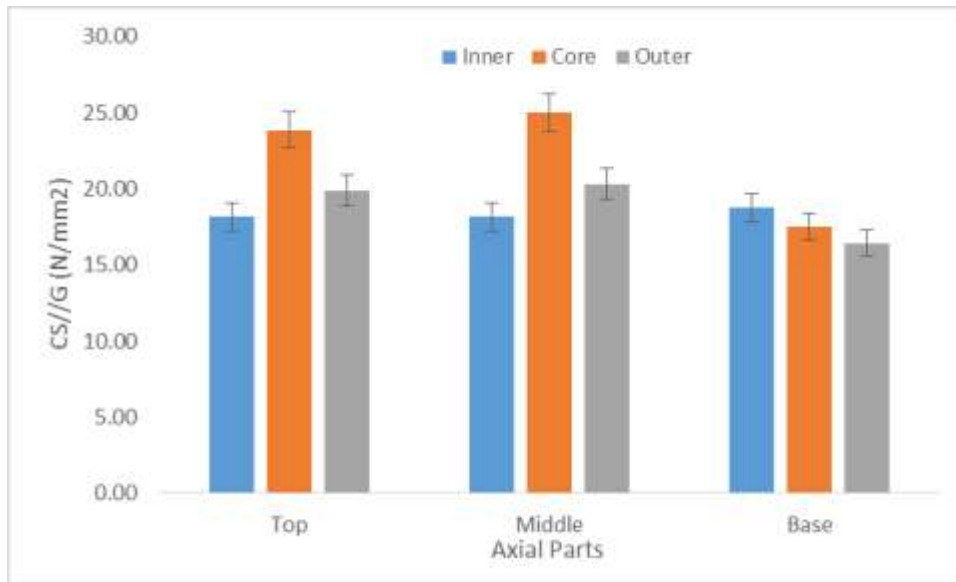


Figure 4 Compressive strength parallel to grain of *Terminalia catappa*

#### Shear strength parallel to grain of *Terminalia catappa*

The result on the Shear strength parallel to grain of *Terminalia catappa* wood species presented in figure 5 below shows a range from 12.69N/mm<sup>2</sup> to 19.47N/mm<sup>2</sup> with an increase from base to top with the top having a highest value of 19.47N/mm<sup>2</sup> and base having the lowest value of 12.69N/mm<sup>2</sup> along the axial length and with an increase from outer to inner wood across the bole of the tree also a fluctuation in the wood trend at the core of the tree radially with mean values ranging from 12.69N/mm<sup>2</sup> to 16.63N/mm<sup>2</sup> respectively with the core having the highest value of 16.63N/mm<sup>2</sup>. There no significance difference ( $P>0.05$ ) at both radial and axial.

The reported results are supported and contextualised by a number of investigations. The observed increase in shear strength from the base to the top of the tree, with the top section displaying the highest value of 19.47 N/mm<sup>2</sup>, aligns with patterns documented in other tree species. This trend suggests a common characteristic in the distribution of shear strength within trees. For example, Oda and Sato (2016); Sakai and Yoshihara (2017); Huang and Liang (2018) reported that as tree matures, the wood in the upper sections is subjected to greater external environmental forces which tends to develop higher shear strength, reflecting the tree's adaptive response to these stresses. Conversely, David-Sarogoro, and Aleru, (2016) noted otherwise in the trend wherein *Mangifera indica* hardwood species could be identified as having significantly lower values in top sections as against the bottom sections. This is evident to the fact that the upper parts of a tree are younger and grow more rapidly than the lower sections. This rapid growth can result in wood with lower density and mechanical strength in the top sections (Schreuder and Lewis, 2001). The proportion of earlywood (the lighter, less dense part of the growth ring) to latewood (the darker, denser part) varies along the tree's height. Latewood fibers generally exhibit greater strength and stiffness than earlywood fibers. In some species, the distribution of earlywood and latewood can differ between the top and bottom sections, affecting the overall mechanical properties (Mott et al., 2002). Moisture content influences wood's mechanical properties. The upper sections of a tree may have higher moisture content due to transpiration processes, potentially leading to reduced strength compared to the drier bottom sections

The increase in shear strength from the outer wood to the core wood of aligns with findings from other hardwood species. In many tree species, the outer wood (sapwood) is denser and stronger than the inner wood (heartwood). This variation is primarily due to differences in fiber orientation and lignin content between the two regions. The arrangement of cellulose fibers in wood significantly influences its mechanical properties. In the outer growth rings, fibers are typically more aligned and oriented,

contributing to increased strength and stiffness. Conversely, the inner growth rings often exhibit less organized fiber structures, resulting in lower mechanical strength (Engler, n.d.). Lignin, a complex polymer in the cell walls of wood, provides strength and rigidity. Higher lignin content in the outer growth rings enhances the wood's density and strength. In contrast, the inner growth rings may have lower lignin content, leading to reduced strength properties. (Gui *et al.*, 2020).

A study on *Pinus radiata* found that wood density, tracheid length, fiber coarseness, and cellulose content all increase from the pith to the bark, while microfibril angle and lignin content decrease (Raymond and Anderson, 2005). Research on *Azadirachta indica* indicated that within-tree variation affects wood density, grain orientation, and anisotropic shrinkage, with the outer wood exhibiting higher density and more favorable grain orientation compared to the inner wood (Sotannde *et al.*, 2010).

The higher shear strength observed with a mean value of 16.63 N/mm<sup>2</sup>, is somewhat unexpected, as corewood often exhibits lower mechanical properties in many species. However, reverse is the case in this study. This is possibly influenced by its anatomical structure, particularly the characteristics of early wood, denser latewood or variations in fiber alignment. For example, research carried out on *Larix kaempferi* found that latewood possesses thicker tracheid cell walls and smaller microfibril angle (MFA), leading to better shear performance compared to earlywood (Li *et al.*, 2021). Similarly, a study on Scot pine (*Pinus sylvestris* L.) demonstrated that latewood sections exhibit higher strength properties than earlywood sections, attributed to their denser structure and variations in fiber alignment (Büyüksarı *et al.*, 2017).

The lack of significant differences ( $P > 0.05$ ) across both radial and axial directions is noteworthy. This suggests that the variations observed in might be more influenced by natural variability within the wood, rather than structural differences between the inner and outer wood or base and top sections (Minnesota Department of Transportation, 1992; Vilkovský *et al.*, 2022).

The relatively high shear strength values observed in the top sections and the corewood could indicate that *T. catappa* wood might be useful for applications where shear forces are prevalent, such as in construction, furniture making, and plywood manufacturing. However, given that shear strength is not significantly different between sections of the tree, the wood can be uniformly processed without the need to distinguish between different parts of the tree.

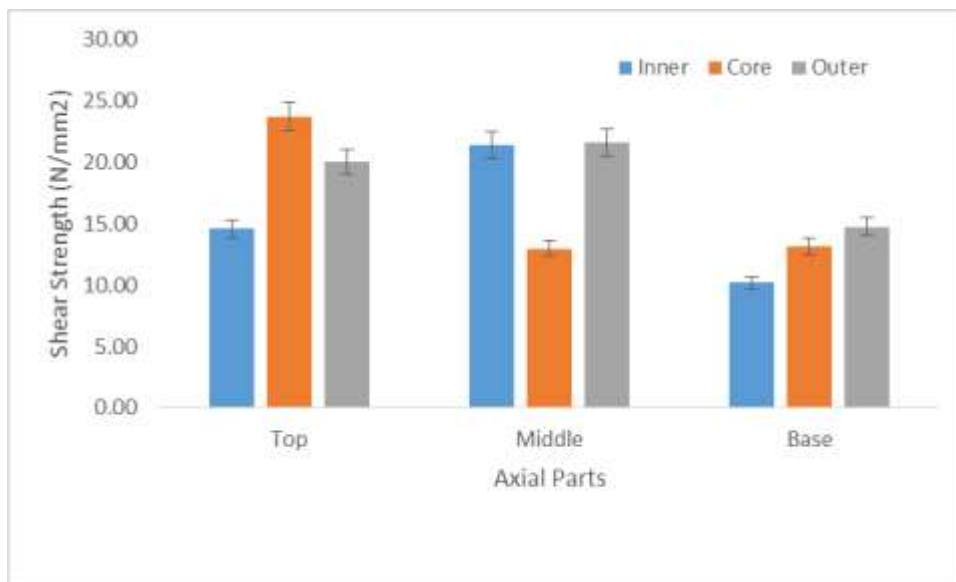


Figure 5: Shear strength parallel to grain of *Terminalia catappa*

**Impact strength parallel to grain of *Terminalia catappa***

The result on the Impact strength parallel to grain of *Terminalia catappa* wood species presented in figure 6 below shows a haphazard range of 3.20N/mm<sup>2</sup> at the middle, 3.99N/mm<sup>2</sup> at the base and 4.12N/mm<sup>2</sup> at the top with the top having a highest value of 4.12N/mm<sup>2</sup> and middle having the lowest value of 3.20N/mm<sup>2</sup> along the axial length and with an increase from inner to outer wood across the bole of the tree radially with mean values ranging from 3.60N/mm<sup>2</sup> to 3.92N/mm<sup>2</sup> respectively with the core having the highest value of 3.92N/mm<sup>2</sup>. There was no significance difference (P>0.05) at both radial and axial.

A growing body of research underscores the influence of tree height and wind exposure on the mechanical properties of wood, emphasizing how trees adapt to withstand environmental stresses. One such study by Palacios *et al.* (2006) focused on *Pinus sylvestris* and found that impact bending strength decreases as you move higher up in the tree. This finding is supported by Schönfelder *et al.* (2019), who discovered that the strength characteristics of wood also diminish with increasing trunk height. These variations in wood properties along the trunk suggest that the position within the tree has a significant effect on its structural integrity.

Interestingly, while wood strength may decrease with height, the upper sections of trees seem to show enhanced impact strength. This increase in resilience is likely an adaptive response to the greater mechanical stresses encountered at the tree's upper levels. The tops of trees are more exposed to wind forces and the weight of branches, necessitating stronger, more flexible strength properties. Over time, trees in these more challenging environments develop such adaptations, reflecting their ability to adjust and persist. In addition to the effect of height, exposure to wind is another crucial factor in shaping tree biomechanics. Research on Sitka spruce trees in western Scotland, conducted by Bruchert and Gardiner (2006), demonstrated that trees at the forest edge, where wind exposure is most pronounced, exhibited greater strength despite being shorter. These trees were more tapered, a feature that enhanced their stability at the base while increasing crown flexibility. The structural adaptations of these edge trees underscore their ability to better distribute mechanical stress, thus increasing their resistance to wind forces.

Furthermore, research has highlighted the role of wind-induced torsional stresses on tree structures. Asymmetrical wind loads on tree crowns and individual branches can cause twisting forces that make trees more vulnerable to failure. However, over time, trees may develop resistance to these torsional stresses. One such adaptation involves the formation of spiral grain in the xylem, a phenomenon that enables trees to better manage twisting and bending forces (Coder, 2021). This resilience further exemplifies the remarkable plasticity of trees, allowing them to thrive even under continuous mechanical stress. Altogether, these studies paint a picture of how trees, particularly in wind-exposed environments, adapt both structurally and biologically to endure mechanical challenges. From changes in wood strength along the trunk to the evolution of spiral grain in response to torsion, trees continuously refine their internal architecture to better cope with the forces of nature.

Similar trends of increasing impact strength from the inner (heartwood) to outer (sapwood) wood have been reported in other studies. These variations are often attributed to differences in wood density, moisture content and the structural roles of innerwood and outerwood. A study on *Anogeissus leicarpus* examined the strength properties along both the axial and radial position. The findings showed that impact strength increased from inner towards outer wood. This suggest that the outer wood possesses higher impact strength compared to the inner wood (Fasiku and Ogunsanwo, 2020). Additionally, Kretschmann (2010) noted that in hardwood species, the strength of specimens tested at 12% moisture content averages about 32% higher compared to those at higher moisture contents. This indicates that the outer wood, which typically has lower moisture content than the inner wood, may exhibit greater strength properties, including impact strength.

The finding that the core wood exhibits the highest mean impact strength (3.92 N/mm<sup>2</sup>) is relatively uncommon. In many species, the core wood tends to be weaker due to its higher moisture content, irregular fiber alignment, and lower density (Escobar, 2008; Korkmaz and Büyüksarı, 2019; Build in

Wood, 2020); Fu *et al.*, 2023). The higher impact strength of the top and core wood in *T. catappa* suggests that specific sections of the tree may be more suitable for applications involving impact resistance, such as in construction or furniture manufacturing. The uniformity of properties across the tree, despite the non-uniform axial distribution, means that *T. catappa* wood may be easily processed without significant variation in mechanical properties. The no significant differences ( $P > 0.05$ ) between the axial and radial directions, which could suggest that the observed variations are within the natural variability of the wood.

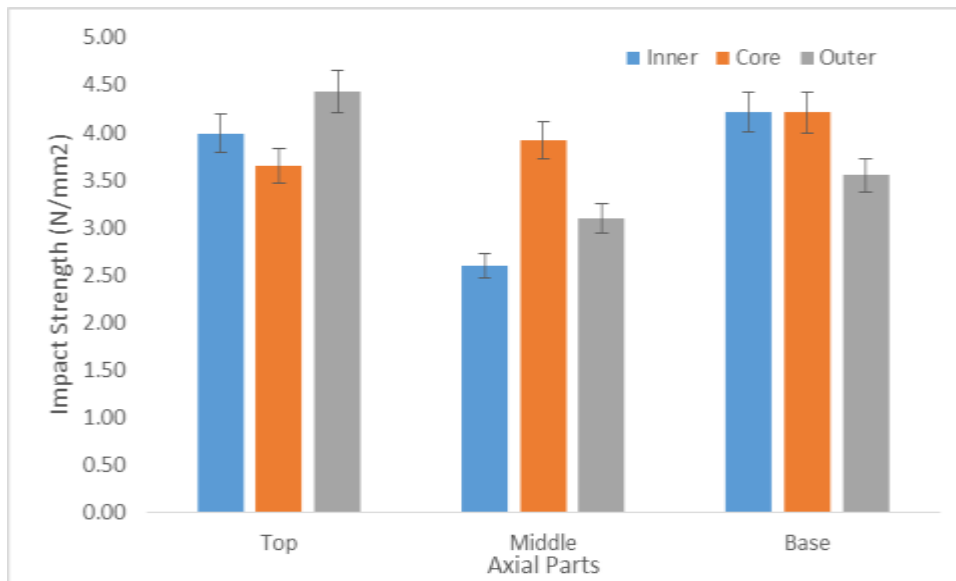


Figure 6: Impact strength parallel to grain of *Terminalia catappa*

## CONCLUSION

This study highlights the mechanical performance of *Terminalia catappa* wood, reinforcing its potential as an alternative material for medium-density applications. The observed trends in MOR, MOE, CS//G, SS, and IS suggest that the species maintains a relatively uniform mechanical structure, with an increase in strength from the inner to outer wood and from base to top. Although no significant differences were detected across axial and radial planes, the consistent mechanical properties make *Terminalia catappa* a viable candidate for furniture production, joinery, and other light construction uses. Given the growing emphasis on sustainable forestry and the need to reduce reliance on overexploited commercial species, further research is necessary to enhance its industrial applicability and understand its long-term durability under varying environmental conditions.

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