CIVIL TECHNOLOGY FACULTY

DEPARTMENT OF WOOD SCIENCE AND TECHNOLOGY MANAGEMENT

INVESTIGATION OF THE PHYSICAL AND MECHANICAL PROPERTIES OF *CORDIA AFRICANA (WANZA)* GROWN AROUND AHFEROM TIGRAY, ETHIOPIA

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ID.NO/TTMR/111/16

A THESIS SUBMITTED TO THE FACULTY OF CIVIL TECHNOLOGY FOR THE PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE MASTER OF SCIENCE IN WOOD TECHNOLOGY

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Approval Sheet-I

The thesis entitled "Investigation of the physical and mechanical properties of *Cordia africana (Wanza)* grown around Ahferom, Tigray, Ethiopia," written by Gebregergis Hailu (ID No. TTMR/111/16), has been thoroughly reviewed and approved as meeting the necessary criteria for the Master of Science in Wood Science, Technology & Management. This research work was conducted under the guidance of Dr. Yashwant Singh (PhD), Department of Wood Science and Technology Management, Faculty of Civil Technology.

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APPROVAL SHEET – II

We, the undersigned members of the Board of Examiners, have reviewed the thesis titled "Investigation of the Physical and Mechanical Properties of *Cordia africana (Wanza)* grown in Ahferom, Tigray, Ethiopia" written by Gebregergis Hailu.

We do hereby certify that the thesis fulfills all the academic requirements and is accepted in partial fulfillment of the requirements for the award of the degree of Master of Science in Wood Science, Technology, and Management.

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Acceptance and Approval of this thesis will be subject to the submission of the final corrected version of this thesis to the Department of Wood Science and Technology Management, Faculty of Civil Technology.

DECLARATION

I hereby declare that the thesis titled "Investigation of the Physical and Mechanical Properties of *Cordia africana (Wanza)* grown around Ahferom, Tigray, Ethiopia" is an original work done under the supervision of Dr. Yashwant Singh Rawat (PhD).

The present thesis has not been presented, wholly or partly, to any other university/institution for the award of any degree/diploma/other academic qualification. All sources of information, both published/unpublished materials and references used in this research, have been duly acknowledged and referenced.

Name of candidate Signature Date

Name: Gebregergis Hailu ______________ ________________________

Supervisor's Certification

I hereby certify that the above declaration made by the candidate is correct, to the best of my knowledge, and that this thesis has been done under my supervision.

Name of advisor Signature Date

Dr. Yashwant Singh Rawat (PhD) ________________ ________________________

Final acceptance of this thesis will be conditional on the submission of the final version to the Department of Wood Science & Technology Management.

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Title: Investigation of the physical and mechanical properties of *Cordia africana* grown around Ahferom, Tigray, Ethiopia.

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ABSTRACT

Cordia africana (Wanza) is one of the most important indigenous timber species in Ethiopia. It is widely used for furniture, construction and joinery. However, there is little information on its physical and mechanical properties under the highland conditions of northern Ethiopia. The study was conducted to evaluate the physical and mechanical properties of *Cordia africana* grown in Ahferom Woreda, Tigray, Ethiopia and to assess the effects of wood type (sapwood and heartwood) and tree height position (bottom, middle and top). Three healthy 45-year-old trees were sampled and 1620 specimens were tested using ISO standard procedures. Data were analyzed by two-way ANOVA, Tukey's HSD test and Pearson correlation analysis at 5% level of significance. The average values of moisture content, basic density and oven dry density were 120.10%, 469.78 kg/m^3 and 510.75 kg/m^3 respectively. The average values of shrinkage were 2.90% (radial), 5.53% (tangential), 0.11% (longitudinal), and 8.36% (volumetric), and swelling values were 2.89%, 5.53%, 0.10%, and 8.76%, which indicated good dimensional stability. Average mechanical properties were 41.30 N/mm^2 for compression strength, 73.03 N/mm^2 for modulus of rupture, 5353.85 N/mm^2 for modulus of elasticity, 69,247.22 Nm/m^2 for impact bending strength, 3487.05 N for radial hardness and 3387.26 N for tangential hardness. Heartwood had higher density, better dimensional stability and higher mechanical strength ($p < 0.05$) than sapwood and most properties decreased from bottom to top of the stem. Basic density had very strong positive correlation with oven-dry density ($r = 0.987$). Moisture content showed negative correlation with density and modulus of rupture showed positive correlation with modulus of elasticity ($r = 0.7165$). *Cordia africana* generally exhibited moderate density, good dimensional stability and favorable mechanical properties which confirmed its suitability for furniture, construction and joinery. These findings provide baseline information for wood grading, efficient utilization and sustainable management of the species in northern Ethiopia.

Keywords: *Cordia africana*, compression strength, density, hardness, impact strength, modulus of elasticity, modulus of rupture, moisture content, shrinkage, swelling.

Acronyms

ANOVA	Analysis of Variance
BD	Basic Density
CS	Compression Strength Parallel to Grain
CV	Coefficient of Variation
DBH	Diameter at Breast Height
DF	Degrees of Freedom
EEFRI	Ethiopian Environment and Forest Research Institute
F Value	F-statistic
FPURC	Forest Products Utilization Research Center
HSD	Honest Significant Difference
HW	Heartwood
IBS	Impact Bending Strength
ISO	International Organization for Standardization
LS	Longitudinal Shrinkage
LSW	Longitudinal Swelling
MC	Moisture Content
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
MS	Mean Square
N	Total Specimens
ODD	Oven-Dry Density
P -Value	Probability value (p-value)
RH	Radial Hardness
RS	Radial Shrinkage
RSW	Radial Swelling
SS	Sum of Squares
SW	Sapwood
TH	Tangential Hardness
TS	Tangential Shrinkage
TSW	Tangential Swelling
UTM	Universal Testing Machine
VS	Volumetric Shrinkage
VSW	Volumetric Swelling

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Chapter 1. Introduction

1.1. Background of the study

Wood is one of the most important renewable biological resources and plays an important role in the global bioeconomy for its sustainability, capacity for carbon storage, versatility, and wide spectrum of applications (He et al., 2023). It is widely used in building, furniture making, interior uses, and several value-added forest products due to its good strength-to-weight ratio, good workability, aesthetic appearance, and availability (Ross, 2021). Because of the growing global demand for sustainable and low-carbon materials, wood is becoming an increasingly important environmentally preferable engineering material for sustainable development (He et al., 2023). The successful use of wood as an engineering material depends on reliable knowledge of its quality characteristics, because different) Applications require specific performance requirements (Ross, 2021). Therefore, scientific assessment of wood properties is important for appropriate material selection, engineering design, product development, and efficient utilization of forest resources (Teischinger et al., 2023).

Physical and mechanical properties of wood products largely determine their quality and performance (Ross, 2021). Physical properties such as moisture content, density, shrinkage, and swelling are important parameters of wood quality because they influence dimensional stability, processing behaviour, durability, and service performance of wood in different environmental conditions (Glass, 2021; Niemz et al., 2023). The mechanical properties of wood, including compression strength, modulus of rupture (MOR), modulus of elasticity (MOE), hardness, and impact strength, determine its ability to withstand external loads and mechanical stresses in service, which affect structural performance and engineering suitability (Arriaga et al., 2023).

These properties vary not only among species but also within individual trees due to differences in genetic characteristics, growth conditions, age, and wood anatomical features (Barrette et al., 2023). Therefore, it is important to evaluate the properties of wood for individual species in order to make efficient and reliable use of timber resources.

In Ethiopia, the indigenous tree species are important sources of timber and other forest products for use in construction, furniture manufacturing, household utensils, and wood-based industries (Girma et al., 2021). Furthermore, tree planting has been a long-standing practice throughout the country with farmers actively managing indigenous multipurpose tree species as key components of agricultural landscapes and ecosystem services (Lelamo & Kemal, 2021). Among these indigenous species, *Cordia africana* Lam. has been regarded as one of the most valuable multipurpose timber trees in Ethiopia (Lelamo, 2021).

Cordia africana is naturally found in the dry, moist, and wet Weyna Dega agroecological zones of Ethiopia (Alemayehu et al.,2016). It is one of the fast-growing species with high economic value for its wide timber use (Tamene, 2017, as cited in Elzaki et al., 2020). The wood is widely used for construction, furniture making, joinery, doors, windows, cabinets, veneer, household utensils, agricultural implements, musical instruments, beehives, and other value-added wood products (Jansen, 1981; ICRAF, 2008; Loha et al., 2009; as cited by Derero et al., 2011). In addition to its economic importance, *Cordia africana* is also of cultural importance, especially in the Amhara region of Ethiopia, where it is used in Orthodox Christian religious practices (Baye, 2016, cited by Elzaki et al., 2020b). The wood of this species has moderate strength and hardness, making it suitable for the production of high-quality furniture and household products(Alemayehu et al.2016). *Cordia africana* is one of the most preferred indigenous timber species for the furniture industry in Ethiopia due to its attractive texture, strength, durability, and high customer preference. It is utilized by 86.3% in the furniture sector, and 92.9% of industries still utilize it (Kaba et al., 2022).

Good knowledge of the physical and mechanical properties of the wood is essential to evaluate the suitability of using *Cordia africana* for engineering, structural, and furniture applications. Physical properties such as density and moisture content directly affect the performance, dimensional stability, and durability of wood, while mechanical properties such as compression strength, modulus of rupture, modulus of elasticity, hardness, and impact strength are known to determine the load-bearing capacity and service performance of wood (Ross, 2021; Arriaga et al., 2023). Wood density is one of the most important indicators of wood quality among physical properties due to its close relation to mechanical, optical, and chemical properties, end-use performance, and economic value (Li et al., 2023), Reliable information on these properties allows engineers, designers, and manufacturers to predict the performance of the *Cordia africana* wood in various service conditions and select appropriate materials for structural and furniture applications (Smardzewski & Łabęda, 2018).

There is limited scientific information on the physical and mechanical properties of the economically important and widely available *Cordia africana* in Ethiopia, particularly for trees growing in Ahferom Woreda, Tigray Region. Previous studies have mainly focused on the species ecology, agroforestry importance, distribution, propagation, conservation, and utilization, or studied trees from other parts of Ethiopia, such as central, southern, and south-western parts (Lelamo & Kemal, 2021). Therefore, there is limited information on the variation and properties of the physical and mechanical properties of *Cordia africana* grown in the environmental conditions of Ahferom Woreda.

Cordia africana has been widely studied in terms of its ecological significance, agroforestry value, conservation importance, and socioeconomic contributions in Ethiopia and other parts of sub-Saharan Africa (Rawat & Tekleyohannes, 2021; Biru & Cheru, 2025). However, studies that comprehensively assessed its wood quality traits, especially physical and mechanical properties, are relatively few. Previous studies have mainly addressed ecological functions, propagation, distribution, conservation, and general utilization, but detailed information on wood properties for engineering and industrial applications remains limited. Hence, more research is required to generate reliable scientific data to promote the efficient utilization, value addition, and sustainable management of this important indigenous timber species.

Therefore, the present study was conducted to assess the physical and mechanical properties of *Cordia africana* wood from Ahferom Woreda, Tigray Region, and generate scientific information for its proper utilization, value addition, and sustainable management.

1.2. Problem Statement

In Ethiopia, *Cordia africana* is extensively used for furniture, construction, and interior applications; however, its application in engineering and value-added industries is limited and inconsistent. This limitation is largely due to the absence of reliable, region-specific, and experimentally generated information on its physical and mechanical properties.

Empirical data on key wood properties such as density, moisture content, shrinkage, swelling, compression strength, bending strength, impact strength, and hardness are insufficient in Ahferom Woreda, Tigray. The lack of such scientific information restricts proper grading, processing, material selection, and efficient utilization of the species.

In addition, the lack of easily accessible standard experimental data for Ethiopian hardwood species, especially for dimensional stability characteristics, restricts the ability to compare *Cordia africana* with commercially important timber species and to determine reliable engineering design values. Therefore, it is essential to study the physical and mechanical properties of *Cordia africana* wood grown in Ahferom Woreda, Tigray, Ethiopia, to generate reliable empirical data for its efficient utilization and engineering application.

1.3. Objectives

1.3.1. General Objective

To evaluate the physical and mechanical properties of *Cordia africana* trees grown around Ahferom, Tigray, Ethiopia.

1.3.2. Specific Objectives:

1. To evaluate the physical properties of *Cordia africana* wood.
2. To determine the mechanical properties of *Cordia africana* wood.
3. To compare the obtained results with other commercial hardwood species grown in Ethiopia.

1.4. Research questions

1.What are the physical properties of *Cordia africana* wood?

2.What are the mechanical properties of *Cordia africana* wood?

3.How do the physical and mechanical properties of *Cordia africana* wood compare with those of other commercial hardwood species in Ethiopia?

1.5. Significance of the Study

This study presents empirical data on the physical and mechanical properties of *Cordia africana* wood from Ahferom Woreda, Tigray, Ethiopia. The results will assist local communities and wood users to use efficiently, add value, and sustainably manage the species.

The results will be of value to the wood processing industries, furniture manufacturers, and construction sectors in material selection, timber grading, and product development. The research will also serve as baseline data for researchers and academic institutions working on indigenous timber species and wood quality evaluation.

In addition, the results could help forest managers and policymakers promote sustainable forest resource management and evidence-based utilisation of indigenous timber resources.

In general, the study helps to produce credible region-specific information that can support local development and advancement of the forest and wood sector in Ethiopia.

1.6. The scope of the study

The objective of this study was to determine the physical and mechanical properties of wood from three 45-year-old *Cordia africana* trees grown in Ahferom Woreda, Tigray, Ethiopia, to find the suitability of the wood for wood products and structural applications.

Physical properties studied were moisture content, basic density, oven-dry density, radial, tangential, longitudinal, and volumetric shrinkage, and radial, tangential, longitudinal, and volumetric swelling. The mechanical properties evaluated were compressive strength parallel to grain, static bending strength (modulus of rupture [MOR] and modulus of elasticity [MOE]), impact bending strength, and Janka hardness in the radial and tangential directions. The selected samples were taken from the bottom, middle, and top of the stem as well as heartwood and sapwood to assess axial and radial variation in the properties.

The physical and mechanical properties of *Cordia africana* were compared with five commercially important Ethiopian hardwood species to assess its relative performance and utilization potential. The Pearson correlation analysis was also performed to examine the relationships among selected physical and mechanical properties, especially MOR and MOE, for a better understanding of their engineering significance.

1.7. Limitations of the Study

The study was limited to *Cordia africana* trees sampled from Ahferom Woreda, Tigray, Ethiopia, and therefore, the results may not be representative of the physical and mechanical properties of the species growing under different environmental and site conditions elsewhere in Ethiopia. Furthermore, only three trees of approximately 45 years of age were included, which could limit the generalizability of the results.

Some selected physical and mechanical properties were studied. Other important properties were not studied. These include wood anatomy, chemical composition, natural durability, drying behavior, preservative treatment, long-term performance, and variations due to age, silvicultural practices, and genetic factors.

Another limitation was the scarcity of published data on the physical properties of *Cordia africana*, particularly shrinkage and swelling, and similar data for many Ethiopian commercial hardwood species. This limited comparison, benchmarking, and validation of some findings. Moreover, environmental factors, including soil conditions, climate, altitude, and site variability, could not be fully controlled and may have affected the measured wood properties.

Chapter 2. Literature review

2.1. Description of *Cordia africana*

Cordia africana Lam. is a multipurpose indigenous hardwood tree that belongs to the family of Boraginaceae and is one of the most important native timber species in the tropics of Africa (Legese Ngash, 2021). The species is highly valued for its high-quality timber, ecological functions, and socioeconomic importance, especially in Ethiopia, where it is widely used for furniture, joinery, cabinetry, veneer, and other value-added wood products (Kamau et al., 2024).

In addition to its economic importance, *Cordia africana* has a significant role in sustainable land management, biodiversity conservation, and agroforestry (Rawat & Tekleyohannes, 2021). However, increasing pressure from overexploitation and habitat degradation has raised concerns regarding its sustainable utilization, underlining the need for scientific information to support its effective management and utilization (Rawat & Tekleyohannes, 2021). From an ethnobotanical perspective, *Cordia africana* Lam. is among the most valued indigenous tree species in Sudan and Ethiopia (Yirgu et al., 2019; Sabry et al., 2022)

In Ethiopia, *Cordia africana* is one of the most indigenous timber tree species subject to commercial harvesting. Over-exploitation and over-harvesting, however, have caused its local extinction, which has necessitated that it be protected by law under Ethiopia's Forestry Conservation, Development, and Utilization Proclamation No. 94/1994 (Alemayehu et al., 2016). The ecological and economic importance of *Cordia africana* wood necessitates a thorough understanding of its physical and mechanical properties to support its efficient utilization, sustainable management, and value-added applications. This information is particularly important for the evaluation of wood from Ahferom Woreda, Tigray, where the species is widely used.

2.2. Taxonomy and Distribution of *Cordia africana*

2.2.1. Taxonomy

Cordia africana R. Br, which is synonymous with *Cordia abyssinica*, *Cordia holstii*, and *Cordia ubanghensis*, is a plant in the family Boraginaceae, subfamily Cordioideae. The family, with more than 148 genera and more than 2,700 species, occurs throughout the world and is characterized by hairy trees, shrubs, and herbaceous plants. The genus Cordia honors the 16th-century German botanist Valerius Cordus, while the species africana signifies its African origin(Legese Ngash, 2021). This is also commonly referred to in English as East African cordia, large-leafed cordia, and Sudan teak, a deciduous tree(Negash, 2016).

2.2.2. Distribution

Cordia africana grows naturally in an array of countries, including Angola, the Democratic Republic of Congo, Djibouti, Eritrea, Ethiopia, Ghana, Guinea, Kenya, Malawi, Mozambique, South Africa, Sudan, Tanzania, Uganda, Zimbabwe, and the nations of Saudi Arabia and Yemen, as documented by Friis (1992) and Warfa (1988) and cited by (Alemayehu et al., 2016). As a multipurpose tree-climbing species, *Cordia africana* (*C. africana*) is widely prevalent in nearly 17 countries of Africa, predominantly found to occur in both primary and secondary forest ecosystems as well as the woodland of West Africa, with the distribution predominantly confined to montane and submontane biomes (Makhiya et al., 2021)

In Ethiopia, *C. africana* has a wide distribution across a variety of agro-ecological zones and is predominantly found in montane and sub-montane forest ecosystems. It performs well at altitudes of 550 to 2,600 meters ASL and in annual precipitation zones of 700 to 2,000 mm (Alemayehu et al., 2016; Lelamo & Kemal, 20212021). It is usually present in primary and secondary forest habitats, woodlands, and agroforests, where it is a shade crop in coffee agroecosystems and integrates with traditional farming practices(Negash, 2016). Despite its wide distribution, *C. africana* is under severe threat due to deforestation, habitat fragmentation, and overexploitation for timber. In northern Ethiopia, native forests have been reduced to small, isolated patches, occurring mainly in church forests and other remnant habitats within agricultural landscapes (Aerts et al., 2016).

The efficacy of Tigray protected areas to safeguard *C. africana* is critically low under present and future climatic conditions. The Max Ent model finds that only 17% of the total area being protected in the Tigray region offers a livable environment to the species based on the prevailing climatic conditions(Makhiya et al., 2021).

2.3. Economic and Cultural Significance

Cordia africana is a multipurpose deciduous tree species that has been widely valued for timber production, agroforestry, and cultural uses in most African societies (Tamene & Ababa, 2017). It is also viewed as a valuable source of quality timber for making office and domestic furniture;

thus, the owners of coffee plantations give maximum protection to the *C. africana* trees in their coffee farms.(Raga & Denu, 2017). It is also now a valuable economic tree species, with farmers planting it on their farms as an agroforestry tree. The overall objective of scaling up the adoption of conservation agriculture is to provide a variety of products like timber, fuelwood, construction poles, farm tools, biomass, nutrients, and fencing, and facilitate both productive and service functions. (Lameso & Bekele, 2020) In Tigray, Ethiopia (the northern region of the country), the dried fruit of *Cordia africana* can contribute towards meeting the daily nutrient requirements of families living in Tigray (Tewolde-Berhan et al., 2015).

2.4. Morphological characteristics of *Cordia africana*

Morphological parameters: The tree has perfumed, creamy-white flowers and small, yellowish drupes. Like total tree height, bole length, branching height, stem diameter, crown architecture, and stem form are important attributes affecting timber quality, growth performance, and wood utilization. These traits are widely applied to the assessment and management of forest tree species and to timber valuation (Raj et al., 2013).. According to Nigussie et al (2021), *C. africana* is a small to medium-sized, evergreen, tropical African native tree, typically growing from 4 to 15 (30) meters tall, with a spreading, umbrella-shaped, or rounded crown with numerous branches.

Negash (2016) also defined *Cordia africana*, which commonly reaches 15–25 m in height but may exceed 30 m under favorable conditions, with a stem diameter of about 1 m. The species has a spreading, umbrella-shaped crown, brown fissured bark, and a straight or slightly curved bole depending on growing conditions. Leaves are alternate, broadly ovate, rough above and hairy beneath, and the fragrant white flowers are borne in terminal panicles and develop into small yellow to dark-brown drupes containing one or two seeds. These morphological features make it adaptable and suitable for timber production and agroforestry systems. There is morphological variation observed among provenances of *Cordia africana* in Ethiopia. Under forest conditions, Guyassa et al. (2013) reported only small differences between provenances, while under farmland conditions, more variation was observed. The provenances of Zegie, Dejen, and Finote-Selam produced relatively taller and slenderer stems, and Mekelle and Kemisie produced shorter and thicker stems. The highest H ratio was found in Tikil-Dingay under farmland conditions, and the lowest H ratio was in Mekelle, which implies that environmental conditions are a major factor in stem form and tree growth.

Similarly, Alemayehu et al., (2016)reported significant morphological variation among Ethiopian provenances of *Cordia africana*. The study showed that climatic factors, particularly temperature and isothermality, influence tree morphology, demonstrating the species' phenotypic plasticity and adaptability to different ecological conditions. Such variability is important for provenance selection, sustainable forest management, and enhanced timber production.

2.5. Anatomical characteristics of *Cordia africana*

2.5.1. Macroscopic Features:

The investigation of wood's mechanical and physical properties shows that both structural and macroscopic studies play significant roles in identifying the quality and usability of wood. While macroscopic characteristics like color, grain, and texture, which are determined by environmental and genetic factors, enable identification, density, moisture content, shrinkage, bending, compression, tension, and hardness determine its suitability for structural and industrial uses (Hounlonon et al., 2021) It is required to know wood's macroscopic structure and how it develops to accurately identify wood and determine its properties and quality, because these characteristics differ by genetic, environmental, and growth stage factors (Ruffinatto et al., 2023). Macroscopic characteristics, such as color, grain pattern, texture, and surface characteristics, are significant reference points for preliminary wood identification and species discrimination (De Blaere et al., 2023). Wood analysis of the Cordia genus and *Cordia africana* in particular needs both macroscopic and microscopic analyses to be completely described in terms of its mechanical and structural properties (Matias et al., 2015; Nigussie et al., 2021). This macroscopic description is a baseline factor for the determination of the behavior of the wood and its potential future applications (Hwang & Sugiyama, 2021).

2.5.2. Microscopic Features

According to Donaldson (2019), the microscopic structure of wood, including cell wall thickness, cell type distribution, and fiber orientation, plays a fundamental role in determining its physical and mechanical properties. Variations in these anatomical characteristics directly influence the wood density, stiffness, permeability, strength, and dimensional stability of the wood. For instance, mechanical strength can be increased by thicker cell walls and a higher proportion of fibers, while vessel size and distribution influence permeability and shrinking behavior. These relationships are crucial to understand for construction and material science purposes.

Microscopic anatomical characteristics of wood are necessary for species identification and understanding the physical and mechanical properties of wood. Microscopic analysis of wood samples involves cutting thin sections in three directions, which are perpendicular to each other: transverse (cross-sectional), radial, and tangential (Hwang & Sugiyama, 2021)Observe the cellular structure, including the types of cells (e.g., vessels, fibers, parenchyma), the arrangement of cells, cell size, and cell wall thickness (Rosa da Silva et al., 2017)The density, strength, and permeability of the wood are defined by the nature and arrangement of these cells (Von Arx et al., 2016).

Although detailed anatomical information of *C. africana* is limited, the anatomical studies on the closely related species C. alliodora in the same genus indicate that the distribution of vessels, the structure of rays, and the fiber wall thickness influence the wood density and mechanical performance. These properties provide valuable additional information for the interpretation of the physical and mechanical properties of *Cordia africana* (Nobre et al., 2019)

2.6. Heartwood and Sapwood Characteristics

In both gymnosperms and angiosperms, secondary xylem matures into sapwood, the lighter-colored, outer zone with living parenchyma cells that are involved in conduction, and heartwood, the darker-colored, inner zone beneath it. (Forest Service & Products Laboratory, 2010b) .These structural and chemical differences significantly influence wood's physical and mechanical properties. A higher proportion of heartwood is linked to increased density and dimensional stability and reduced radial and tangential shrinkage. Sapwood has a higher moisture content compared to heartwood (Arisandi, 2023). (Ayobi et al., 2011), Studying Quercus castaneaefolia in Iran, found that the heartwood had superior physical and mechanical properties, including higher density, shrinkage, swelling, modulus of rupture (88.67 MPa), and compressive strength (74.63 MPa). Density follows an increasing longitudinal trend from pith to heartwood and a decreasing trend from base to the top, with the base heartwood being the densest (Kimberley et al., 2015). In *Cordia africana*, heartwood is pinkish to reddish-brown and is clearly distinguished from pale greyish sapwood, which is approximately 2.5–4 cm wide)(Negash, 2010). The moderately durable heartwood resists decay well and thus can be used for furniture, but the sapwood is less durable and also more vulnerable to insect attack. The interlocked grain and medium-to-coarse texture of the wood favor good machinability. Sapwood, however, does not possess the extractives. Phenolics, terpenoids, and resins deposited during heartwood formation enhance resistance to decay and insects. These extractives also influence color and scent, enabling the identification of wood (Jesus et al., 2024). In summary, a comprehensive exploration of *Cordia africana* wood should integrate macroscopic description and detailed microscopic study to guarantee a unified understanding of its structural and mechanical properties, required for its effective use and conservation.

2.7. Physical properties

Physical properties are measurable characteristics of wood influencing its quality, dimensional stability, durability, and performance in processing and service. The most important physical properties are the moisture content, density, shrinkage, and swelling, which are of great importance for assessing the suitability of wood for different applications (Ross, 2021; Niemz et al., 2023).

2.8. Wood Density

Wood density, a fundamental property, significantly influences the physical and mechanical strength and suitability of wood for any end use. Wood density is an important parameter for the determination of wood qualities, and it's required for the estimation of wood strength, durability, and suitability for different uses (construction, furniture, etc.). Due to the interplay of mechanical, optical, and chemical properties (Li et al., 2023), Wood is a non-homogeneous material composed of conducting tissue for conducting sap, supporting tissue for providing structural strength, and parenchyma for metabolic activities such as heartwood formation and starch storage (Rosa da Silva et al., 2017).This, too, the density or relative density of a solid is the ratio of its mass per unit volume to the mass per unit volume of water (pure water at 4 °C under atmospheric pressure, i.e., 1,000 kg/m^3). It has no unit. Indicated density is expressed on wood at 12% moisture content. This characteristic is more or less directly related to the wood's main physical and mechanical characteristics, and with certain working characteristics(Glass & Zelinka, 2021).

2.8.1. Basic Density

Basic density of wood is the ratio of oven-dry weight of a wood sample to its green volume, and it is usually expressed in kilograms per cubic meter (kg/m^3) or grams per cubic centimeter (g/cm^3). It is a fundamental property for the determination of wood quality as it defines the ratio of cell wall material to volume and influences mechanical strength, shrinkage, and pulp yield. Basic density is widely used in forestry and wood science to compare species, assess growing conditions, and predict end-use suitability (Wiemann, 2021). This strengthens since Basic density is the ratio of oven-dry weight to the green volume, expressed in weight per unit volume. The green volume of wood (Vmax) was determined by employing the water displacement (Carrillo et al., 2017).

Wood basic density (WBD) is the most significant wood property in trees and mainly dictates the ultimate utilization of wood for industry. However, WBD is time- and cost-demanding to measure, so an alternative, rapid, and non-destructive measurement is needed (Li et al., 2021).

Cordia africana, a native Sudanese hardwood species, was studied for its potential for pulp and papermaking. Important wood characteristics such as basic density (410 kg/m^3), bark-to-wood ratio (Elzaki et al., 2020). The density of heartwood *Cordia africana* is normally between 440 and 580 kg/m^3 at 12% moisture content, and is a moderately light timber12%.

Other evidence to suggest that *C. africana* has similar density characteristics can be provided by another species that is closely related to it. For instance, according to Desalegn (2011), Cordia alliodora from Ethiopia has a basic density of 350 kg/m^3. Because Cordia alliodora and *Cordia africana* belong to the same genus (Cordia), the density property of C. alliodora gives useful supporting evidence where published data for *C. africana* are limited.

2.9. Oven-dry density of wood

The oven-dry density is defined as the ratio of the mass of oven-dry wood divided by the volume of oven-dry wood at approximately 103 ± 2°C. The term is very important because it is used to refer to the true density of wood without the presence of moisture, hence the reliable basis for comparison of different woods (Watanabe et al., 2012; Moron et al., 2016).

Research studies have demonstrated the great variation in oven-dry density in commercial hardwood species and their relation to wood strength, stiffness, and stability. The research conducted by Kiaei & Samariha (2011) has revealed the significant differences in oven-dry density among different commercial hardwood species, where denser woods are characterized by better mechanical properties. In addition, the researchers' studies (Hendrigo de Almeida et al., 2015) found that there was a positive correlation between the oven-dry density and volumetric shrinkage in tropical hardwood species, whereas Lachowicz et al. (2018). Indicated that the oven-dry density was dependent on age, growth conditions, and site parameters.

Even though there is limited data concerning the oven-dry density of *Cordia africana* in the literature, available literature suggests that *Cordia africana* is a moderate hardwood species. The density of *Cordia africana* was found to be 410 kg/m^3 at a moisture content of 12% according to Desalegn et al. (2015). Additionally, according to Hamza et al. (2024), the average basic density of *Cordia africana* is around 400 kg/m^3. These studies reveal the moderate density of the species, though limited data are available regarding the oven-dry density of *Cordia africana*. Therefore, it is important to determine the oven-dry density of *Cordia africana*.

2.9.1. Basic density variation in the axial and radial directions

The basic density of wood generally varies with the radial and axial directions because of the variation of wood anatomy related to the growth and maturation of the tree. As wood matures, the increase in cell wall thickness and lignification causes a change in basic density that is normally radial from the pith to the bark. However, in the longitudinal direction, basic density generally decreases from the bottom of the stem to the top because the upper parts have a higher proportion of juvenile wood Gendvilas et al., 2022).

Similar patterns of variability in basic density have been reported in several studies on hardwood species. Riki et al.(2019) investigated radial and axial variation in wood density in hardwood trees and reported a significant increase in density from the pith to the bark, while the decrease in density from the base to the top of the stem was not statistically significant. They found that the radial variation was more responsible for the density differences than the longitudinal variation.

Andrade et al. (2025)reported that there was a great deal of longitudinal variation in the basic density of Prosopis juliflora. The highest basic density was at the bottom of the trunk (0.96 g/cm^3), followed by the middle (0.86 g/cm^3), while the lowest density was at the top (0.78 g/cm^3). This indicates a gradual reduction in density with increasing tree height. Similarly, Tichi et al. (2021) observed that the oven-dry and basic densities of Parrotia persica showed significant variations in the radial and longitudinal directions. Their study revealed that density increased from the pith to the bark and decreased from the base to the crown of the stem, with the highest basic density (0.67 g/cm^3) near the bark at breast height and the lowest (0.42 g/cm^3) near the pith and close to the crown.

Hamza et al. (2004) reported that the species is classified as a medium-density hardwood with an average basic density of about 0.40 g/cm^3 (400 kg/m^3) for trees grown in the Lushoto agroforestry system (Hamza et al., 2004). Geographical variation was also reported, with trees grown in the Moshi agroforestry system having a basic density of 0.33 to 0.37 g/cm^3. The study also revealed a large variation in basic density in radial and axial directions. Density increased radially from approximately 0.37 g/cm^3 near the pith to approximately 0.41 g/cm^3 before decreasing slightly toward the bark. The basic density decreased longitudinally from the butt of the stem to the tree top. These results suggest that tree height and radial position affect the basic density of *Cordia africana*, which is important for wood quality assessment and utilization.

2.10. Moisture Content

In wood, moisture content (MC) refers to the water mass that exists in the wood, stated as a percentage of the oven-dry mass of the wood (Ross, 2021). The moisture content of wood is one of the most significant physical properties of wood since it affects such parameters as density, dimensional stability, drying characteristics, strength, stiffness, and durability (Thybring & Fredriksson, 2021; Dietsch et al., 2015). To understand the fundamental and universal relationship between moisture content (MC) and the mechanics of timber, it becomes important to examine these impacts on a varied taxonomical basis, including both softwoods and hardwoods. For example, the study conducted by Teodorescu et al. (2021) analyzed the effect of different MC levels (8%, 12%, and 16%) of untreated softwood (Picea abies) and hardwood (Castanea sativa) to simulate the effect of a changing climate. Their study showed that regardless of species category, changes in moisture content have a direct bearing on dimensional changes and deformations in timber that negatively impact its mechanical performance.

Further, studying the impact of moisture on different anatomical regions, even in the case of softwoods, becomes necessary to understand its local impact. Hassan Vand & Tippner (2024), analyzed how MC affects the impact behavior of the sapwood and heartwood in Scots pine (Pinus sylvestris L.), a common softwood species, at a low (12%) and high (45%) MC level. They found that at a lower MC level, there is little difference in the deflection and strain behaviors of the sapwood and heartwood; however, heartwood has higher impact bending strength (IBS) values. But, at a high MC level, differences between the two regions become obvious, but this shows that for green wood under high impact loading, performance is relatively independent of the heartwood to sapwood ratio, a mechanical dynamic which illustrates the importance of assessing zone-specific moisture behavior in other marketable woods.

According to Desalegn et al.(2015), the average initial moisture content of *Cordia africana* was found to be 71% for fresh wood harvested from the tree. The higher moisture content of the wood suggests that there is quite a lot of free water in the wood at harvest, and thus, proper seasoning should be done on this wood before any further process is performed.

Furthermore, moisture content is one of the factors affecting the physical and mechanical properties of the wood. This is because, beyond the fiber saturation point, the increase in moisture content leads to a reduction in strength and stiffness, while dimensional changes are likely to be experienced during the drying process of the wood.

2.11. Shrinkage and Swelling of Wood

Shrinkage and swelling can characterize a change in volume or alteration in one dimension (e.g., length along the radial, tangential, or longitudinal axis). Swelling is the volume or length change relative to the dry value, whereas shrinkage is the volume or length change relative to the water-saturated value. In the case where the cell wall absorbs water, the wood swells, and when water is evaporated from the cell wall, the wood shrinks (Thybring et al., 2022). Also claimed by Hartwig-Nair et al. (2024), Shrinkage and swelling of wood result as it desorbs or absorbs water below the fiber saturation point. These hygroscopic effects are caused by the interaction between hydroxyl groups within cell wall polymers, i.e., cellulose, hemicellulose, and lignin, and water molecules (Ruffinatto et al., 2023). It has long been generally understood that the swelling and shrinking properties of the wood depend on density and the direction of cellulose microfibrils in wood (Zhan et al., 2021).

As far as the shrinkage of *Cordia africana* is concerned, the shrinkage is rather low as compared to most other commercial hardwoods, implying that *Cordia africana* possesses good dimensional stability. According to PORTA (Lemmens et al., 2012), the shrinkage from green to oven dry state is around 3.4% radially and 5.7% tangentially. The relatively low shrinkage rate is due to the dimensional stability that arises from the presence of an interlocked grain in this wood.

Similar results have also been observed in *Cordia alliodora*, which is part of the same genus as *Cordia africana*. According to Desalegn (2011), radial shrinkage was 4.08%, tangential shrinkage was 6.33%, and volumetric shrinkage was 10.61%. These results demonstrate good dimensional stability and further prove that the species under the genus Cordia exhibit favorable shrinkage characteristics and can be used in furniture and other wood-based products.

2.12. Factors affecting physical properties.

Wood density is quite variable among species of trees and geographical regions, mainly due to climatic factors and species-specific features, as well as due to the age of the tree and its growth rate. There are climatic factors such as temperature and rainfall that are responsible for regional variations in wood density (Yang et al., 2024). The angiosperms have higher wood density than the gymnosperms due to their high amount of fibres and thick cell walls. Therefore, the wood density in the tropical forests is higher than that in the boreal forests (Mo et al., 2024).

Moreover, the density of wood shows systematic variation across individual trees. Specifically, radially, there is a tendency for higher densities near the bark compared with lower densities close to the pith because of the progression from juvenile to mature wood, while longitudinally, there is a tendency for low densities at the top relative to high densities at the bottom of the stem due to differences in the development of the wood. Moreover, wood density is influenced by several other factors like age, growth rates, and site conditions, among others (Diao et al., 2022; Hietz et al., 2022). All these characteristics are equally applicable to *Cordia africana*, a hardwood tree, whose density depends on the position of the stem and its growing conditions. According to Hamza et al. (2004), the basic density of *Cordia africana* increases from pith to bark and decreases from the butt to the top of the tree. Also, Desalegn (2011)identified similar variations in the basic density of another species belonging to the same genus as *Cordia africana* - Cordia alliodora. Therefore, knowing all these characteristics is crucial for the assessment of the physical characteristics of *Cordia africana*.

2.13. Mechanical properties of *Cordia africana*

Wood, as a naturally formed composite material, exhibits a most striking degree of variability in mechanical properties, where a complex relationship of factors plays on them, including species, growth conditions, anatomical characteristics, and water content. These properties are being identified and characterized as of utmost interest to a broad range of engineering applications, from structural design and furniture manufacturing to the manufacturing of musical instruments (Fernando Castanheira Rodrigues & Luis Christoforo, 2019).

In regard to mechanical properties, much interest has been gained due to the significance of the tree as a source of timber for many uses. The average density and high stability of the tree make it have good mechanical properties, which make it useful in construction, furniture, and joinery. Hence, assessing the mechanical properties of *Cordia africana* is necessary for its efficient use.

2.13.1. Compression strength parallel to the grain, *Cordia africana*

Compression strength parallel to the grain refers to the highest amount of compressive stress that wood can withstand when compressed along the direction of wood fibers(Olorunnisola, 2018) .This property of wood is one of the most significant mechanical properties that are considered during timber design since it is responsible for the resistance to compression forces in posts and columns (Ruthes et al., 2023).

The relationship between compression strength parallel to the grain and wood density has been established during research on tropical hardwoods. Specifically, Taha et al. 2020) have determined the compressive strength of two species of tropical hardwood, Anogeissus leiocarpa and Commiphora africana of North Darfur, Sudan. As a result, it was found that the denser species had significantly higher compression strength compared to the less dense species. The relationship between basic density and mechanical properties of trees grown in agroforestry systems in Lushoto, Tanzania, was studied by (Hamza et al., 2004.-b)) for *Cordia africana*. The study reported a compression strength parallel to the grain of 23.50 N/mm^2 and showed a positive relationship between basic density and mechanical strength, which indicated that the denser the wood, the greater the resistance to compressive loading. Lemmens et al.(2008) also gave a value of compression strength parallel to the grain of about 47 N/mm^2 at 12% moisture content. They described *Cordia africana* as having moderate compressive strength for furniture, framing, and other structural applications.

In Ethiopia, Desalegn et al. (2015) reported a parallel-to-grain compression strength of 29 N/mm^2 for *Cordia africana*. The reported values for compressive strength are not the same, probably because the wood was taken from different locations, had different moisture contents, came from trees of different ages growing under different conditions, and was tested in different ways.

There is supporting evidence from *Cordia goeldiana*, a species in the same genus (Cordia). Mascarenhas et al. (2021) reported a compressive strength parallel to the grain of 32.32 MPa with moderate wood density, indicating that species of the genus Cordia generally have moderate compressive strength suitable for furniture, joinery, and light structural uses. These results confirm the possibility of using *Cordia africana* for similar end uses.

2.13.2. Static bending (MOR and MOE) of *Cordia africana*.

The static bending is a method to evaluate the bending performance of wood through the measurement of the modulus of rupture (MOR), which is the maximum stress that a wood sample can sustain before failure, and the modulus of elasticity (MOE), which is an indicator of the stiffness of wood and its resistance to deformation under load (Mvolo et al., 2022).

Getachew Desalegn et al.(2015) reported the static bending properties of *Cordia africana* in Ethiopia with a modulus of rupture (MOR) of 64 N/mm^2 and modulus of elasticity (MOE) of 6996 N/mm^2. This indicates that the species has moderate bending strength and stiffness for a wider range of wood products. Studies on tropical hardwoods have indicated the strong influence of wood density and anatomical features on the bending strength. Taha et al. (2020) found that the harder hardwood species usually had a higher MOR and MOE than the lighter species, which supports the idea that wood density and bending performance are positively related. Similarly, to Kana et al. (2024), found that variation in bending strength and stiffness between species with similar density was due to differences in wood anatomy and moisture characteristics.

Species within the same genus and family provide additional support. Fernandez et al. (2019) reported that the modulus of rupture (MOR) of *Cordia alliodora* was 45.60 N/mm^2 and the modulus of elasticity (MOE) was 9,150 N/mm^2, indicating moderate bending strength and high stiffness. These findings support the hypothesis that species of the genus *Cordia exhibit* favorable static bending properties. Similarly, Mascarenhas et al. (2021) reported a modulus of rupture of 63.5 MPa for Cordia goeldiana, another species of the genus Cordia, which showed good flexural performance comparable to many tropical hardwoods.

(Lemmens et al., 2008) reported the modulus of rupture and the modulus of elasticity of 91 and 8040 N/mm 2, respectively, for *Cordia africana* at 12% moisture content. This indicates good bending strength and stiffness for furniture, joinery, panels, and light structural members. Reported differences in values of MOR and MOE are probably related to differences in wood origin, moisture content, age of the tree, growth conditions, and testing procedures. The results indicate that *Cordia africana* and other Cordia species have moderate to good static bending properties and are suitable for furniture, interior joinery, and other value-added wood products in total.

2.13.3. Impact Strength

Impact strength of wood refers to the ability of wood to absorb energy and withstand fracture when subjected to suddenly imposed loads or shocks, which reflects its toughness and suitability for dynamic loading applications. Even when *Cordia africana*, Boraginaceae family, was not one of the species that had been studied in the work by Pinto Moreira et al. (2017) within the Laboratory of Wood and Timber Structures (LaMEM), São Paulo University, Brazil, a comparison may be made using species with similar densities. Cedrela odorata (cedro), which has a mean density of 400 kg/m^3, and Cedrelinga cateniformis (cedrorana), with a mean density of 520 kg/m^3, exhibit densities ranging within or just above that of *Cordia africana*, typically 500–560 kg/m^3 at 12% moisture content. The impact strength (fbw) of Cedro and Cedrorana was determined to be 19.46 kJ/m^2 and 20.02 kJ/m^2, respectively. But even though not belong to the same plant family as *Cordia africana*, the same relative densities could be indicative of similarities.

According to Getachew Desalegn et al. (2015) Frost Product Utilization Research in Ethiopia: Highlights on Major Achievements and Contributions, *Cordia africana*'s impact strength has been reported as 6588 Nm/m^2. In a recent study, hardwood in the same report and author, *Eucalyptus deglupta*, which has the same density as *Cordia africana*, 410 kg/m^3, impact strength is reported as 6338 Nm/m^2.

2.13.4. Hardness

Hardness is a strong attribute to check the deformation behavior of materials. It is guaranteed quality control for most processes (Pintaude, 2023)

It is generally expressed as resistance to indentation in terms of the modified Janka hardness test by the load that penetrates an 11.28-mm (0.444-in.) ball to half of its diameter. Values reported are the average of radial and tangential penetrations (Kretschmann, 2010). In terms of hardness, Cordia goeldiana attained Janka values of 2,373.33 N (parallel) and 2,326.67 N (perpendicular). The values signify excellent surface indentation resistance, and thus the species is eligible for high-end applications like furniture and flooring. With a moderately dense weight and high dimensional stability (longitudinal: 0.25%, radial: 4.27%, tangential: 6.83%), the hardness and wearing capacity of the wood are standard for tropical hardwoods and provide a useful reference point against *Cordia africana* (Mascarenhas et al., 2021).

Cordia africana also has moderate hardness characteristics. Side Brinell hardness is 23.5 N/mm², whereas end hardness is 40 N/mm². These figures set the wood to endure moderate wear and dents, which is particularly important for floors, tabletops, and other surfaces under friction or impact. Though impact strength values are not included in particular, hardness values indicate a satisfactory resistance to mechanical wear under normal conditions of use (Lemmens et al., 2008). According to *Cordia africana* (PORTA), the hardness is measured by Brinell side hardness 23.5 N/mm² and Brinell end hardness 40 N/mm². According to Mussa & Bekele, (2021),The hardness values of "*Acacia melanoxylon* Grown in Chencha, SNNPR, Ethiopia, were obtained by using the Janka method (ISO 3348, 1975). The specimens were tested using UTM, with the rate of loading was 0.11mm/s for both radial and tangential faces." The Janka radial hardness of *Cordia africana* is reported as 2213N by Mussa et al. (2025).

2.13.5. Factors affecting Mechanical properties

The mechanical properties of wood are governed by several structural characteristics at various scales. Macroscopic features that are significant include the angle of the grain, orientation of annual rings, sapwood and heartwood distribution, juvenile and adult wood, growth ring width, latewood percentage, and presence of reaction wood. At the microscopic level, the influencing factors are tissue proportions, tissue arrangement, tissue dimensions, fibre length, and fibre wall thickness. At the sub-microscopic level, cell wall layer thickness, microfibril orientation (especially of the S2 layer), and the degree of lignification of the cell wall layers are important. Additionally, grain angle, ring angle (annual ring orientation), and density are critical parameters, and bulk density has been indicated as a major factor. Load duration, wood quality, and temperature are other factors that influence them (Arriaga et al., 2023).

In microstructural characteristics, the microfibril angle (MFA) is of high significance. Lower MFA is higher tensile strength and stiffness. Cellulose crystallinity is also to blame for higher mechanical strength in that higher crystallinity enhances cell wall stiffness (Wang et al., 2024). From the chemical composition, the relative proportion of cellulose, hemicellulose, and lignin significantly influences wood density and strength. Most importantly, additional lignin tends to be present with increased compressive strength. Porosity also influences mechanical behavior, with denser woods tending to have improved strength characteristics(Duarte et al., 2020). While these factors are important to enhancing the mechanical qualities of wood, the anisotropic nature of wood presents opportunities for limitations. This anisotropy could result in irregular performance in terms of wood grade and grain condition.

2.13.6. Conceptual Framework of the Study

The conceptual framework used in this study is premised on the fact that the physical and mechanical properties of woods vary based on intrinsic and extrinsic factors related to tree development and wood formation. From past research, variations in wood properties arise based on the difference in wood structure and growth pattern, as well as the variation in young and mature wood throughout the stem. Among the most important factors of wood, the wood type (sapwood and heartwood) and tree height (bottom, middle, and top of the stem) play significant roles in determining its quality. Therefore, this study aims to explore the effects of the aforementioned two independent variables (wood type – sapwood and heartwood, and tree height bottom, middle, and top) on certain physical and mechanical properties of *Cordia africana* wood samples harvested from three trees that were 45 years old and grown in Ahferom Woreda, Tigray, Ethiopia. The physical properties assessed in this study include moisture content, basic density, oven-dry density, shrinkage, and swelling, while the mechanical properties include compression strength parallel to grain, modulus of rupture (MOR), modulus of elasticity (MOE), impact strength, and Janka hardness. Based on this assumption, this study employed an analytical approach that considers variations in wood type and tree height as determinants of wood physical characteristics that affect the mechanical behavior of the wood. To conduct this evaluation, the data gathered from both the physical and mechanical tests were analyzed using descriptive and inferential statistical methods such as descriptive statistics, coefficient of variation, two-way ANOVA, Tukey HSD mean comparison test, correlation analysis, histogram analysis, box plot analysis, and interaction effects analysis. The outcome of this analysis was compared with existing literature on five important commercial timbers in Ethiopia. Comparing this study's results with those from existing literature gives an understanding of how competitive *Cordia africana* can be compared to other timber species in terms of mechanical performance. This conceptual framework, therefore, guides the reader through the logic behind the selection of three characteristics influencing wood properties and their mechanical behavior.

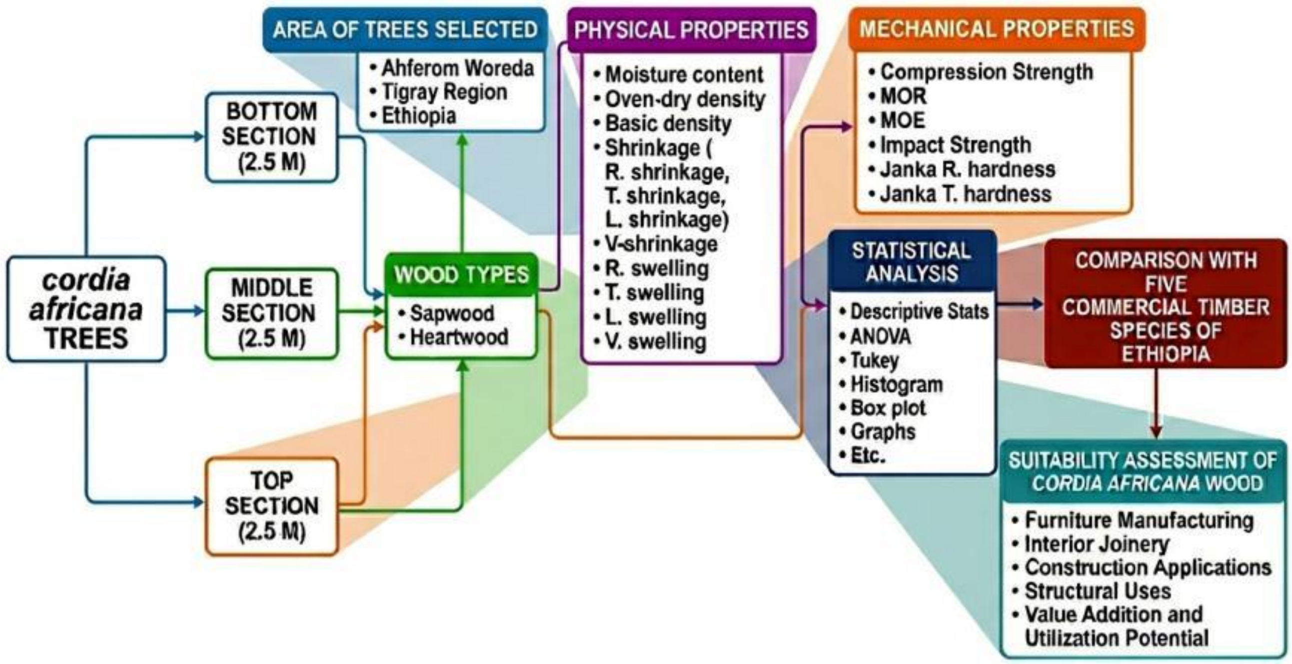


Figure 2.1. Conceptual Framework of the Study

2.14. Research Gap

To use wood effectively in furniture and structural applications, particularly under changing environmental conditions, knowledge of its physical and mechanical properties is required. Properties such as density, moisture content, shrinkage, swelling, and strength parameters (MOR, MOE, compression strength, hardness, and impact strength) have a strong influence on the performance and quality of wood products. In addition, empirical laboratory-based data on the physical and mechanical properties of *Cordia africana* are still inadequate and not well documented. Information on dimensional stability properties such as shrinkage and swelling that are important for the utilization of wood is, in particular, still limited for this species, and for many Ethiopian hardwoods in general.

Thus, there is a definite research gap in empirical studies because of the scarcity of exhaustive and region-specific experimental data on the physical and mechanical properties of *Cordia africana* wood, particularly under the growing conditions of Ahferom Woreda, Tigray, Ethiopia.

Chapter 3. Materials and Methods

3.1. Study Area Description

The study was conducted in Wereda Ahferom, an administrative district in the Tigray Regional State of northern Ethiopia. The site was selected based on its diverse topography, mesic climatic regime, and the presence of natural *Cordia africana* forests, which form the main focus of the research. The study sought to record topographic and ecological conditions, including altitude, slope gradient, soil, and vegetation cover, through field notes.

Ahferom district is located in northern Tigray, Ethiopia (14°19′60″ N; 39°09′60″ E), approximately 65 km north of the ancient town of Axum (Figure 1). The landscape in the Ahferom district will be composed of rugged lands with gentle slopes and steep slopes (more than 30 degrees), from an elevation of 1000 to 3200 meters above sea level. A mean annual rainfall of between 300 and 800 millimeters will be experienced in the area, with Nitosol, Cambisol, and Vertisol being the prevailing soils (Hailemariam et al., 2024).

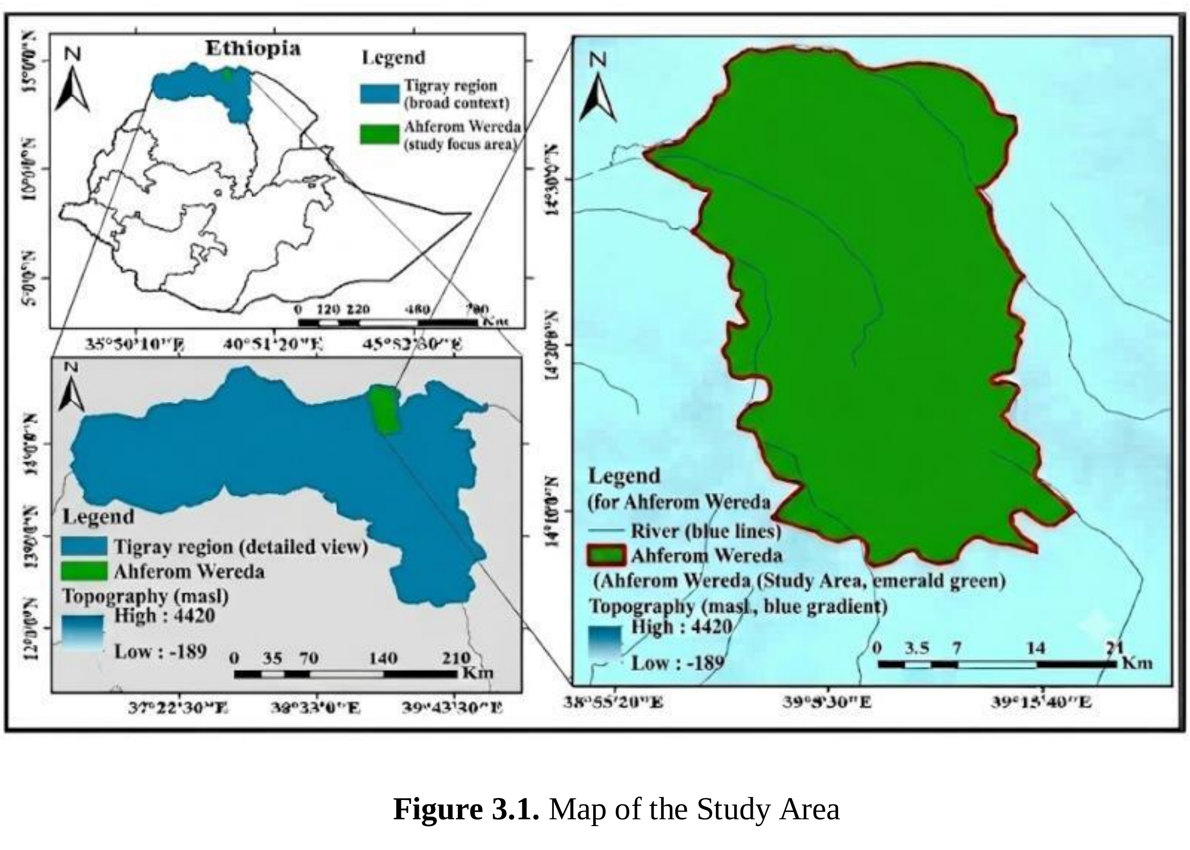


Figure 3.1. Map of the Study Area

3.2. Experimental Research Design

This study employed a quantitative experimental research design to investigate the physical and mechanical properties of *Cordia africana* .

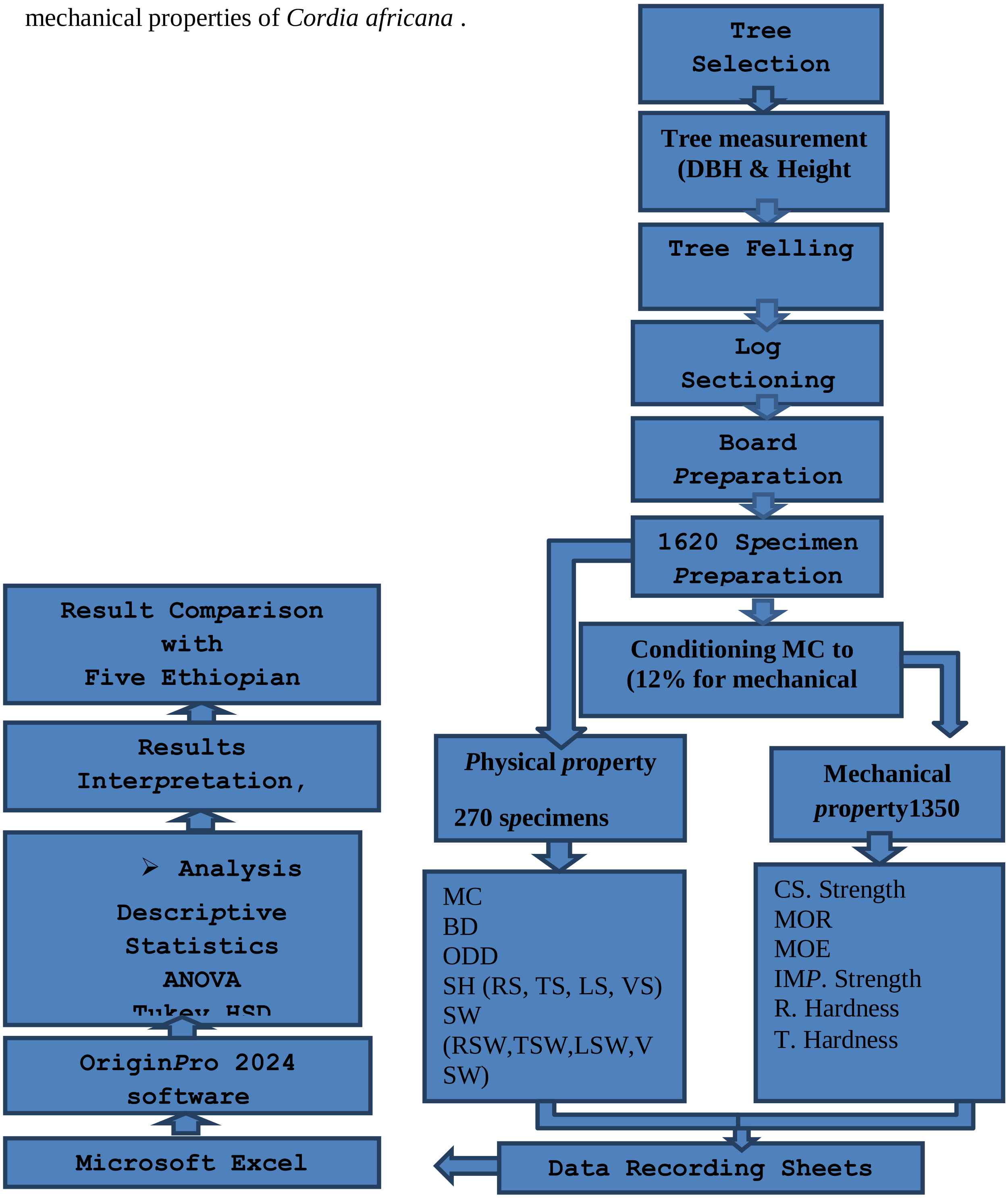


Figure 3.2. Quantitative Experimental Research Design

3.3. Selection of Sample Trees

A total of three mature, healthy Cordia africana trees, approximately 45 years old, were selected and harvested in November 2025 from different agroforestry sites in Ahferom Woreda, Tigray Region, Ethiopia. The trees were selected because they were fully mature, with well-developed heartwood and stable physical and mechanical properties, making them suitable for wood property evaluation (Ross, 2021). The selection of the three trees was random to ensure they represented the study area well. Before the trees were collected and cut, thorough examinations of each tree were conducted to confirm that there were no visible defects, such as knots, decay, insect attack, reaction wood, cracks, and other growth defects that could affect the physical properties of the wood.

The use of three sample trees was justified by various scientific studies on wood properties that used only a few representative trees in their analyses. For example, (Hashemi & Kord 2011)studied the physical properties of *Cupressus sempervirens* using three representative sample trees, and Tampori et al. (2024) also used three trees aged 45 to evaluate mechanical and physical properties. As observed in that research, the selection and preparation of trees were done according to international standards for wood testing, ISO 3129 (1975) and TS 2476.

Similarly, the current research was conducted in accordance with the guidelines of ISO 3129 (1975) and TS 2476 standards for the preparation of test material and clear wood specimens. ISO 3129 (1975) recommends that test specimens should be taken from defect-free wood that does not include knots, reaction wood, decay, checks, or any other defects that might affect the test results. In this regard, only defect-free wood from the stems was used for preparing the test specimens. After the harvesting of the trees, test specimens were prepared according to the guidelines. After selection, logs were taken from each tree and converted into clear wood specimens for physical and mechanical testing. Trees were sampled from different agroforestry systems in the study area to account for the natural variability in growth conditions. This study also followed this method.

The DBH and total height of selected trees were different between the samples. Tree 1 has a DBH diameter of 34 cm and a height to the first branch of 7.30 m; Tree 2 has a DBH diameter of 37 cm and a height of 8.1 m; and Tree 3 has a DBH diameter of 41 cm and a height of 7.70 m. These variations provided a representative range of growth characteristics of *C. africana* in the study area.

3.4. Felling of Trees and Sectioning of Logs

Controlled and safe conditions were met when felling and sampling *Cordia africana* trees in December 2025. Before cutting, the diameter at breast height (DBH), total height, and merchantable height were recorded for each tree.

Each sample tree was felled manually with an axe, and the stem was immediately cross-cut into three sections of logs, which represented the bottom, middle, and top portions of the merchantable height. Each log section was 2.5 m long, and then each 2.5-meter log was cut into two equal pieces, so each section was 1.25 meters (Mussa & Bekele, 2019). This method resulted in a total of nine log sections (3 logs x 3 trees = 9 logs, length of 2.5 m, and then 18 logs, length of 1.25 m sectioned) and provided a systematic representation of the variation in the vertical direction along the stem of the tree.

The logs were sealed at all the cut ends quickly with animal dung to prevent the logs from drying or splitting at the ends. It even maintained the moisture of the samples close to what it would be during transport and storage in the field. Once the logs had been cut, the team loaded them onto camels and transported them from the harvest sites at Ahferom Tahtay Daerka and Agamo to the Fersmay HaHaile Brhane sawmill. Again, following the procedures of previous studies, they sawed the logs tangentially into boards 3 cm thick with the blade kerf.

(Mussa et al., 2025a) .To minimize moisture exchange during transportation and subsequent transportation to Adwa, the lumber was packed with plastic sheets. Specimens were prepared at the Polytechnic College, Adwa. The lumber was stored in a controlled room in which the relative humidity was held constant. This was done by wetting the floor from time to time and by observing and measuring the environmental humidity conditions continuously using a relative humidity clock. This procedure allowed for the appropriate conditioning and preservation of the wood samples before being machined into clear test specimens for the evaluation of physical and mechanical properties.

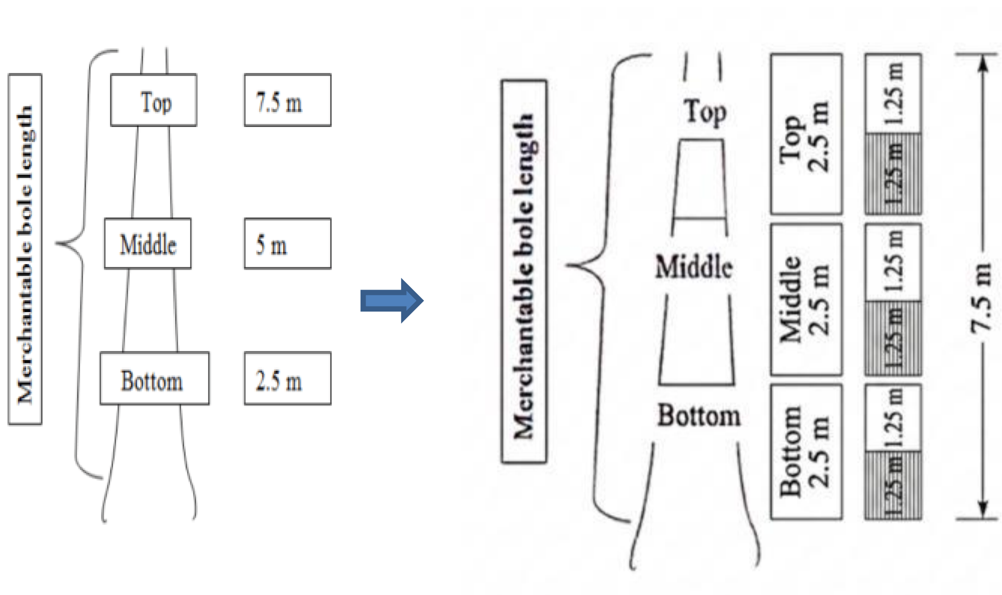
(a) *Cordia africana* in the site (b), Felled *Cordia africana*

(C), Felling *Cordia africana* (d), Sealing end log using dung (e), Transporting using a camel

Figure 3.3. Trees felling, sealing, and transporting

Figure 3.3. shows the photos of the main stages of *Cordia africana* log harvesting, preparation, and transportation for this study. Upper left and upper middle (a) photos show mature *Cordia africana* trees growing in natural conditions at the sampling sites before harvesting. The upper right (b) image shows the manual felling operation with traditional tools, an axe, depicting the controlled cutting process used in the field. The picture in the bottom left (c) shows the felled tree being cut into logs. The lower-middle image (d) shows the use of animal dung on the cut ends of

the logs, a traditional technique to help reduce moisture loss and to prevent end checking and splitting during transportation and storage. The lower right image(e) shows the logs being transported by camels, which was the most practical means of moving the wood from the remote harvesting sites to the sawmill. Together, these photographs illustrate the field methods employed in harvesting trees, preserving the logs, and transporting them before specimen preparation and testing.



(a) Adapted from Mussa & Bekele (2019) (b) Developed in this study (2026)

Figure 3.4. Log sectioning at three height positions.

3.5. Preparation of Specimens

The collected boards, sawn 3 cm thick, were resawn after sawing and initially converted into rough specimen dimensions. At this stage, specimens were prepared with a rough thickness of 25 mm. These specimens were then carefully stacked on shelves to allow even and uniform drying and avoid moisture gradients, thus minimizing drying defects. For the mechanical testing, Conditioning was conducted in an environment where temperature and relative humidity were precisely controlled (temperature 20 ± 2 °C and relative humidity 65 ± 5%). The moisture content of the specimen, about 12%, was checked using a hygrometer and the oven-dry method. Once the desired moisture content level was attained, specimens were accurately machined and squared from their rough size to standard test sizes, with a thickness of 20 mm. The final thickness was made to be 20mm, as well as the correct width and length of the specimens for the various tests (as indicated in Tables 3.1).

Clear wood specimens were chosen based on quality considerations, such as straight grain alignment, absence of knots, and other defects. Specimen preparation was done separately for heartwood and sapwood, as well as for the bottom, middle, and top sections of each sample tree to take into account within-tree variations. Altogether 1,620 specimens were made for physical and mechanical tests, including 270 for physical properties tests and 1,350 for mechanical tests. 15 samples were prepared for each test at each height section (bottom, middle, and top) for both types of wood materials (sapwood and heartwood).

The preparation process was done following the requirements set by the ISO standards for ensuring the consistency and validity of test results. Selection of clear wood specimens for testing was performed based on quality characteristics such as straight grain orientation, the absence of knots, and the absence of any other visible imperfections of the material.

Figure 3.5. Preparation of Specimens

Figure 3.5. shows the methodical workflow for transforming raw timber into standardized clear wood specimens. The procedure started with the main breakdown and resawing of logs and 3 cm thick boards into rough dimensions with a primary thickness of 25 mm (Figure 3.5). The sample boards were then sorted to account for the within-tree variation by separating sapwood from heartwood along bottom, middle, and top height sections and then stacked for uniform drying

(Figure 3.5). Environmental conditioning of the wood was carried out to avoid drying defects. The ambient conditions were continuously monitored with a digital hygrometer in order to keep a strict target of 20 +2 °C and 65 +5% relative humidity, which ensures an equilibrium moisture content of about 12% (Figure 3.3). The stabilized wood was then machined down to the required test thickness of 20 mm using a surface planer and sliding table saw to perfectly square the blocks for all 1,620 physical and mechanical tests (Figure 3.5).

Figure 3.6. Drying green specimens to 12% MC.for mechanical testing

Figure 3.6. illustrates the drying procedure of green *Cordia africana* specimens to 12% moisture content (MC) prior to mechanical testing. Then the specimens were stacked and arranged on shelves under shaded laboratory conditions to facilitate a gradual reduction in moisture and air circulation. Environmental conditions during the drying period were continuously monitored with

a digital humidity clock and showed a temperature of about 21.4°C and a relative humidity of about 64 %, 20.9°C, 70% relative humidity. Also, the moisture content of the specimens was monitored at different times with a hand-held moisture meter (hygrometer). Moisture meter readings show a gradual decrease in moisture content with readings of approximately 12.6%, 12.5%, 12.3% and 11.5% at different stages of drying. The measurements indicate that the specimens progressively lost moisture until they reached the target moisture content range of about 12%, which is commonly required for the evaluation of mechanical properties. The combination of a humidity clock and moisture meter provided for continuous monitoring of the drying conditions and moisture content of the specimens, and ensured that the wood samples reached a stable and consistent moisture content for further mechanical testing. Both the relative humidity and the moisture meter reading are representative measurements.

Figure 3.7. Measuring weighting specimens for physical property

The samples of the physical property, like moisture content, the wood samples were cut into standard size specimens, 20*20*30 mm, and labeled by wood type and sampling position to guarantee proper identification during the testing process. Each specimen was then studied and systematically arranged for measurement and data recording. The dimensions of the specimens were measured with a digital vernier caliper, while the mass was measured with a precision electronic balance. The images are representative measurements to show the accuracy of the preparation procedure, such as the specimen weight of 12.32 g and the cross-sectional dimension of 30. mm. From these measurements, physical properties such as MC. density, shrinkage, and swelling were calculated.

3.5.1. Specimen Dimensions and Quantity

Table 3.1: Specimen dimensions and number of specimens used for physical and mechanical property testing of *Cordia africana*

<table>
<tr><th rowspan="2">Property Category</th><th rowspan="2">Test Property</th><th rowspan="2">Standard(s)</th><th rowspan="2">Specimen Dimensions (mm)</th><th colspan="3">Sapwood Specimens per height per tree (SW)</th><th colspan="3">Heartwood Specimens per height per Tree (HW)</th><th rowspan="2">Total Specimens per Tree (Three Heights)</th><th rowspan="2">Total Specimens Used (Three Trees)</th><th rowspan="2">Reference</th></tr>
<tr><th>Bottom</th><th>Middle</th><th>Top</th><th>Bottom</th><th>Middle</th><th>Top</th></tr>
<tr><td>Physical</td><td>Density, Moisture Content, Shrinkage, and Swelling</td><td>ISO 3131</td><td>20 × 20 × 30</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>90</td><td>270</td><td>Kana et al. (2024); Taha et al. (2020)</td></tr>
<tr><td rowspan="5">Mechanical</td><td>Compression parallel to the grain</td><td>ISO 3387:1975</td><td>20 × 20 × 60</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>90</td><td>270</td><td>Taha et al. (2020b)</td></tr>
<tr><td>Impact strength to the radial</td><td>ISO 3348:1975</td><td>20 × 20 × 300</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>90</td><td>270</td><td>Taha et al. (2020)</td></tr>
<tr><td>Static bending (MOR & MOE)</td><td>ISO 3133:1975</td><td>20 × 20 × 300</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>90</td><td>270</td><td>Taha et al. (2020)</td></tr>
<tr><td>Janka hardness (Radial)</td><td>ISO 3348,1975</td><td>20 × 20 × 45</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>90</td><td>270</td><td>Mussa & Bekele (2020)</td></tr>
<tr><td>Janka hardness (Tangential)</td><td>ISO 3348,1975</td><td>20 × 20 × 45</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>15</td><td>90</td><td>270</td><td>Mussa & Bekele (2020)</td></tr>
</table>

Table *Notes*:

The specimens were collected from three stem-height levels (bottom, middle, and top) of each tree. At each height, 15 sapwood and 15 heartwood specimens were prepared, resulting in 90 specimens per tree and 270 specimens for three trees.

The same set of 270 specimens (20 × 20 × 30 mm) was sequentially used to determine density, moisture content, shrinkage, and swelling. The appropriate ISO standard for each physical property was followed as described in the methodology.

A total of 1,620 specimens were used in this study, comprising 270 specimens for physical property tests and 1,350 specimens for mechanical property tests.

3.6. Equipment and Tools Used

Preparation, conditioning, and testing of *Cordia africana* wood specimens were done using various laboratory instruments and woodworking tools. Calibration of all instruments was done before the testing was carried out.

Specimen weight measurement was done using an electronic balance of accuracy ±0.01 g, which was useful in the density measurement of the specimen, both dry and wet. A laboratory oven was used for the moisture content analysis and shrinkage measurements at 100 ± 3°C. Dimensional measurements, including thickness, width, length, shrinkage, and swelling, were done using a digital Vernier caliper and a steel ruler of precision 0.01 mm.

UTM was used for the mechanical testing, including the bending strength (Modulus of Rupture and Modulus of Elasticity) and compression strength parallel to the grain using ISO 3133 (1975) and ISO 3387 (1975), respectively. Impact bending strength was measured using a Charpy-type impact pendulum tester according to ISO 3348 (1975). Janka radial and tangential hardness testers were done using UTM following ISO standards.

A moisture meter was used for monitoring the moisture content of specimens while conditioning, whereas a relative humidity meter was used for controlling and measuring the environmental conditions inside the conditioning chamber. Panel circular saw machine and table saw machine.

3.7. Physical Properties Test

Tests for determining the physical properties of *Cordia africana* wood were performed to study the wood's behavior depending on changes in moisture and assess the suitability of the wood for specific applications. The tests involved measuring the moisture content, density, shrinkage, and swelling. Tests for moisture content were done to find out how much water is contained in the wood sample, and those for density were done to determine the quality and strength of the wood. Testing for shrinkage and swelling was done to determine the dimensional stability of the wood when there is a moisture change.

3.7.1. Determination of Moisture Content

Moisture content was determined through the use of the oven-dry method following the corresponding ISO standards. The experiment was conducted to determine the quantity of moisture content existing within the wood of *Cordia africana* and serve as baseline information in determining the physical and mechanical properties of the wood.

A total of 270 samples were used in measuring the moisture content. Specimens were obtained from separate sections of heartwood and sapwood. Each sample had dimensions of 20 mm x 20 mm x 30 mm. Right after obtaining the specimens, their green mass was weighed in the workshop using an accurate electronic balance and noted as the initial weight.

The samples were thereafter taken to the laboratory at Axum University. They were dried in the lab oven set at 103 ± 2°C until a constant mass was obtained. This can be verified by weighing the samples repeatedly until three successive readings are observed to have no substantial difference. This whole drying process took about five days before reaching a constant mass. After the completion of drying, the final mass of each sample was measured and recorded. Moisture content was thus obtained based on the dry mass of the Schedule.

Figure 3.8. Measuring moisture content green to oven–dry using oven-dry and controlling moisture absorption using silica Gel

$$\mathbf{MC}(\%) = \frac{\mathbf{W_g - W_{od}}}{\mathbf{W_{od}}} \boldsymbol{X}\ \mathbf{100}$$ --Equation 3.1

Where MC = Moisture content (%), W_g = Green weight of the specimen (g) and W_{od} = Oven-dry weight of the specimen (g)

3.7.2. Basic Density Determination

Wood density is one of the most important physical properties of wood as it is closely related to wood quality, cell structure, strength, and stiffness (Ross, 2021).

Basic density of wood was estimated based on the appropriate ISO standards. A total of 270 wood specimens were prepared from both the heartwood and sapwood fractions of the bottom, middle, and top portions of the selected tree stems. The dimensions of each specimen were 20 mm × 20 mm × 30 mm. These dimensions were measured with the aid of a digital Vernier. A vernier caliper with an accuracy of 0.01 mm was used to measure the green dimensions, whereas a digital electronic balance with an accuracy of ±0.01 g was used to measure the specimen mass.

The green dimensions and green masses of the specimens were first measured and recorded. Then, the specimens were dried in the laboratory oven that was heated at 103 ± 2 °C until a constant oven-dry mass was attained. Once the specimens reached their constant masses, they were taken out of the oven and cooled down for about 30 min before weighing. In order to minimize the moisture, gain from the atmosphere due to cooling and weighing of the specimens, they were weighed after being kept inside a covered metal container containing silica gel. Silica gel served as a desiccant by absorbing moisture from the atmosphere(Kosasih et al., 2022). Specimens' volumes were computed based on their green dimensions. Then, the density was determined based on the mass and volume values measured. Basic density is defined as the ratio of oven-dry mass to green volume and is given in kg/m³.

Figure 3.9. Basic density determination by measuring oven-dry mass and controlling moisture absorption with silica Gel.

Figure 3.9 Determination of basic density of wood samples of *Cordia africana*. The specimens were oven-dried at 103 ± 2°C until the oven-dry mass was obtained after the moisture content test was performed. The oven-dried specimens were then immediately transferred to a desiccator with silica gel to prevent reabsorption of moisture from the surrounding air before weighing.

The oven-dry mass of each specimen was then measured using a precision electronic balance. A representative specimen weighed 5.72 g. The oven-dry mass was then added to the green volume previously measured, and the basic density was calculated by the standard procedure. The specimens were handled in the presence of silica gel, which ensured complete drying, which improved the accuracy and reliability of the basic density measurements.

Basic density was calculated from Equation (3.2):

$$\boldsymbol{Basic\ Density} = \frac{\boldsymbol{Oven-Dry\ Mass\ (g)}}{\boldsymbol{Green\ volume\ (cm^3)}} \text{ --- Equation 3.2}$$

The obtained density values were subsequently used to evaluate the variation in wood quality between heartwood and sapwood and among the bottom, middle, and top portions of *Cordia africana* trees.

3.7.3. Determination of Oven Dry Density

The determination of Oven-dry density (kg /m³) was performed on the same set of specimens used for measuring the moisture content and basic density. In total, 270 specimens measuring 20 mm x 20 mm x 30 mm were tested. Specimens were extracted independently from heartwood and sapwood and from the bottom, middle, and top regions of the chosen *Cordia africana* trees.

Oven-dry density refers to the ratio of oven-dry mass and oven-dry volume. To attain an oven-dry condition, the specimens were dried using an oven kept at 103 ± 2°C until a constant mass is attained. First, the specimens were dried in the laboratory oven for 24 hours. Afterward, they were taken out of the oven to cool down and weigh. A significant drop in the mass of the specimens was recorded during this initial drying process since moisture was lost.

The subsequent steps entailed placing the samples back in the oven for periods of around 12 hours until the samples came closer to having a constant mass; after which, drying periods of about 6 hours would be used. Upon drying each period, the samples would be removed from the oven, cooled in a moisture-controlled environment, and thereafter weighed with the aid of an accurate electronic balance, which could accurately weigh up to ±0.01 g. The subsequent step involved measuring the dimensions of each sample using a digital Vernier caliper with a precision of 0.01 mm. Using these measurements, the oven-dry volume was determined, and hence the oven-dry density. The oven-dry density can thus be determined from Equation (3.3):

$$Oven - Dry\ Density = \frac{Oven{-}Dry\ Mass\ (g)}{Oven{-}Dry\ volume\ (cm^3)}$$ ---------------------------- Equation 3.3

The resulting oven-dry density values were used to assess density variation between heartwood and sapwood and among the bottom, middle, and top sections of the *Cordia africana* trees.

3.7.4. Shrinkage Determination

The shrinkage values were obtained by determining the dimensional change of wooden samples from the green state to the oven-dry state following the respective ISO standards. A total of 270 samples measuring 20 mm x 20 mm x 30 mm were employed in obtaining shrinkage values. The same samples that were used in moisture content determination and density determination were used in shrinkage determination. The original dimensions of the samples in the radial, tangential, and longitudinal directions were recorded in the green state using a digital vernier caliper with an accuracy of 0.01mm. The samples were oven-dried at 103 ± 2°C until constant mass. The dimensions in the three anatomical directions after oven drying were recorded. Linear shrinkage was calculated from the difference between the green and oven-dry dimensions in radial, tangential, and longitudinal directions. Furthermore, volumetric shrinkage was evaluated from the corresponding dimensional changes from the green state to the oven-dry state.

Figure 3.10. Measurement of the shrinkage of *Cordia africana* specimens using a digital vernier caliper

The dimensions of each specimen were recorded in the green condition and then again after oven drying at 103 ± 2°C to constant mass. The measurements were carried out in the directions radial, tangential, and longitudinal axes by means of a digital caliper with an accuracy of 0.01 mm. The images show the exact measurement of the oven-dried dimensions, which were compared with the respective green dimensions to determine the linear shrinkage in each anatomical direction. These dimensional measurements were also used to calculate the volumetric shrinkage of the wood specimens and hence provided reliable data for the evaluation of the dimensional stability of *Cordia africana*.

The percentage shrinkage values were calculated using Equation (3.4):

$$\boldsymbol{S}(\%) = \frac{\mathbf{D_g - D_{od}}}{\mathbf{D_g}}\ \boldsymbol{X}\ \mathbf{100}$$ ---Equation 3.4

Where S = Shrinkage (%), Dg = Green dimension of the specimen (mm) and Dod = Oven-dry dimension of the specimen (mm).

Volumetric shrinkage was calculated using Equation (3.5):

$$\boldsymbol{VS}(\%) = \frac{\mathbf{V_g - V_{od}}}{\mathbf{V_g}}\ \boldsymbol{X}\ \mathbf{100}$$ ---Equation 3.5

Where VS = Volumetric shrinkage (%), Vg = Green volume of the specimen (cm^3) and Vod = Oven-dry volume of the specimen (cm^3)

The obtained shrinkage values were used to evaluate dimensional stability and variation between heartwood and sapwood and among the bottom, middle, and top sections of *Cordia africana* wood.

3.7.5. Swelling

The swelling properties of the *Cordia africana* were established through the testing of 270 oven-dried samples that had been prepared to establish their shrinkage properties. Swelling tests were carried out in the radial, tangential, longitudinal, and volumetric planes. In order to carry out the test, the initial dimensions of each sample were recorded using a digital vernier caliper, which measures dimensions with an accuracy of 0.01mm. The samples were then placed in water and left to soak for 72 hours(Performance et al., 2012).

This test helped determine the level of swelling exhibited by the wood. This was done by determining the difference between the oven-dry and wet samples. While some of the samples reverted to their original dimensions after being immersed in water, some of them did not revert, probably because of irreversible deformation of the cell wall caused by the drying process. In accordance with observations made in hardwoods, the largest swelling occurred in the tangential plane, followed by the radial plane, with the least swelling occurring in the longitudinal plane(Pepin et al., 2019). Swelling in percentage was estimated as follows:

Figure 3.11. *Cordia africana* specimens swelling test procedure & measuring swollen dimensions

Plastic bags were used to collect the oven-dried specimens and placed in water containers for soaking. The specimens were measured after a soaking period with a digital vernier caliper with an accuracy of 0.01 mm. The images display the specimens during water immersion and the measurement of swollen dimensions in preparation for the determination of radial, tangential, longitudinal, and volumetric swelling percentages.

Linear Swelling (%)

$$\textbf{Linear swelling}\ (\%) = \frac{\mathbf{Dw-Do}}{\mathbf{Do}}\ \boldsymbol{X}\ \mathbf{100}$$ ------------------------------Equation 3.6

Where Dw = Wet (swollen) dimension (mm) and Do = Oven-dry dimension (mm)

Volumetric Swelling (%)

$$\mathbf{VS} = \frac{\mathbf{Vw-Vo}}{\mathbf{Vo}}\ \boldsymbol{X}\ \mathbf{100}$$ ---Equation 3.7

Where VS = Volumetric swelling (%), Vw = Wet (swollen) volume (cm^3 or mm^3) and Vo = Oven-dry volume (cm^3 or mm^3)

3.8. Mechanical Property of *Cordia africana* tests

Mechanical properties such as the strength of *Cordia africana* wood were analyzed at Mekelle University to evaluate the mechanical properties of the wood. Some of the mechanical tests performed include compression strength parallel to the grain, static bending strength in terms of Modulus of Rupture (MOR) and Modulus of Elasticity (MOE), impact bending strength in the radial direction, and the Janka hardness test for both radial and tangential surfaces.

A total of 1350 samples were used in evaluating mechanical properties in this study. The reason behind choosing these mechanical properties was that they were commonly used to analyze the structural performance, stiffness, toughness, and surface resistance of wood used in construction and the furniture industry. The experiments were performed according to standard methods of wood mechanical property tests. A testing machine called a universal testing machine (UTM) was used to test some mechanical properties of the wood samples. This machine was an SI-1000 kN microcomputer-controlled electro-hydraulic servo universal testing machine having a load of 1000 kN and controlled through a computerized data acquisition and control unit.

(a), Specimens before testing (b), Specimens after testing

Figure 3.12. Specimens for mechanical testing

3.8.1. Compression Strength (Parallel to Grain)

Compressive strength parallel to the grain was measured using an SI-1000 kN microcomputer-controlled electro-hydraulic servo universal testing machine (UTM). A total of 270 samples were tested during this investigation. The testing specimens were cut from both wood types (i.e., sapwood and heartwood) and from three different heights of the trees (low, medium, and high sections). All the specimens were conditioned to reach an equilibrium moisture content of approximately 12% before testing. The dimensions of all the specimens were 20 mm x 20 mm x 60 mm, with their grain orientation parallel to the applied load. These specimens were placed at the center between the compression platens. The load was continuously applied at a loading rate of 0.01 mm/s until the occurrence of fracture(Mussa et al., 2025a). Then, the maximum load at failure was automatically recorded by the testing machine and used in calculations to determine compressive strength parallel to the grain. This test was carried out according to ISO 3787 (and other ISO standards for compression parallel to the grain testing). Stress values were obtained using the recorded maximum loads divided by the corresponding specimen areas. All the testing operations were computerized using UTM. The compressive strength parallel to the grain (N/mm2) was calculated using equation 3.9:

$$\boldsymbol{\sigma_c} = \frac{\boldsymbol{P_{max}}}{\boldsymbol{bd}} \text{ -- Equation 3.8}$$

Where σ_c = Compressive strength parallel to the grain (MPa), Pmax = Maximum load at failure (N), b = Specimen width (mm) and d = Specimen thickness (mm).

(a), Testing setup before & after load application.

(b) Heartwood specimen compressed (c), Sapwood specimens compressed

Figure 3.13: Testing of compression strength parallel to the grain using SI-1000 kN UTM

The first photograph (a) is the specimens placed between the upper and lower compression platens of the SI-1000 kN Universal Testing Machine (UTM) before loading. The second photograph (b & c) shows the prepared heartwood and sapwood specimens after testing, with visible compression failure and splitting along the grain. The pictures show the specimen preparation, loading arrangement, and typical failure patterns during the compression strength test.

3.8.2. Static Bending (MOR and MOE)

The static bending test was done using an SI-1000 kN Microcomputer Controlled Electro-Hydraulic Servo Universal Testing Machine, complete with a three-point bending fixture. In preparation for the test, all specimens were conditioned to 12% moisture content. Each specimen was 20 mm × 20 mm × 300 mm and was set on two supports, with a span length of 280 mm. The force was applied at mid-span at the radial surface at a rate of 6.6 mm min^{-1} until fracture(Mussa et al., 2025a). Data on load and deflection were captured automatically throughout the test. The modulus of rupture (MOR) was computed using the maximum load attained and the modulus of elasticity (MOE) from the elastic region of the load/deflection curve. The test was executed following ISO 3133. Modulus of elasticity and Modulus of rupture are calculated using equations 3.10 and 3.11, respectively.

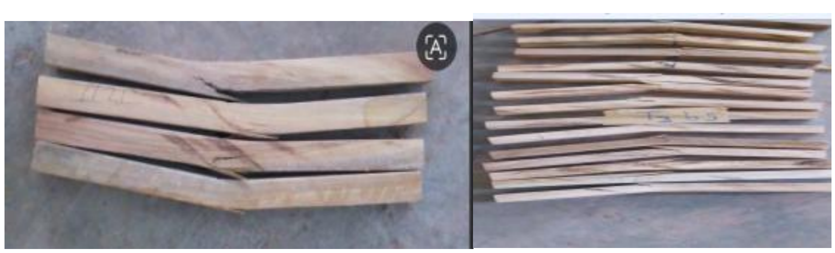
$\mathbf{MOR} = \frac{3PL}{2db^2}$ --Equation 3.9

$\boldsymbol{MOE} = \frac{PL^3}{4dbh^3}$ --Equation 3.10

Where Modulus of elasticity is in (N/mm2), Modulus of rupture is in (N/mm2): modulus of rupture, P1: is load at the limit of proportionality in ‘N’, P: maximum load in ‘N’, L: the span length in ‘mm’, and d: deflection at the limit of proportionality.

(a), Static bending strength

(b), Heartwood specimens before and after testing



(C), Static bending strength tested sapwood specimens

Figure 3.14. Testing of specimens' static strength (MOR &MOE) using UTM.

3.8.3. Impact Bending Strength (radial direction)

Impact bending strength test was done using a Charpy pendulum impact testing machine with a 12.5 kg hammer. All specimens were conditioned to 12% moisture content before being subjected to the impact load. The specimens were 20 mm × 20 mm × 300 mm and were arranged horizontally with respect to each other in such a way that a span length of 240 mm was achieved. The specimens were impacted radially by the hammer, and the energy absorbed during the process was recorded. The testing was executed following ISO 3348. The impact bending strength was calculated using equation:

$\boldsymbol{Impact\ strength} = \frac{\boldsymbol{E}}{\boldsymbol{bd}}$---Equation 3.11

Where P is the Joule value in Nm, b is the specimen's width in mm, and h is the specimen's thickness in mm.

(a), Charpy pendulum hammer (b), Tested SW specimens (c), Tested HW specimens

Figure 3.15. Testing impact strength using the Charpy Pendulum hammer

3.8.4. Janka Hardness (Radial and Tangential)

Janka hardness test was carried out using an SI-1000 kN Microcomputer Controlled Electro-Hydraulic Servo Universal Testing Machine, complete with a steel ball indentation device. In preparation for the test, all specimens were conditioned to 12% moisture content. According to (Mussa & Bekele, 2019b), the specimens were 20 mm × 20 mm × 45 mm in size and tested radially and tangentially. The testing consisted of indenting a steel ball having a diameter of 11.28 mm (approximately 11.3 mm) into the wood until a penetration depth of 5.65 mm (one-half of the ball diameter) was obtained at a rate of 0.11 mm s^{-1}. The load attained was automatically captured throughout the test and reported as the Janka hardness value. Testing was executed following ISO 3350. The Janka hardness was calculated using the following equation:

$H=P_{max}$---Equation 3.12

Where H = Janka hardness (N) and Pmax = Maximum load required to embed the steel ball to a depth of 5.65 mm (N)

(a), UTM (b), Hardness tested HW specimens (c), Hardness tested SW specimens

Figure 3.16. Tangential and radial janka hardness testing using UTM

3.9. Data Collection and Recording

All specimens in the study were given an identification code before data collection. Specimen ID Codes consisted of three numbers, wood type (Heartwood/Sapwood), stem height section (Bottom/Middle/Top), and specimen number.

Specific data record sheets were developed for each of the physical and mechanical properties studied. Specific physical property record sheets included the moisture content, oven-dry density, basic density, radial shrinkage, tangential shrinkage, longitudinal shrinkage, volumetric shrinkage, radial swelling, tangential swelling, longitudinal swelling, and volumetric swelling. Mechanical properties record sheets included compression strength parallel to the grain, static bending properties (Modulus of Rupture & Modulus of Elasticity), impact strength, and Janka hardness on radial and tangential faces.

During the experiment in the laboratory, data from each specimen measured in each test were directly entered on its specific hard-copy data record sheet with the specimen identification codes. Information collected for each specimen included tree number, wood type, position in stem (bottom/middle/top), specimen number, measurements (mass/dimensions), and mechanical test parameters. Measurements were made for each specific specimen separately to make comparisons between different wood types, heights, and trees.

After the end of the laboratory tests, all data were carefully checked for any possible errors and mistakes in calculations, and then transferred from the hard-copy record sheets into Microsoft Excel spreadsheets. The Microsoft Excel database contained data arranged by tree number, wood type, stem position (bottom, middle and top), specimen number, and physical/mechanical test parameters. This Microsoft Excel database was used for further statistical analysis of *Cordia africana* wood properties.

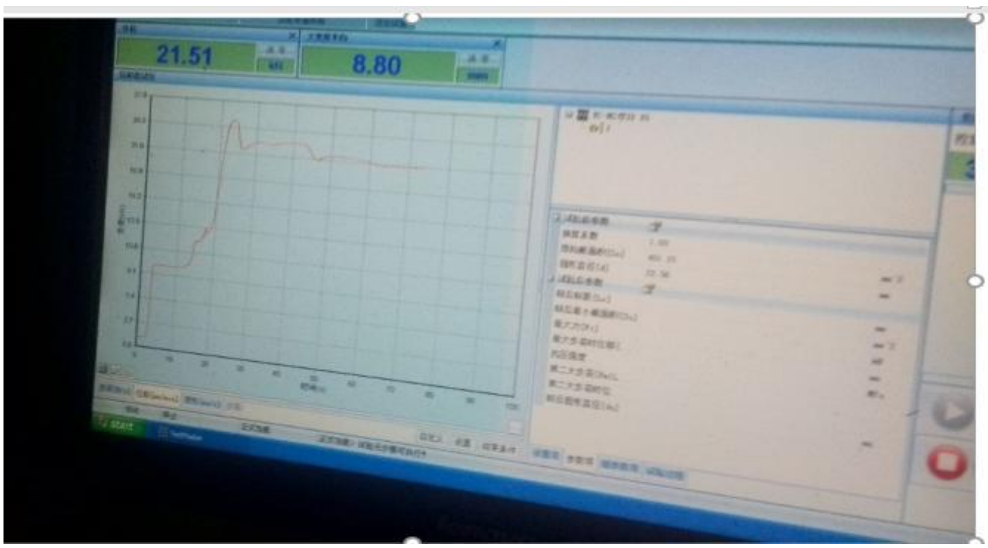


Figure 3.17. Data recording system using a computerized UTM during testing specimens.

3.10. Data Analysis

Data from experimental tests were recorded in Microsoft Excel then imported into OriginPro 2024 software for statistics, tabulation, and data visualization. Systematic data analysis methods and procedures were followed for correct and reliable data analysis. Specific data were analyzed by the statistical OriginPro 2024 software; the analyses done included the following:

Descriptive statistical analysis was done to summarize the whole dataset, i.e., Mean, Standard Deviation, Coefficient of Variation (CV), Minimum Value, Maximum Value, etc. Two-way ANOVA was conducted to analyze the impact of wood type (sapwood and heartwood) and tree height (upper, middle, and bottom log parts), as well as their interaction effect on the measured properties of *Cordia africana*.

The interaction effect of the independent variables was examined to investigate the effect of the interaction between two factors on the dependent variables and to check whether an interaction between them occurred. Comparative analysis was done by comparing the current findings with the available literature data on five selected timber species in Ethiopia.

Before conducting inferential statistics, data distribution assumptions were examined. In particular, a normality test was performed to verify if the data were normally distributed. Data skewness was also analyzed. Furthermore, data distributions were studied for outliers and data patterns using histograms and boxplots for each experimental set of data. In case a significant difference existed, Tukey's Honestly Significant Difference test was used to perform multiple comparisons and group the means. Thus, letters were used to identify statistically significant differences between groups of treatments. The interaction grouping letters were also thoroughly analyzed and explained. In order to provide clear visualization and analysis of the results according to thesis requirements, graphs (bar plots, interaction plots, etc.) were plotted using OriginPro 2024.

Chapter 4. Results and Discussion

4.1. Physical Properties of *Cordia africana*

The physical properties of *Cordia africana* wood were evaluated in terms of moisture content, density, shrinkage, and swelling. These properties are key indicators of wood quality and affect drying behavior, dimensional stability, and end-use performance (Glass & Zelinka, 2021; Fu et al., 2023). The physical properties were evaluated according to wood type (sapwood and heartwood), stem position (bottom, middle, and top), and their interaction. Two-way analysis of variance (ANOVA) and descriptive statistics (Mean ± SD) were used to determine the differences between wood types and stem positions, as these are factors affecting the physical properties of wood (Fu et al., 2023).

Table 4.1. Descriptive statistics (Mean ± SD) of the physical properties of *Cordia africana* as affected by wood type and tree height position

Property	N	Bottom SW	Bottom HW	Middle SW	Middle HW	Top SW	Top HW
MC (%)	45	122.02 ± 6.34	106.80 ± 6.70	126.53 ± 6.06	109.31 ± 8.97	136.72 ± 14.38	119.24 ± 7.44
BD (kg/m³)	45	485.74 ± 9.30	506.37 ± 13.38	455.69 ± 12.07	484.04 ± 17.72	432.46 ± 27.35	454.39 ± 14.87
ODD (kg/m³)	45	533.81 ± 11.32	552.70 ± 14.52	495.31 ± 14.49	525.44 ± 19.62	468.89 ± 30.01	488.38 ± 15.65
RS (%)	45	3.26 ± 0.23	2.87 ± 0.21	3.06 ± 0.19	2.76 ± 0.15	2.81 ± 0.19	2.66 ± 0.11
TS (%)	45	6.10 ± 0.18	5.71 ± 0.41	5.64 ± 0.19	5.34 ± 0.28	5.29 ± 0.18	5.10 ± 0.15
LS (%)	45	0.09 ± 0.02	0.09 ± 0.03	0.12 ± 0.01	0.11 ± 0.02	0.13 ± 0.01	0.12 ± 0.01
VS (%)	45	9.19 ± 0.29	8.51 ± 0.51	8.62 ± 0.24	8.04 ± 0.37	8.10 ± 0.18	7.72 ± 0.20
RSW (%)	45	3.31 ± 0.24	2.88 ± 0.17	3.04 ± 0.17	2.73 ± 0.14	2.72 ± 0.18	2.66 ± 0.13
TSW (%)	45	6.09 ± 0.15	5.71 ± 0.41	5.64 ± 0.19	5.34 ± 0.28	5.29 ± 0.18	5.10 ± 0.15
LSW (%)	45	0.09 ± 0.02	0.09 ± 0.02	0.10 ± 0.00	0.10 ± 0.00	0.12 ± 0.01	0.11 ± 0.01
VSW (%)	45	9.73 ± 0.57	8.98 ± 0.62	9.03 ± 0.34	8.38 ± 0.42	8.37 ± 0.29	8.13

Note: N = 45 specimens for each wood type and tree height position

Table 4.1 Descriptive statistics of the physical properties of *Cordia africana* wood, which vary with the type of wood and the location on the stem. Heartwood generally showed higher density values (BD and ODD) than sapwood in all stem positions, while sapwood had higher moisture content and shrinkage characteristics in most cases. A decreasing trend in density-related properties was observed from bottom to top of the stem, while moisture content generally increased towards the top position. The shrinkage and swelling properties were dependent on the type of wood and the location within the stem, with the tangential and volumetric changes usually having higher values than the radial and longitudinal changes. The extent of variation in the measured properties is a consequence of anatomical differences between the sapwood and heartwood and the variation in the vertical direction within the stem. Statistical analysis of the significance of the effects of wood type, stem position, and their interaction on the measured physical properties was further conducted using two-way ANOVA.

Table 4.2 Two-way ANOVA for the physical properties of *Cordia africana*

Property	Source	df	SS	MS	*F-value*	*P*-value
MC	Wood type	1	18680.95	18680.95	241.25	<0.0001
	Tree height	2	8929.91	4464.95	57.66	<0.0001
	Interaction	2	68.91	34.46	0.44	0.64
BD	Wood type	1	37708.95	37708.95	133.54	<0.0001
	Tree height	2	124645.38	62322.69	220.70	<0.0001
	Interaction	2	769.54	384.77	1.36	0.26
ODD	Wood type	1	35213.65	35213.65	101.62	<0.0001
	Tree height	2	187962.05	93981.03	271.22	<0.0001
	Interaction	2	1799.41	899.71	2.60	0.08
RS	Wood type	1	5.28	5.28	154.91	<0.0001
	Tree height	2	4.85	2.43	71.23	<0.0001
	Interaction	2	0.64	0.32	9.33	0.001
TS	Wood type	1	5.70	5.70	90.64	<0.0001
	Tree height	2	22.88	11.44	182.02	<0.0001
	Interaction	2	0.43	0.22	3.45	0.03
LS	Wood type	1	0.00227	0.00227	6.57	0.01091
	Tree height	2	0.05420	0.02710	78.30	<0.0001
	Interaction	2	0.00234	0.00117	3.38	0.03544
VS	Wood type	1	20.24	20.24	197.57	<0.0001
	Tree height	2	39.47	19.74	192.62	<0.0001

	Interaction	2	1.10	0.55	5.38	0.01
RSW	Wood type	1	4.94	4.94	164.57	<0.0001
	Tree height	2	7.35	3.68	122.45	<0.0001
	Interaction	2	1.58	0.79	26.26	<0.0001
TSW	Wood type	1	5.68	5.68	93.91	<0.0001
	Tree height	2	22.84	11.42	188.75	<0.0001
	Interaction	2	0.43	0.21	3.55	0.03
LSW	Wood type	1	0.00022	0.00022	1.44	0.23045
	Tree height	2	0.02073	0.01036	67.19	<0.0001
	Interaction	2	0.00003	0.00001	0.09	0.91105
VSW	Wood type	1	20.17129	20.17129	94.64	<0.0001
	Tree height	2	55.50135	27.75067	130.20	<0.0001
	Interaction	2	3.17575	1.58787	7.45	0.0007

Table 4.2 presents the results of the two-way ANOVA, which indicated that wood type and tree height had a significant effect on most of the physical properties studied in *Cordia africana*. Wood type had a significant effect ($P < 0.0001$) on the moisture content, the density related properties, shrinkage and swelling properties except for longitudinal swelling which was not significantly affected ($P=0.23045$). Likewise, tree height had a highly significant effect on all physical properties measured ($P < 0.0001$), suggesting a high degree of variation along the stem from bottom to top positions. The interaction effect of wood type x tree height was significant for most of the shrinkage and swelling properties, indicating that the effect of stem position was different between sapwood and heartwood. However, no significant interaction effect was found on moisture content, density properties, and longitudinal swelling. Overall, the results indicate that wood type and vertical stem position are important factors influencing the physical characteristics of *Cordia africana*, and their combined influence varies with the specific property investigated.

4.1.1. Moisture content (%) of *Cordia africana* affected by wood type and tree height.

Moisture content is one of the most important physical properties of wood because it is very important for drying behavior, dimensional stability, mechanical performance, and the overall processing and utilization of wood products(Fu et al., 2023). This study examines the moisture content of *Cordia africana* under the influence of the wood type and the position of trees based on their height.

From the results obtained in Table 4.1, it is evident that moisture content differed greatly depending on both the wood type and the position of the tree stem. Moisture content in the upper sapwood showed the highest mean values (136.72 ± 14.38%) compared to middle sapwood (126.53 ± 6.06%) and bottom sapwood (122.02 ± 6.34%). However, moisture content values were lower for heartwood, varying from 106.80 ± 6.70% in the bottom section up to 119.24 ± 7.44% in the top section. Therefore, moisture content values were higher in sapwood than in heartwood across the entire stem. There was an observable trend longitudinally within both types of wood. Moisture content increased gradually from the bottom to the top sections of the tree stem. For sapwood, moisture content increased by about 12.0% from the bottom (122.02%) to the top (136.72%) sections, while in heartwood, it rose by about 11.6%, from 106.80% to 119.24%. The increase in moisture content from bottom to top sections might be due to higher amounts of juvenile and physiologically young cells in the upper sections, which normally have more free water content and take part in water transport processes. It is due to the change in sapwood to heartwood where the conducting cells cease their functions, extractives accumulate, and thus the wood becomes less able to store and convey moisture. Coefficients of variation (CVs) ranged from 5% to 11%, indicating moderate variation across the analyzed groups.

Cordia africana moisture content value found in the current research (120%) is consistent with moisture content values observed in other tropical hardwoods. Yamamoto et al. (2003), showed in relative study, that moisture content values observed in *Acacia mangium*, A. auriculiformis, and hybrid Acacia were very high, with 253% moisture content found in heartwood and 154% in sapwood, while there was a lot of variability along the stem. Also, Florisson et al.(2019),Showed moisture content values varying from 120-200% in sapwood and 30-60% in heartwood, thus proving that moisture content is higher in sapwood than in heartwood. In Ethiopia, for example, the Forest Products Utilization Research Center observed an initial green moisture content of 71%, 108%, and 191% for *Cordia africana*, *Grevillea robusta*, and *Olea welwitschii*, respectively (Desalegn et al., 2015). In this sense, the moisture content found in the current study was higher compared to the previous report on *C. africana* and *G. robusta*, but lower compared to that of *Olea welwitschii*. These variations may be due to site factors, tree age, growth patterns, sampling point along the stem, and anatomical characteristics. The high moisture content found in the current study is indicative of a high water storage capacity of *C. africana*. This finding corroborates the results reported by (Gindaba et, al . (2004) , who noted that *C. africana* is drought-resistant and possesses adaptive mechanisms such as stomata closure and leaf shedding during moisture stress periods.

Such traits enable the species to conserve water under dry environmental conditions. Hence, the moisture content of *C. africana* is dependent on the wood anatomy and physiology of the species.

4.1.1.1. Two-way ANOVA of moisture content (%) of *Cordia africana*.

The two-way analysis of variance (Table 4.2) demonstrated that wood type significantly affected moisture content (F = 241.25, p < 0.0001). Therefore, there is a difference in the moisture capacity of sapwood and heartwood due to different physiological roles performed by the two types of wood. Sapwood is responsible for the main water transportation role, while heartwood comprises dead tissues containing less moisture. The effect of tree height was also found to be significant (F = 57.66, p < 0.0001), implying that the moisture content varied depending on tree height, which might have been caused by different wood maturity and physiological features at different tree heights. However, the effect of the interaction between wood type and tree height on moisture content was insignificant (F = 0.445, p = 0.6413), showing that the effect of tree height on moisture content was similar for both types of wood. Thus, wood type and tree height significantly affected the moisture content of *Cordia africana*, while their interaction did not.

4.1.1.2. Interaction Effect of Wood Type and Tree Height on Moisture Content

Figure 4.1. presents the interaction effect of wood type and tree height position on the moisture content of *Cordia africana*. Though there was no significant interaction effect between wood type and tree height, it is evident from the figure below that there is an observable trend of moisture distribution in the stem in the radial and longitudinal directions.

Top sapwood had the highest value of moisture content (136.72%) among all the treatment combinations and was grouped into Group A, thus having significantly higher moisture content than any other treatment combination. On the other hand, the bottom heartwood had the lowest moisture content (106.80%) and was grouped into Group D. Moisture content increased gradually from the bottom level (122.02%; Group BC), through the middle level (126.53%; Group B), to the top level (136.72%; Group A) in sapwood.

Similarly, there was a gradual increase in the moisture content from 106.80% at the bottom (Group D), through 109.31% at the middle (Group D), to 119.24% at the top (Group C) levels for heartwood. Bottom and middle heartwood were not significantly different because of their similar group letter. Top heartwood showed significantly higher moisture content than that at lower levels. This is further shown by the observation that the moisture content of the sapwood remained higher than that of the heartwood at each tree height. This shows the high radial variation in moisture distribution in the stems. Although there is some overlap in the groupings, it is evident that moisture content was higher in the sapwood and at higher levels of tree height.

The almost similar increase in moisture content with increasing tree heights for both sapwood and heartwood indicates why there was no significant interaction effect between tree heights and wood types. However, the figure clearly brings out the independent effects of the two on moisture distribution in *Cordia africana*.

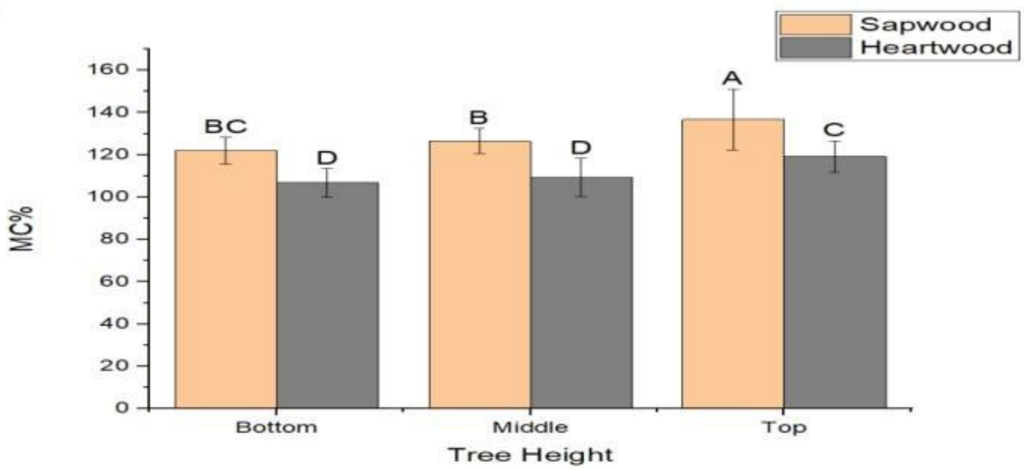


Figure 4.1. Interaction effect of wood type and tree height on the moisture content (%) of *Cordia africana*.

Note: Error bars represent standard deviation. Different letters indicate significant differences among means according to Tukey's HSD test ($p \leq 0.05$).

4.1.2. Basic density (kg/m³) of *Cordia africana* affected by wood type and tree height

The basic density of *Cordia africana* was determined in relation to wood type (sapwood and heartwood) and tree height (bottom, middle, and top).

Table 4.1. shows fluctuations in the basic density of *Cordia africana* across wood types and tree heights. It is clear that both wood type and stem longitudinal position affect basic density. In both sapwood and heartwood, basic density decreases from the bottom of the stem. In sapwood, the density decreases from about 485 kg/m^3 to 432 kg/m^3, while in heartwood, it decreases from approximately 506 kg/m^3 to 454 kg/m^3. The basic density of heartwood is always greater than that of sapwood at any height of the stem.

These variations are related to the process of wood formation and its structural characteristics, which increase wood density.

The results of the radial and longitudinal variation in densities lead to wide variations in density for this particular species, with density varying from around 432 kg /m³ up to around 506 kg /m³. Therefore, it can be concluded that for the particular tree in question, there exist both radial and longitudinal variations of density, where longitudinal variation leads to an upward decrease in density from the base upwards, while the radial variation leads to consistently higher density of heartwood.

The value of the basic density of *Cordia africana* determined in the current study is slightly higher than those found in earlier studies (Hamza et al., 2004; Desalegn et al., 2015;Elzaki et al., 2020).Forexample, according to Forest Products Utilization Research in Ethiopia, the density of *C. africana* was 410 kg /m³ at 12% moisture content(Desalegn et al., 2015), whereas the value reported in a Tanzanian study was 400 kg /m³ for the same species(Hamza et al., 2004). (Elzaki et al., 2020), found the average basic density of *C. africana* to be 410 kg/ m³. The current densities vary between 432 and 506 kg/ m³ owing to the radial and longitudinal variation in the stem, and it has been indicated that density is usually high in the heartwood part and decreases progressively from the bottom to the top of the tree.

4.1.2.1. Two-way ANOVA of basic density (kg/m³) of *Cordia africana*.

As can be seen from Table 4.2, the wood type and tree height had a significant impact on the basic density of *Cordia africana (p* < 0.0001). It is noted that there were differences in the density values of heartwood and sapwood, as well as in the density values of the bottom, middle, and top parts of the stem. Nonetheless, the interaction between the two factors did not show any significance ($p = 0.25779$), implying that tree height had an equal effect on the basic density for both wood types. The significant effect of the model ($p < 0.0001$) indicates the importance of the aforementioned factors.

4.1.2.2. Interaction of Wood Type and Tree Height on Basic Density

Figure 4.2. shows the interaction between wood type and tree height on the basic density of *Cordia africana*. Despite a lack of statistical significance (Table 4.1; $p = 0.25779$), the basic density reduced gradually from the bottom to the top part of the stem in both sapwood and heartwood. It was evident that heartwood had a higher density than sapwood irrespective of stem height position. The maximum basic

density was found in the bottom heartwood (506.37 ± 13.38 kg /m³) while the minimum density was found in the top sapwood (432.46 ± 27.35 kg/ m³).

Tukey's HSD test revealed that bottom heartwood belonged to group A, bottom sapwood and middle heartwood to group B, middle sapwood and top heartwood to group C, while top sapwood to group D. The relatively high density of heartwood can be explained by accumulation of extractives and mature wood tissues while low density towards the top is because of more juvenile wood. These results are consistent with the ANOVA analysis (Table 4.2.).

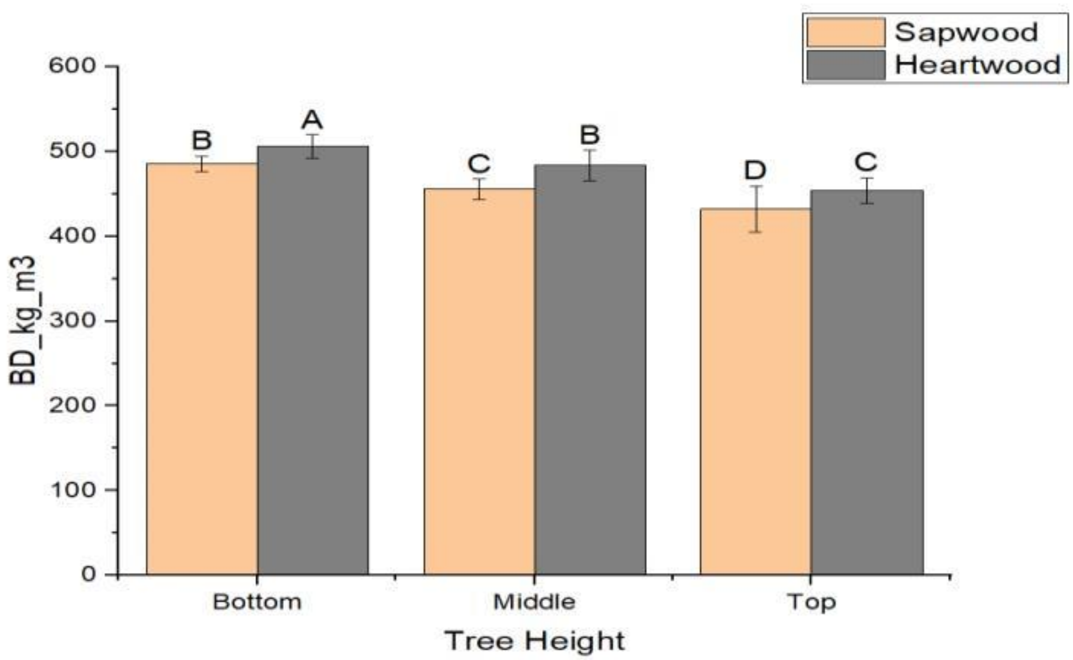


Figure 4.2. Interaction effects of wood type and tree-height position on basic density (kg/m³) of *Cordia africana*.

Note: Bars sharing the same letter are not significantly different according to Tukey's HSD test at $p \leq 0.05$.

4.1.3. Oven-dry density (kg /m³) of *Cordia africana as* affected by wood type and tree height position.

The descriptive statistics shown in Table 4.1 demonstrate a significant variability in oven-dry density of *Cordia africana* depending on wood type and height of the trees. Heartwood had a significantly higher mean oven-dry density than sapwood as a result of the different properties of this material. In both cases, oven-dry density decreased with an increase in the height from the bottom part to the upper part of the stem. In sapwood, the oven-dry density varied from 534 kg/ m³ in the bottom part to 469 kg/ m³ in the upper part of the stem, and in heartwood, from 553 kg/ m^3 to 488 kg/ m^3. The maximum value of oven-dry density was observed in the bottom part of the heartwood, while the minimum value was registered in the top part of the sapwood. Such a difference can be explained by the maturation and deposition of extractives in heartwood and by the water transportation functions of sapwood.

Since there are limited published studies on the longitudinal variation of the oven-dry density in *Cordia africana*, comparisons were made with studies reporting basic density. The present results are consistent with those of Mahonge (Mahonge, 2007), who observed a decline in wood density with increasing stem height in *Cordia africana* grown under agroforestry conditions in Tanzania. Likewise, reported that the basic density decreased from the butt section to the top of the stem. The consistency of these studies with the present findings suggests that the decrease in density from base to apex is a characteristic feature of *Cordia africana*, which is probably due to the greater proportion of mature wood in the lower stem and juvenile wood in the upper stem.

4.1.3.1. Two-way ANOVA of oven-dry density (kg/m^3) of *Cordia africana*.

The outcomes of the two-way ANOVA (Table 4.2) revealed that the oven-dry density of *Cordia africana* is significantly affected by both wood types and tree height positions. The effect of wood type on the oven-dry density was highly significant (F = 101.62, p < 0.0001). As can be seen from the analysis results, sapwood and heartwood have considerable differences in density. Such a differentiation is justified by the natural structure of the wood, which includes differences in extractive content and compactness. Tree height also has a highly significant effect on the oven-dry density (F = 271.22, p < 0.0001). It should be assumed that tree height affects the longitudinal variation along the stem. Different wood parts in the stem have different properties, and such properties affect the wood density.

On the other hand, the effect of the interaction between wood type and height of the tree was not significant (F = 2.60, p = 0.0764). The above observation suggests that the way density changes with the height of the stem remains the same whether it is the sapwood or the heartwood. Thus, even though density varies among wood types and height of the stem, its trend remains similar as one moves from the bottom to the top of the stem. Therefore, the results suggest that the density of wood depends on independent factors, which include wood type and height of the tree.

4.1.4. Interaction Effect of Wood Type and Tree Height on Oven-Dry Density

Figure 4.3 presents the interaction effect of wood type and tree height on the oven-dry density of *Cordia africana*. Although the interaction effect was not significant ($F = 2.60$, $p = 0.0764$), it is clear from the figure that the oven-dry density decreased gradually from the bottom to the top of the stem in both sapwood and heartwood. A higher density of heartwood as compared to sapwood was observed at all heights of the stem. The highest value of oven-dry density was found in bottom heartwood (552.70 ± 14.52 kg /m^3) and the lowest in top sapwood (468.89 ± 30.01 kg/ m^3).

As per Tukey's HSD test results, the bottom heartwood belongs to group A, the bottom sapwood and middle heartwood to group B, the middle sapwood and top heartwood to group C, and the top sapwood to group D. The identical decline in density at increased tree height in both wood types corroborates the non-significant interaction effect. Higher density in heartwood may be attributed to the deposition of extractives and the maturity of wood cells, while lower density in sapwood may be due to the role of sapwood in water transport. In general, the density values were high in the lower stem segments, reducing as one moves upwards, while there were significant main effects of wood species and tree height, but no significant interaction effect.

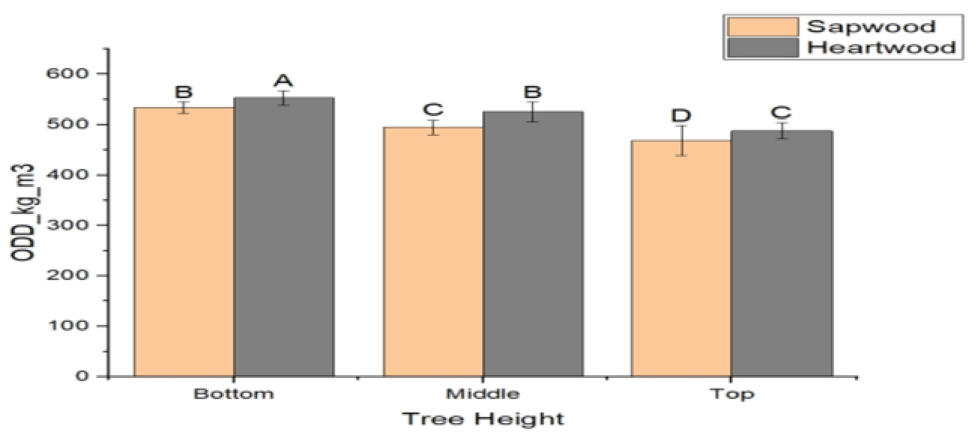


Figure 4.3. Interaction effect of wood type and tree height on oven-dry density (kg/m^3) of *Cordia africana*.

Note: Error bars represent standard deviation. Means sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.1.5. Radial Shrinkage (%) of *Cordia africana* as affected by wood type and tree height position

Radial shrinkage refers to the shrinking of wood in size along the radial orientation in the process of drying from the green stage to the oven-dry stage (Sandberg & Niemz, 2025). Radial shrinkage of *Cordia africana* was determined by its wood types and positions along the heights of the trees in Table 4.1.

Radial shrinkage of *Cordia africana*, as given by Table 4.1, revealed variation with respect to the type of wood and vertical height position in the stem. Overall, it was found that sapwood had greater radial shrinkage values compared to those of heartwood in both cases. The highest mean radial shrinkage occurred in bottom sapwood (3.26 ± 0.23%), while the lowest occurred in top heartwood (2.66 ± 0.11%). These values indicate that there exists variation in the dimensions of wood during drying depending on the type of wood.

In addition, radial shrinkage values showed a distinct decrease when progressing upwards from the bottom to the top of the stem in the case of both types of wood tissues. Radial shrinkage decreased from 3.26% at the bottom to 2.81% at the top of the stem in the case of sapwood and 2.87% to 2.66% in heartwood. This decrease in radial shrinkage could be attributed to wood maturity since woods at lower positions were relatively mature, hence underwent greater changes in dimensions when losing water.

In general, the variation in radial shrinkage was observed, the shrinkage decreases as the height of the stem increases in both sapwood and heartwood. These radial shrinkage rates are within the range described for *Cordia africana* in the PROTA database (3.4%) (Lemmens et al., 2012). This trend of observation is in accordance with the findings made previously that lower stem heights possess greater shrinkage, and it is directly proportional to the density of wood (Arzola-Villegas et al., 2019). Similarly, another study carried out on *Eucalyptus pellita* and its hybrids reported the greater dimensional change in wood samples with high density(Falade et al., 2025). Thus, in the current study, the trend of greater radial shrinkage at lower stem height is in line with what has been reported before.

From Ethiopia, hardwoods similar results were reported for *Acacia melanoxylon* grown in Chencha, Southern Ethiopia (Mussa & Bekele, 2019), where radial shrinkage green to 12% decreased from 2.38% at the bottom of the stem, to 1.93% at the middle, and 1.60% at the top. Tree height significantly influenced radial shrinkage, and the trend of change was the same as that of basic density. Wood density decreased from the bottom to the top of the stem, and shrinkage decreased accordingly. Hence, the increased radial shrinkage occurring at the lower stem can be explained by the existence of denser and more mature wood tissues than at the upper stem.

4.1.5.1. Two-way ANOVA of radial shrinkage (%) of *Cordia africana*.

From the analysis of variance (ANOVA) of two-way (Table 4.2), it can be concluded that there is a highly significant effect of wood type, tree height, and their interaction on radial shrinkage of *Cordia africana*. Wood type has shown a highly significant effect ($F = 154.91$, $p < 0.0001$) on radial shrinkage, implying that there is a variation in radial shrinkage of sapwood and heartwood in terms of dimensional change due to variation in moisture content (Dzurenda et al., 2023). Tree height has a highly significant effect ($F = 71.23$, $p < 0.0001$) on radial shrinkage since the amount of radial shrinkage changes with height due to variation in wood properties from one position to another along the height of the stem(Mussa & Bekele, 2019). It is worth noting that there is a highly significant interaction effect of wood type and tree height on radial shrinkage ($F = 9.33$, $p < 0.0001$).

4.1.5.2. Interaction Effect of Wood Type and Tree Height on Radial Shrinkage

Figure 4.4 depicts the interaction effect of wood type and tree height on the radial shrinkage of *Cordia africana*. Based on the results obtained from two-way ANOVA (Table 4.2), the interaction was statistically significant ($F = 9.33$, $p < 0.0001$), suggesting that the impact of tree height on radial shrinkage varied according to whether the wood type is sapwood or heartwood. Decrease in radial shrinkage was observed gradually from the bottom to the top of the stem for both wood types. Radial shrinkage of bottom sapwood reached its maximum value (3.26 ± 0.23%) while the minimum value (2.66 ± 0.11%) was found for the top heartwood. Generally, the sapwood had more radial shrinkage compared to the heartwood in all stem heights.

Based on Tukey's HSD test, the bottom sapwood was classified into group A, middle sapwood into group B, bottom heartwood into group C, top sapwood into group CD, middle heartwood into group DE, and top heartwood into group E. The greater decrease in radial shrinkage from the bottom to the top of the stem for sapwood is responsible for the interaction effect. This could probably be attributed to the moisture content being high in sapwood, hence the greater shrinkage when the wood dries. In general, there was reduction in radial shrinkage with an increase in tree height and was greater in sapwood than heartwood.

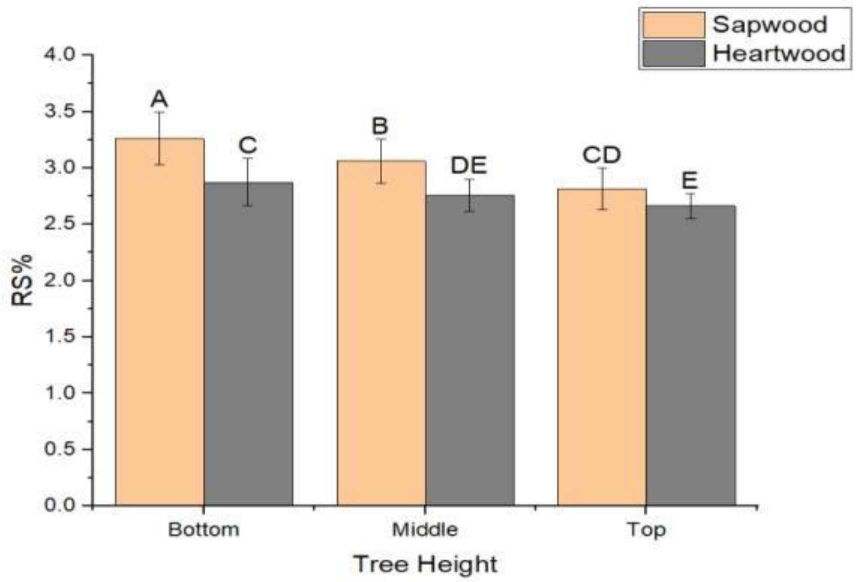


Figure 4.4. Interaction effect of wood type and tree height on radial shrinkage (%) of *Cordia africana*.

Note: Error bars represent standard deviation. Means sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.1.6. Tangential Shrinkage (%) of *Cordia africana* as affected by wood type and tree height position

The tangential shrinkage of the wood material is greater than the radial shrinkage and influences the dimensional stability of the wood.

Tangential shrinkage of *Cordia africana* depending on wood type and tree height is shown in Table 4.1. Tangential shrinkage proved higher than radial shrinkage, which is an essential measure of the stability of wood during drying(Fu et al., 2023). The values of tangential shrinkage varied from 5.10% to 6.10%, being maximum in the bottom sapwood (6.10 ± 0.18%) and minimum in the top heartwood (5.10 ± 0.15%). Generally, sapwood showed higher tangential shrinkage compared to that of heartwood at different tree heights. In both wood types, tangential shrinkage reduced gradually from the bottom to the top of the tree stem from 6.10% to 5.29% for sapwood and from 5.71% to 5.10% for heartwood. These differences can be accounted for by differences in wood maturation, development of cell walls, and structural features of wood in different parts of the stem(Gao et al., 2022). The coefficient of variation varied from 3% to 7%, suggesting low dispersion of results between treatments. As expected, tangential shrinkage was higher than radial shrinkage due to the anisotropy of wood.

The results of this study on tangential shrinkage are in line with the findings of (Mussa & Bekele, 2021a), who reported a significant decrease in tangential shrinkage from bottom to top of *Acacia melanoxylon* stems. They reported tangential shrinkages of 4.34%, 3.60%, and 3.47% for the bottom, middle, and top portions, respectively. The authors stated that the tangential shrinkage was positively correlated with the wood density, which decreased with increasing tree height. The higher density and maturity of the wood were therefore considered responsible for the higher tangential shrinkage at the base of the stem. Similar mechanisms may account for the difference observed in the present study. In comparison, the current result of tangential shrinkage of *Cordia africana* is more stable than green to oven dried, 5.7% from PORTA (Lemmens et al., 2012).In this, the effect of tangential shrinkage of *Cordia africana* depends on wood type and tree height.

4.1.6.1. Two-way ANOVA for tangential shrinkage (%) of *Cordia africana*

The findings from the two-way ANOVA showed that tangential shrinkage of *Cordia africana* wood was significantly influenced by wood type, tree height, and interaction. Wood type was found to have a very significant influence (F = 90.64, p < 0.0001), which is an indication that there were variations in the drying process in sapwood and heartwood. There was a very significant influence of tree height (F = 182.02, p < 0.0001), which implies that there were variations in tangential shrinkage along the stem of the tree. There was significant interaction (F = 3.45, p = 0.0331).

4.1.6.2. Interaction Effect of Wood Type and Tree Height on Tangential Shrinkage (%)

As can be observed from Figure 4.5, the tangential shrinkage reduced gradually from the base to the top of the stem for both sapwood and heartwood samples. The maximum tangential shrinkage was observed in the bottom sapwood, while the minimum shrinkage occurred in the top heartwood. Tukey's HSD test categorized the bottom sapwood in group A and the top heartwood in group D, showing significantly high and low tangential shrinkages, respectively. This could be due to the high moisture content in the case of sapwood and deposition of extractives in heartwood, limiting water movement in the latter case. The decreasing shrinkage towards the upper stem could also be because of the difference in wood structure, density, and development of cell walls. Thus, tangential shrinkage depended on both wood type and tree height, where heartwood and upper stem wood showed more stability.

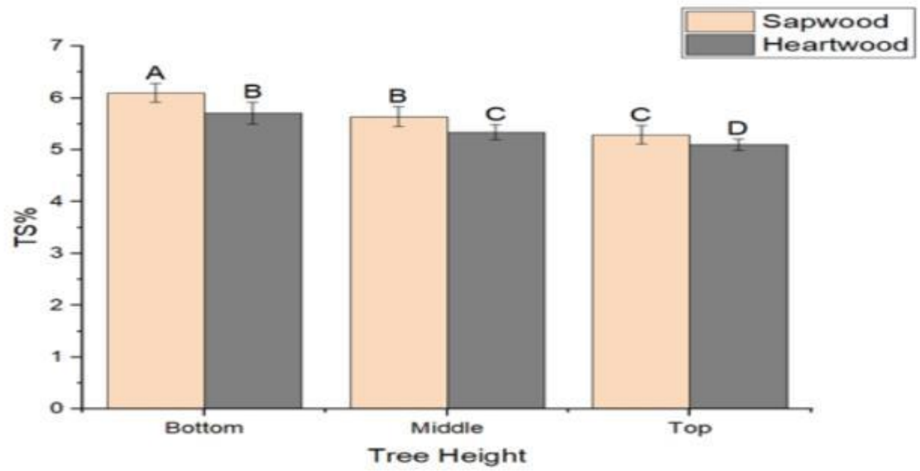


Figure 4.5. Interaction effect of wood type and tree height on tangential shrinkage (%) of *Cordia africana*.

Note: Error bars represent standard deviation. Means sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.1.7. Longitudinal Shrinkage (%)of *Cordia africana* as affectedby wood type and tree height position

Longitudinal shrinkage denotes the decrease in the dimension of wood in the longitudinal direction as it loses moisture content from its green form to its dry form. The *Cordia africana* longitudinal shrinkage is examined in Table 4.1.

The impact of wood species and height of the tree on longitudinal shrinkage in *Cordia africana* is provided in Table 4.1. The longitudinal shrinkage, which is along the grain, was much smaller than radial and tangential shrinkage as the wood fibers run parallel to the stem axis. Longitudinal shrinkage varied from 0.09% to 0.13%, with the maximum mean being in top sapwood (0.13 ± 0.01%) and minimum in bottom sapwood (0.09 ± 0.02%). The same pattern was found for heartwood, in which longitudinal shrinkage varied from 0.09 ± 0.03% (bottom) to 0.12 ± 0.01% (top).

In contrast to radial and tangential shrinkage, longitudinal shrinkage became greater towards the top than the bottom of the stem for both woods. This can be explained by the higher presence of juvenile wood at the top of the stem, where a bigger microfibril angle leads to greater longitudinal dimensional changes while drying. Differences between sapwood and heartwood were quite insignificant; however, sapwood had higher longitudinal shrinkage than heartwood in middle and top stem position. The relatively high coefficients of variation in some treatments, especially in the bottom of the stem, suggest that longitudinal shrinkage is more variable than any other shrinkage properties. Generally speaking, longitudinal shrinkage depends on the tree height and remains rather low in comparison with radial and tangential shrinkage.

This finding, the increase of the longitudinal shrinkage from the bottom to the upper parts of the stem observed in the present study, agrees with (Zhang et al., 2021), who reported that the longitudinal shrinkage increased with log height, while the transverse shrinkage decreased. This variation was attributed to the differences in wood characteristics related to stem position.

4.1.7.1. Two-Way ANOVA Analysis for Longitudinal Shrinkage

The outcome of the two-way analysis of variance (Table 4.2) indicates that wood type and tree height have a significant influence on longitudinal shrinkage of *Cordia africana*. Wood type showed a significant effect ($F = 6.57$, $p = 0.0109$). This implies that there were minor variations in longitudinal shrinkage among sapwood and heartwood samples. Tree height indicated a highly significant effect ($F = 78.30$, $p < 0.0001$). This means that there is an increase in longitudinal shrinkage from the bottom to the top of the stem because of variations in wood maturation and microfibril angle. Furthermore, interaction between wood type and tree height proved to be significant ($F = 3.38$, $p = 0.0354$). This suggests that there is a difference in the effect of tree height between sapwood and heartwood.

4.1.7.2. Interaction Effect of Wood Type and Tree Height on Longitudinal Shrinkage

As indicated in Figure 4.6, there was an increase in longitudinal shrinkage from the base to the tip of the tree in both sapwood and heartwood. The maximum longitudinal shrinkage was found in the top sapwood (0.13%) followed by the top heartwood (0.12%), but the minimum longitudinal shrinkages were found in the bottom part of both the wood types (approximately 0.09%). Grouping of treatment combinations using the Tukey's HSD test showed the top sapwood, top heartwood, and middle sapwood in Group A, while bottom sapwood and bottom heartwood were in Group C. Although significant differences were observed amongst the treatment combinations, longitudinal shrinkage was far lower compared to radial and tangential shrinkages due to orientation of wood fibers along the longitudinal axis of the stem. It is therefore believed that greater longitudinal shrinkages observed in the top stem may be due to high content of juvenile wood and large microfibril angle. Overall, the dimensionally stable nature of longitudinal shrinkage in *C. africana* makes it useful for constructional and joinery purposes.

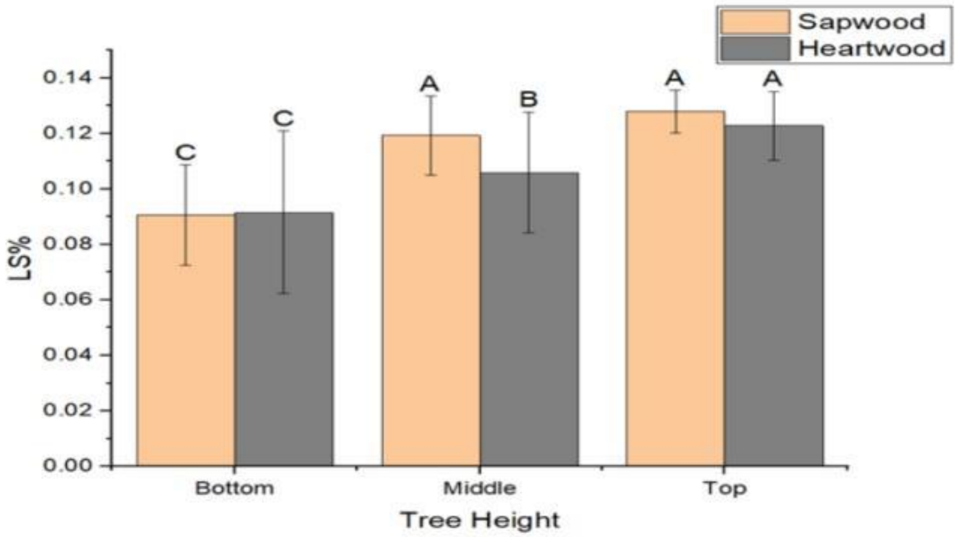


Figure 4.6. Interaction effects of wood type and tree height on longitudinal shrinkage (%) of *Cordia africana*.

Note: Error bars represent standard deviation. Means sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.1.8. Volumetric Shrinkage (%) of *Cordia africana* as affected by wood type and tree height position

Volumetric shrinkage is the total volume reduction of wood when it is dried from the green to the oven-dry condition. As it reflects the combined effect of radial, tangential, and longitudinal shrinkage. Thus, the understanding of volumetric shrinkage is dependent on the evaluation of drying performance, processing characteristics, and end-use suitability of wood.

In Table 4.1, the volumetric shrinkage of *Cordia africana* was observed to be between 7.72 ± 0.20% and 9.19 ± 0.29%, with the maximum value recorded in the bottom sapwood and the minimum in top heartwood. In general, volumetric shrinkage decreased from the bottom to the top of the stem for both wood types, suggesting that the lower parts of the stem were more affected by dimensional change. At all height levels, sapwood consistently showed higher volumetric shrinkage than heartwood. Low coefficients of variation (2.27–6.03%) indicate good consistency of measurements within groups.

The values obtained are within the range reported for *Cordia africana* (7.3-11.8%) from green to oven dry status. Similar trends were found in Ethiopian-grown Acacia melanoxylon, where volumetric shrinkage was highest at the base of the stem and decreased towards the top of the tree with wood density (Mussa & Bekele, 2021a). The authors also found that the decrease in shrinkage with increasing tree height was accompanied by a similar decrease in wood density. In this sense, the higher volumetric shrinkage of the lower stem positions in the present study is likely related to the higher density of wood in the basal part of the stem, supporting the positive relationship between density and shrinkage reported in the literature.

4.1.8.1. Two-way ANOVA for volumetric shrinkage (%) of *Cordia africana*

As indicated by the findings from the two-way ANOVA, the volumetric shrinkage of the *Cordia africana* wood was significantly influenced by the wood type, tree height, and their interaction. Wood type was a factor with a highly significant influence ($F = 197.57$, $p<0.0001$) on the volumetric shrinkage of *Cordia africana* because there were clear distinctions between the sapwood and heartwood regarding volumetric shrinkage in the drying process. Tree height was a highly significant factor ($F = 192.62$, $p<0.0001$) since there was variation in the volumetric shrinkage from the bottom to the top of the tree stem. The interaction between wood type and tree height was highly significant ($F = 5.38$, $p = 0.0051$).

4.1.8.2. Interaction Effect of Wood Type and Tree Height on Volumetric Shrinkage (%) of *Cordia africana*

As indicated in Figure 4.7, volumetric shrinkage gradually declined from the base to the tip of the stem in both the sapwood and heartwood of the stem. The maximum volumetric shrinkage value was attained at the bottom sapwood (9.2%), while the minimum volumetric shrinkage was obtained at the top heartwood (7.7%). Tukey's HSD revealed that the bottom sapwood belonged to group A and the top heartwood belonged to group D, while the rest of the treatments fell in between these two groups. In this case, the trend in volumetric shrinkage followed the trend in radial and tangential shrinkage, as volumetric shrinkage depends on these two components.

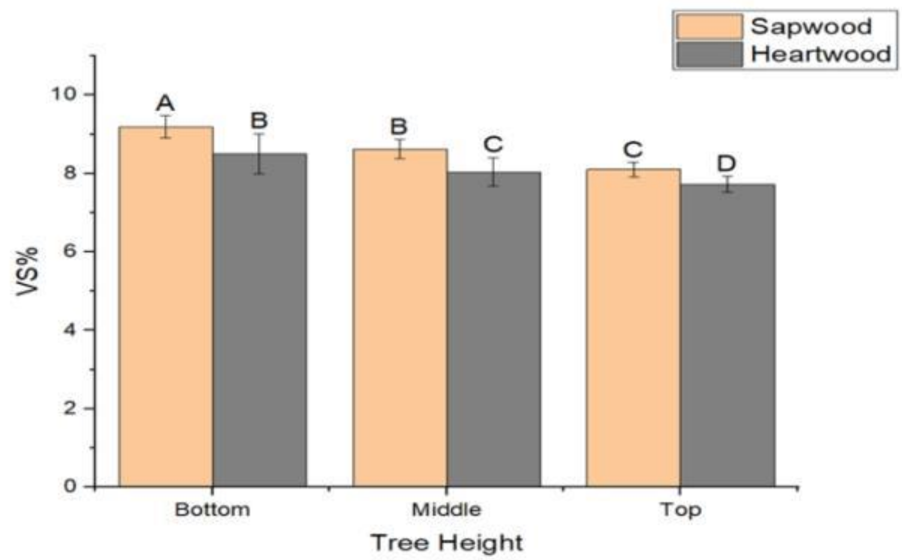


Figure 4.7. Interaction effect of wood type and tree height on volumetric shrinkage (%) of *Cordia africana*.

Note: Error bars represent standard deviation. Means sharing the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.1.9. Radial Swelling (RSW %) of *Cordia africana* as affected by wood type and tree height position

Radial swelling refers to the enlargement of wood in a radial direction caused by moisture absorption at levels below the fiber saturation point. It is a critical measure of dimensional stability since excessive swelling results in warping and product degradation(Thybring et al., 2022). The present study sought to determine the effects of wood type and tree height on the radial swelling of *Cordia africana*.

Descriptive statistics of radial swelling (RSW%) of *Cordia africana* as influenced by wood type and tree height are presented in Table 4.1. The values of radial swelling varied between 2.66 ± 0.13% and 3.31 ± 0.24%, where the largest value was obtained in bottom sapwood and the smallest in top heartwood. For sapwood, radial swelling varied between 3.31% in bottom to 2.72% in top, while for heartwood, radial swelling varied from 2.88% to 2.66%. Radial swelling was larger in sapwood than in heartwood for all heights of stem, signifying greater dimensional change.

The reduction of radial swelling with increasing stem height agrees with the results of a study conducted on Acacia melanoxylon grown in Ethiopia. The study found that the swelling and shrinkage properties were the highest at the base of the stem and the lowest in the upper parts of the stem (Mussa & Bekele, 2021a). Likewise, (Hernández (2007) reported a wide range of swelling properties among tropical hardwoods and found wood density as the main factor positively influencing the transverse and volumetric swelling. Thus, the higher radial swelling at lower stem positions found in this study is consistent with the general pattern reported for hardwood species, where the magnitude of dimensional changes decreases from the stem base to the top and is influenced by wood density and related wood properties.

4.1.9.1. Two-way ANOVA for radial swelling (%) of *Cordia africana*

The outcomes of the two-way ANOVA (Table 4.2) reveal that radial swelling of *Cordia africana* depends significantly on wood type, tree height, and their interaction. Wood type is a highly significant factor in radial swelling ($F = 164.57$, $p < 0.0001$) because there are different swelling characteristics of sapwood and heartwood. Tree height is a highly significant factor ($F = 122.45$, $p < 0.0001$) because there are changes in swelling throughout the height of the tree. The interaction of wood type and tree height is a significant factor ($F = 26.26$, $p < 0.0001$), which means that the influence of tree height is not the same for sapwood and heartwood.

4.1.9.2. Interaction Effect of Wood Type and Tree Height on Radial Swelling (%) of *Cordia africana*

Figure 4.8 indicates that radial swelling progressively decreased from the base to the top of the stem for both wood types, where sapwood demonstrated relatively high swelling while heartwood had relatively low swelling. Tukey's HSD test indicated that bottom sapwood belongs to group A with the highest swelling, followed by middle sapwood (group B), bottom heartwood (group C), and other treatments (group D). Higher swelling of sapwood can be associated with increased moisture absorbency and reduced content of extractives, while higher stability of heartwood is linked to the deposition of extractives, which decreases moisture absorbency. Lower swelling towards the upper stem can be associated with changes in the wood anatomical structure and development. Generally, radial swelling was regulated by the interaction effect of wood type and tree height, where bottom sapwood demonstrates relatively high swelling and top heartwood demonstrates relatively low swelling.

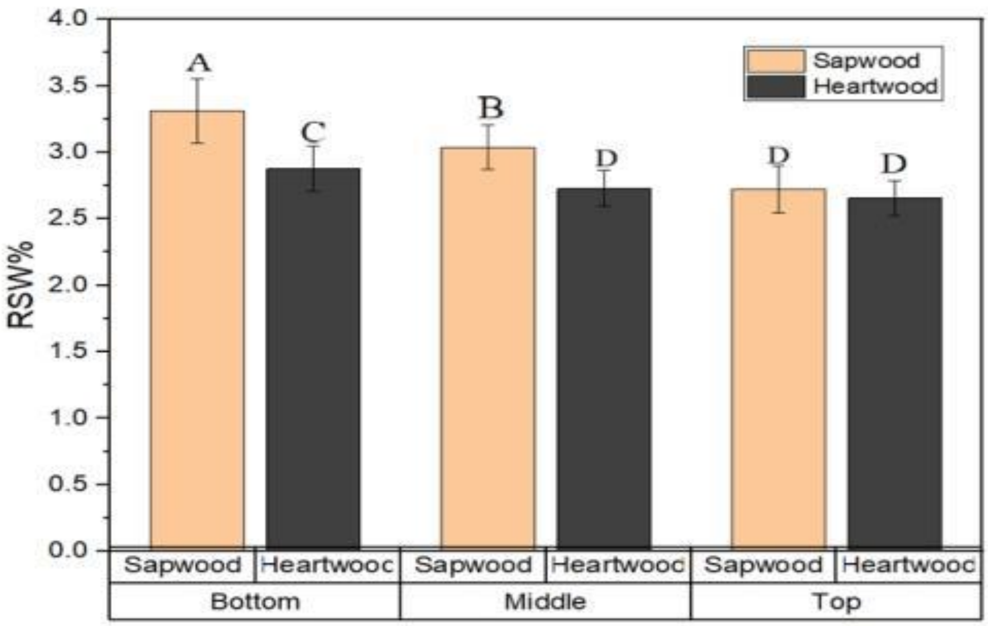


Figure 4.8. Interaction effects of wood type and tree height on radial swelling (%) of *Cordia africana*.

Note: Error bars indicate standard deviation (±SD). Different letters above bars indicate significant differences at $p < 0.05$ based on Tukey's HSD test.

4.1.10. Tangential Swelling (%) of *Cordia africana* as affected by wood type and tree height position

Tangential Swelling occurs as a result of the increase in size of wood fibers in the tangential plane as a result of water absorption. Tangential swelling of *Cordia africana* was assessed based on the type of wood and the height of the tree. Findings are presented in Table 4.1.

The descriptive statistics for TSW% of *Cordia africana* with respect to wood type and tree height are as shown in Table 4.1. The TSW% ranged from 5.10% to 6.09% with maximum occurring in bottom sapwood (6.09%) and minimum in top heartwood (5.10%). Tangential swelling reduced progressively from bottom to top for both wood types, but tangential swelling was relatively higher in sapwood compared to heartwood for all stem positions.

The results obtained in the present study agree with those reported for tropical hardwood species. Shukla & Kamdem ,(2010), studied nine tropical hardwoods of Cameroon and reported that tangential swelling was always higher than radial swelling and varied among species according to density and anatomical characteristics. The authors also observed the positive correlation between wood density and swelling, indicating that drier woods have greater dimensional changes during moisture acceptance. This observation is in agreement with the results of the present study, where higher tangential swelling was observed at the bottom portion of the stem which also had higher oven dry density.

Conversely, the gradual decrease in tangential swelling from bottom to top of the stem is in agreement with the decrease in wood density observed along the longitudinal axis of the tree.

4.1.10.1. Two-way Analysis of variance (ANOVA) for tangential swelling (%) of *Cordia africana* as affected by wood type and tree height

From the results of the ANOVA test (Table 4.2), it was clear that tangential swelling of *Cordia africana* was influenced by the type of wood, tree height, and their interaction. The type of wood had a highly significant influence ($p < 0.0001$) on the behavior of tangential swelling of the wood species, which meant that there were significant differences in the swelling behavior of sapwood and heartwood. The tree height had a highly significant influence ($p < 0.0001$) on the tangential swelling. The interaction between wood type and tree height had a significant influence ($p = 0.0302$).

4.1.10.2. Interaction Effect of Wood Type and Tree Height on Tangential Swelling (%) of *Cordia africana*

In Figure 4.9, we see the interaction effect of wood type and tree height on tangential swelling of *Cordia africana*. It can be seen that there is a decreasing trend in tangential swelling as we move from bottom to top positions in the stem for both sapwood and heartwood. Bottom sapwood has shown the highest tangential swelling value (6.09%), followed by middle sapwood (5.64%) and top sapwood (5.29%). Similarly, bottom heartwood has the highest tangential swelling value (5.71%), which decreases to middle (5.34%) and top heartwood (5.10%).

Based on Tukey's HSD test results, bottom sapwood (A) has the highest and significantly different swelling value compared to other combinations. Middle sapwood (B) and bottom heartwood (B) have statistically similar values, while middle heartwood (C) has slightly lower values than these combinations. The lowest swelling has been observed in the top heartwood (D).

In summary, the figure shows that sapwood normally swells more tangentially than heartwood, while the swelling reduces with height in the stem. In other words, the stability of *Cordia africana* depends on both the type of wood and the height of the tree, which is the least stable.

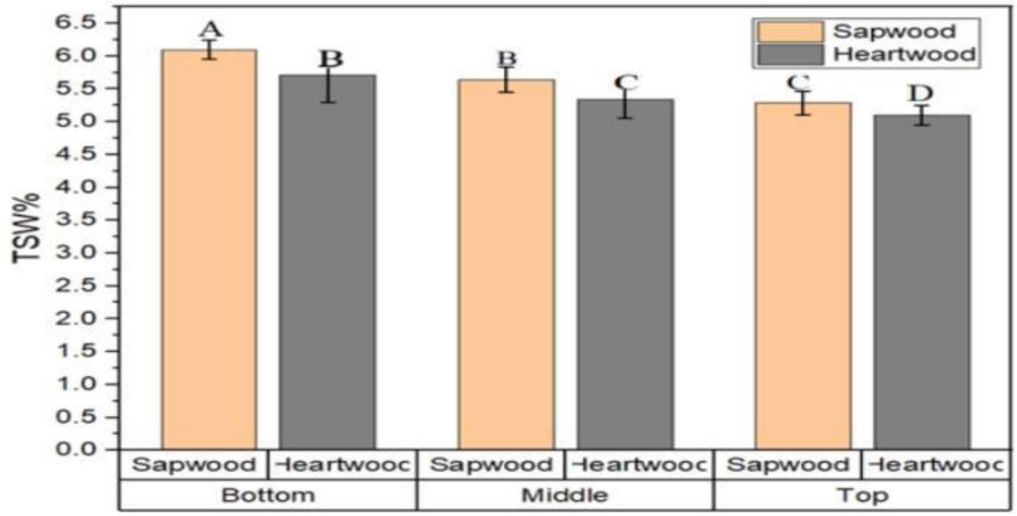


Figure 4.9. Interaction effects of wood type and tree height on tangential shrinkage (%) of *Cordia africana*.

Note: Error bars represent standard deviation. Means followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.1.11. Longitudinal Swelling (%) of *Cordia africana* as affectedby wood type and tree height position.

Thybring et al.(2022) say that longitudinal swelling is the dimensional increase in the direction of the grain in wood and is usually small because of the orientation of the fibers. If too much swelling occurs, distortion can happen. The findings are presented in Table 4.1**.**

Table 4.1 shows the descriptive statistics of longitudinal swelling (%) of *Cordia africana* in relation to the wood type and tree height. Longitudinal swelling was minimal in all the treatments ranging from 0.09% to 0.12%, meaning that there was little dimensional variation as compared to radial and tangential swellings. Longitudinal swelling increased progressively from bottom to the top of the stem for both sapwood and heartwood samples. Maximum longitudinal swelling was observed in the top sapwood (0.115%) while minimum was observed in the bottom heartwood (0.092%).

The differences in swelling along the stem height might result from the differences in the degree of wood maturity and its microfibril angle. The upper parts of the stem usually have more juvenile wood, which swells considerably while taking in moisture. On the other hand, the bottom stem parts are made up of more mature wood that has a stable structure and shows minimal swelling values(Lachenbruch et al., 2011)&(Walker, 2006). From the variation coefficient values, it is clear that there is little variability between measurements. Thus, the measurements have acceptable precision. In summary, it can be stated that the longitudinal swelling of *Cordia africana* is poor but still dependent on wood types and stem heights, with increased values of swelling in sapwood and upper stem parts.

4.1.11.1. Two-way ANOVA Analysis of variance (ANOVA) for longitudinal swelling (%) of *Cordia africana* as affected by wood type and tree height

As illustrated in Table 4.2, the analysis of variance revealed that the longitudinal swelling of *Cordia africana* was significantly influenced by the tree height, whereas wood type and the interaction of wood type with tree height were not significantly influential. The influence of tree height was found to be highly significant ($p<0.0001$), implying that there was variation in the longitudinal swelling along the stem from bottom to top. Wood type ($p=0.23045$) and interaction of wood type with tree height ($p=0.91105$) did not show any significant influences.

4.1.11.2. Interaction effect of wood type and tree height on longitudinal swelling (%) of *Cordia africana*

In Figure 4.10, it is clearly visible that longitudinal swelling increases gradually from the base to the apex of the stem for both sapwood and heartwood. The maximum value was obtained in top sapwood (0.115%) and top heartwood (0.113%), whereas the minimum value was found in bottom heartwood (0.092%). According to the results of Tukey’s HSD test, top sapwood and top heartwood were grouped into group A, while the groups of middle sapwood and heartwood were put into B, showing similar values. Bottom sapwood and bottom heartwood had lesser swellvalues. Tree height affects longitudinal swelling more than the type of wood.

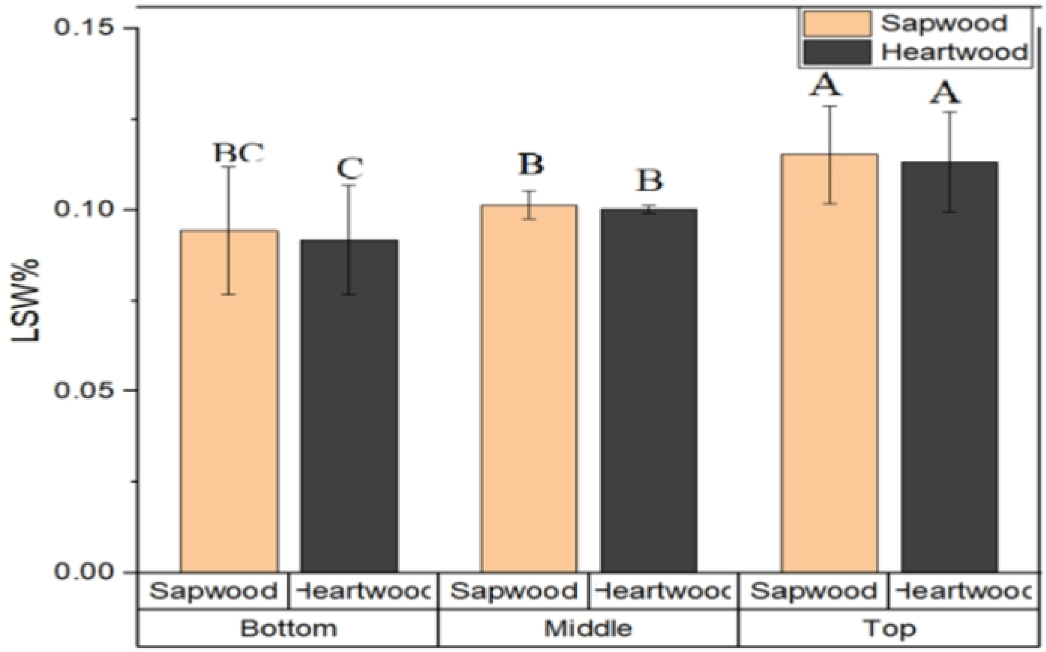


Figure 4.10. Interaction effect of wood type and tree height on longitudinal shrinkage (%) of *Cordia africana*.

Note: Error bars represent standard deviation. Means followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test

4.1.12. Volumetric Swelling (%) of *Cordia africana* as affected by wood type and tree height position.

Swelling in volume refers to the total change in volume of the wood due to water absorption. Results of volumetric swelling are provided in Table 4.2 and Figure 4.11.

Descriptive statistics of volumetric swelling (VSW%) of *Cordia africana* as affected by wood type and stem height are presented in Table 4.2. Volumetric swelling ranged between 8.13% to 9.73%, with the maximum swelling in the bottom sapwood and the minimum in the top heartwood. For both wood types, volumetric swelling decreased gradually from the bottom to the top of the stem. Swelling was always higher for sapwood compared to heartwood at each point of the stem, suggesting that the dimension changes were greater in response to moisture content changes. Such differences may be ascribed to the differences in wood maturity and wood anatomy. Volumetric swelling was therefore affected by wood type and tree height.

4.1.12.1. Two-way Analysis of variance (ANOVA) for volumetric swelling (%) of *Cordia africana* as affected by wood type and tree height

The results of variance analysis (ANOVA) indicated that the volumetric swelling of the *Cordia africana* timber was significantly influenced by wood type and tree height (Table 4.2).

The effect of wood type on volumetric swelling was highly significant ($p < 0.0001$), suggesting that sapwood and heartwood swell differently. Tree height was also shown to have a highly significant effect ($p < 0.0001$), implying that volumetric swelling changes in a height-wise gradient from bottom to top stem positions.

Moreover, an interaction effect between wood type and tree height was highly significant as well ($p < 0.001$). The above results imply that the effect of tree height on volumetric swelling was dependent on wood type, and thus, volumetric swelling changes in a different way in sapwood compared to heartwood. As follows, the volumetric swelling of *Cordia africana* wood was influenced by wood type, tree height, and their interaction.

4.1.12.2. Interaction effect of wood type and tree height on volumetric swelling (%) of *Cordia africana*

Figure 4.11 shows the interactive effects of wood type and tree height on volumetric swelling of *Cordia africana*. Volumetric swelling progressively declined from the bottom to the top of the stem for both sapwood and heartwood. Bottom sapwood registered the highest volume swelling (9.73%) followed by middle sapwood (9.03%) and top sapwood (8.37%). Likewise, heartwood was high at the bottom (8.98%) but low at the top (8.13%).

As per the results of Tukey's HSD test, bottom sapwood fell into category A, which had higher swelling compared to the other categories. Middle sapwood and bottom heartwood were grouped in category B, while middle heartwood, top sapwood, and top heartwood were in category C. Overall, sapwood showed more volumetric swelling than heartwood.

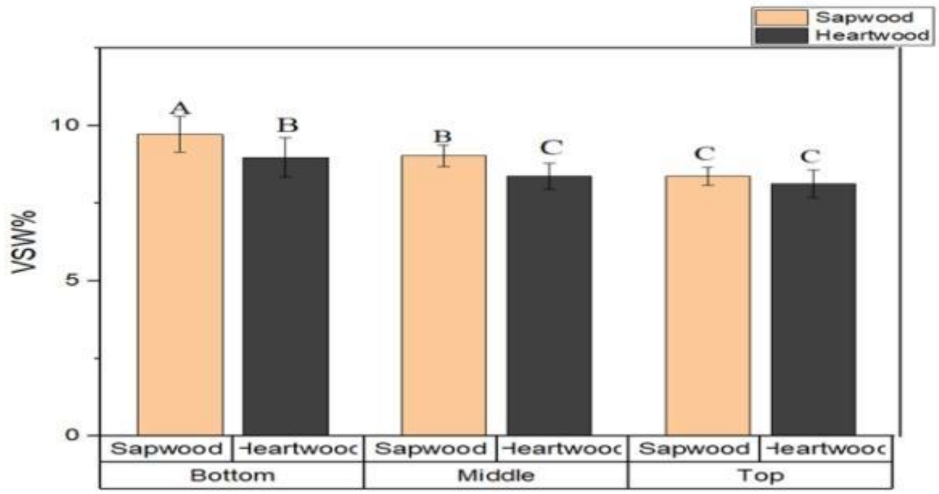


Figure 4.11. Interaction effect of wood type and tree height on volumetric swelling (%) of *Cordia africana*.

Note: Error bars represent standard deviation. Means followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.2. Mechanical properties of *Cordia africana*

Properties related to the mechanical behavior of wood depend on the anatomy, density, and moisture content of wood (Arriaga et al., 2023). This study performed mechanical tests using 12% moisture content of wood in order to provide consistency of strength properties in different woods and different parts of the stem. Information about strength and stiffness of *Cordia africana* wood is important for structural and furniture purposes.

Table 4.3. Descriptive statistics (Mean ± SD) of the mechanical properties of *Cordia africana* as affected by wood type and stem position (at 12% moisture content)

Property	N	Bottom SW	Bottom HW	Middle SW	Middle HW	Top SW	Top H
CS (N/mm^2)	45	40.47 ± 3.30	47.07 ± 5.23	38.32 ± 3.31	44.65 ± 4.41	36.01 ± 1.57	41.31 ± 3.61
MOR (N/mm^2)	45	77.27 ± 9.78	81.11 ± 9.22	68.14 ± 5.29	78.29 ± 10.86	65.15 ± 4.25	68.22 ± 5.33
MOE (N/mm^2)	45	5708.12 ± 443.35	6281.32 ± 334.27	5205.41 ± 335.72	5378.27 ± 453.96	4619.62 ± 269.97	4930.32 ± 397.13

IS (N·m/m²)	45	71666.67 ± 9992.90	78055.56 ± 12237.46	65555.56 ± 8471.86	72416.67 ± 14998.58	63011.11 ± 7226.64	64777.78 ± 8864.07
RH (N)	45	3461.56 ± 171.42	3690.00 ± 255.49	3368.00 ± 149.07	3643.56 ± 208.63	3265.78 ± 156.31	3493.42 ± 196.41
TH (N)	45	3322.00 ± 166.52	3587.56 ± 332.69	3269.33 ± 166.66	3488.22 ± 214.72	3219.78 ± 187.10	3436.67 ± 276.02

Notes

- Values are presented as Mean ± Standard Deviation (SD).
- N = 45 specimens for each wood type × stem position combination.

Table 4.3 shows the descriptive statistics of mechanical properties of *Cordia africana* at 12% moisture content according to wood type (sapwood and heartwood) and stem position (bottom, middle, and top). Generally, the heartwood exhibited higher mean values than the sapwood for all the mechanical properties studied such as compression strength, modulus of rupture, modulus of elasticity, impact strength and hardness. Moreover, mechanical properties generally decreased from bottom to top stem position indicating the influence of longitudinal variation within the tree. The highest mechanical performance was observed in bottom heartwood and the lowest values were mostly observed in top sapwood. The observed differences indicate that the mechanical behavior of *Cordia africana* is influenced by the type of wood and the stem position. The detailed interpretation of each mechanical property is discussed in the following sections.

Table 4.4. Two-way ANOVA for the mechanical properties of *Cordia africana*

Property	Source	df	SS	MS	*F-value*	*P*-value
CS	Wood type	1	2490.98	2490.98	177.53	<0.0001
	Tree height	2	1179.07	589.54	42.01	<0.0001
	Interaction	2	21.28	10.64	0.76	0.47
MOR	Wood type	1	2180.98	2180.98	35.07	<0.0001
	Tree height	2	7041.11	3520.55	56.61	<0.0001
	Interaction	2	679.67	339.84	5.46	0.001
	Wood type	1	8375585.65	8375585.65	58.59	<0.0001
	Tree height	2	67469700.00	33734850.00	236.00	<0.0001

MOE	Interaction	2	1861312.46	930656.23	6.51	0.001
IS	Wood type	1	1691250000.00	1691250000.00	14.99	<0.0001
	Tree height	2	5421250000.00	2710625000.00	24.02	<0.0001
	Interaction	2	356560000.00	178280000.00	1.58	0.21
RH	Wood type	1	4014776.95	4014776.95	107.82	<0.0001
	Tree height	2	1779196.56	889598.28	23.89	<0.0001
	Interaction	2	33866.79	16933.39	0.45	0.6351
TH	Wood type	1	3689013.33	3689013.33	68.42	<0.0001
	Tree height	2	730445.19	365222.59	6.77	0.00135
	Interaction	2	34126.67	17063.33	0.32	0.72898

Table 4.4 shows the results of the two-way ANOVA carried out to investigate the effects of wood types, tree heights, and their interaction on the mechanical properties of *Cordia africana*. Wood type and tree height significantly affected ($p < 0.05$) all mechanical properties tested, implying that these two factors have an important effect on the mechanical performance of the wood. However, the interaction of wood types and tree heights was significant only in the modulus of rupture (MOR) and modulus of elasticity (MOE), but was insignificant in compression strength (CS), impact strength (IS), radial hardness (RH), and tangential hardness (TH). This implies that the effect of wood types and tree heights is independent for most mechanical properties except MOR and MOE, where the combination of the two has a significant effect on t

4.2.1. Compression Strength (N/mm²) Parallel to grain of *Cordia africana* as affected by wood type and tree height position at 12% moisture content.

The compression strength of wood in the direction of the grain denotes its resistance to loads acting in the direction of the grain and is essential in the load-carrying capacity of wood (Totsuka et al., 2022).In this experiment, the effects of wood types (sapwood and heartwood) and tree height (bottom, middle, and top) on the compression strength of *Cordia africana* were investigated. Table 4.22 presents the variation in compression

Table 4.3 provides the variations in the compressive strength of *Cordia africana* wood in the direction of the grain as affected by type and height of the stem at 12% moisture content. The highest compressive strength was observed in bottom heartwood (47.07 N/mm²) compared to the lowest value observed in top sapwood (36.01 N/mm^2). It is clear that the compressive strength of heartwood was higher than that of sapwood, and that the compressive strength decreased from the bottom to the top of the stem.

The results from the Ethiopian Forest Products Utilization Laboratory, which reported an average compression strength parallel to grain of approximately 29 N/mm^2 at 12% moisture content for the species *Cordia africana*, are consistent with this finding, indicating its moderate structural capacity and high variability according to stem position and wood maturity(Desalegn et al., 2015).

Similarly, studies on Tanzania showed lower values of compression strength of *Cordia africana* with an average of about 23.5 N/mm^2(Hamza et al., 2004), suggesting relatively weak performance in samples affected by a higher proportion of juvenile wood and lower density. Besides, research from the Kilimanjaro (Moshi) region had a compression strength of about 27.11 N/mm^{2,} confirming that the species is generally in a moderate strength class under East African conditions, with strength that is heavily dependent on growth site and variation in wood density along the stem (Mosha, 1999). When comparing the results of the present study with those of Ethiopia and Tanzania, it is noted that the higher values in the present study (41.30 N/mm^2) refer to sampling from mature heartwood and lower stem regions, which are known to have better mechanical performance and higher density.

4.2.1.1. Two-way ANOVA for compression strength parallel to grain (N/mm^2) of *Cordia africana* as affected by wood type and tree height

Results from ANOVA (Table 4.4) indicated that compression strength in the direction of the grain in *Cordia africana* was significantly influenced by the wood type and tree height. Wood type was a highly significant factor (F = 177.53, p < 0.0001), suggesting the influence of differences in the anatomical features of sapwood and heartwood, density, and cell wall construction. Tree height was also a significant factor (F = 42.01, p < 0.0001), showing the decrease in compression strength along the tree trunk. The interaction of wood type and tree height was not significant (F = 0.76, p = 0.4696).

4.2.1.2. Interaction effect of wood type and tree height on compression strength parallel to grain (N/mm^2) of *Cordia africana*

The influence of wood type and tree height on the compression strength parallel to grain of *Cordia africana* is presented in Figure 4.12. The data revealed that compression strength decreased gradually from the base to the apex of the stem regardless of whether it is sapwood or heartwood. Additionally, heartwood had a higher compression strength than sapwood at all the stem parts. A similar trend of higher compression strength in heartwood has been observed for Ethiopian hardwood *Senegalia caffra,* where mechanical properties differed according to the stem height (Waktole et al., 2025).

The highest value of compression strength was obtained at the bottom stem part for heartwood (47.07 N/mm²), middle heartwood (44.65 N/mm²), and top heartwood (41.31 N/mm²). On the other hand, compression strength of sapwood decreased gradually from bottom (40.47 N/mm²) to the middle (38.32 N/mm²) and top (36.01 N/mm²).

Based on the results from Tukey's grouping analysis, bottom heartwood (A) was found to have significantly higher strength than all other treatment levels. Middle heartwood (B) and top heartwood (C) were significantly different from each other, depicting a decline in strength from the bottom to the top position of the stem. For the sapwood, bottom sapwood (CD) had intermediate values, while middle (D) and top (E) positions recorded low values, where top sapwood had the least strength.

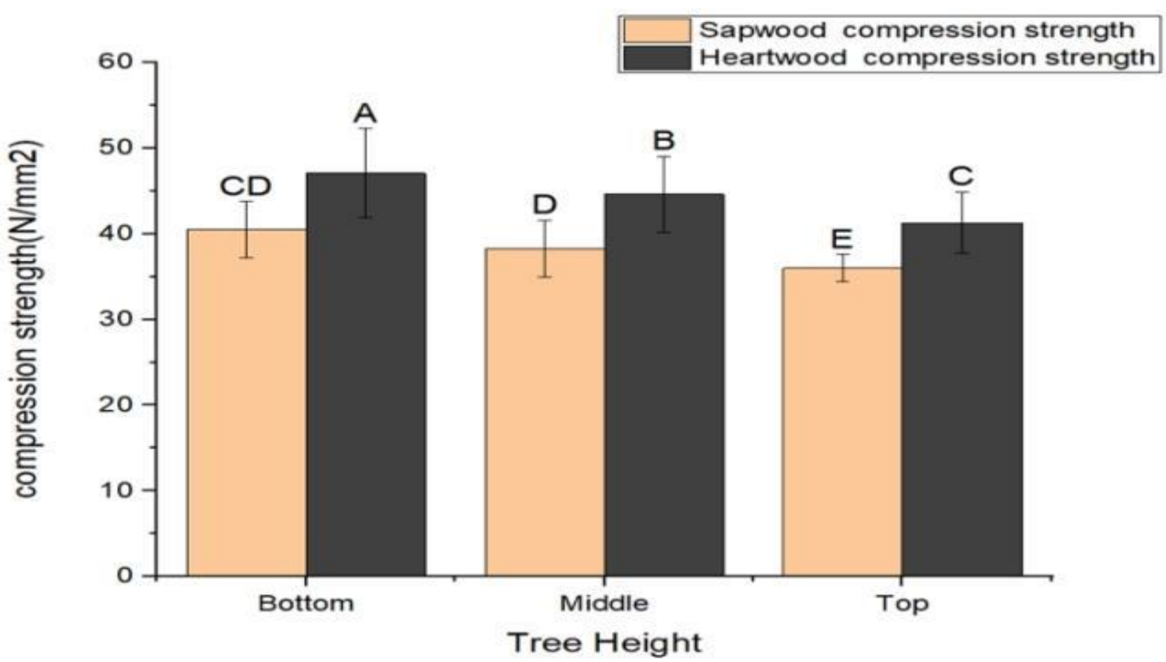


Figure 4.12. Interaction effect of wood type and tree height on compression strength parallel to grain (N/mm²) of *Cordia africana*.

Note: Error bars represent standard deviation. Means followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.2.2. Static bending strength of *Cordia africana*

The static bending properties of wood include modulus of rupture (MOR) and modulus of elasticity (MOE). Modulus of rupture measures the resistance to failure, while modulus of elasticity measures the resistance to deformation. These are key factors in determining how well timber will perform structurally (Arriaga et al., 2023; Forest Service & Products Laboratory, 2010).

4.2.2.1. Modulus of Rupture (MOR) (N/mm^2) of *Cordia africana* as affected by wood type and tree height position at 12% Moisture Content

This study investigates the influence of wood type (sapwood and heartwood) and height of tree from which the timber originates (low, mid, and high) on the MOR of *Cordia africana*. Descriptive statistics are shown in Table 4.3, and interaction effects in Figure 4.13.

The data presented in Table 4.3 reveals that the Modulus of Rupture (MOR) of *Cordia africana* is dependent on the type of wood and longitudinal position of the stem at a moisture content of 12%. MOR varied between 65.15 and 81.11 N/mm^2, where the maximum value was observed in the bottom heartwood and the minimum value in the top sapwood. Higher MOR was observed in the heartwood compared to the sapwood. This suggests that heartwood, being mature wood, has greater strength against bending. Also, MOR was found to be decreasing from the bottom to the top of the stem (Waktole et al., 2025).,possibly due to variation in density, maturity, and anatomical properties of wood(Ross, 2021).

This is in line with studies on the utilization of Ethiopian forest products where *Cordia africana* was found to have a modulus of rupture of 64 N/mm^2, indicating a lower yet similar bending strength to this study and indicating variation due to differences in sample origin, density, and wood maturity (FPICE, Ethiopian Forestry Development, 2022; (Desalegn et al., 2015). Similarly, in Tanzania, studies reported an average MOR value of approximately 37.04 N/mm^2, which was considerably lower than the present findings. The difference is mainly due to the difference in growth conditions, density, and the proportion of juvenile wood in the samples tested (Hamza et al., 2004).

4.2.2.1.1. Two-way Analysis of variance (ANOVA) for modulus of rupture (MOR) (N/mm^2) of *Cordia africana* as affected by wood type and tree height

The results from the ANOVA analysis show that the modulus of rupture (MOR) of *Cordia africana* is significantly affected by both wood type and tree height (Table 4.4).

A highly significant effect was seen on MOR by wood type (*p*<0.0001), indicating that sapwood and heartwood exhibit different capacities when it comes to bending strength. Tree height was also highly significant (*p*<0.0001), which suggests that there is variation of MOR from the bottom part to the top part of the stem.

Moreover, the interaction of wood type and tree height was also highly significant (*p*=0.00473), which implies that the effects of tree height on the MOR value vary depending on the wood type used. This means that the pattern of variation from the bottom to the top part of the stem differs according to sapwood and heartwood type. Conclusively, these findings imply that the MOR value of *Cordia africana* is governed by the interaction of wood type, tree height, and their interaction.

4.2.2.1.2. Interaction Effect of Wood Type and Tree Height on Modulus of Rupture (MOR) (N/mm^2) of *Cordia africana*

Figure 4.13 illustrates the effect of the interaction between wood type and tree height on the MOR of *Cordia africana*. A gradual decline of MOR values was observed from the bottom towards the top of the stem in both sapwood and heartwood; however, there were differences in the rates of decline depending on the wood type. Heartwood always had a higher MOR compared to sapwood at the same stem locations(Yilma et al., 2021). The maximum MOR was registered for bottom heartwood (81.11 N/mm^2), the second maximum for bottom sapwood (77.27 N/mm^2), while the minimum MOR value was registered for top sapwood (65.15 N/mm^2). Based on the findings using Tukey's HSD, bottom sapwood and bottom heartwood were in Group A, signifying no significant difference, as this represents the strongest type of wood in terms of bending strength. Group A was also comprised of middle heartwood which showed strong properties similar to bottom heartwood and sapwood. Middle sapwood and top heartwood and top sapwood fell into Group B, representing lower MOR values than those found in Group A. The overall graph shows that the wood type and height of tree affect MOR.

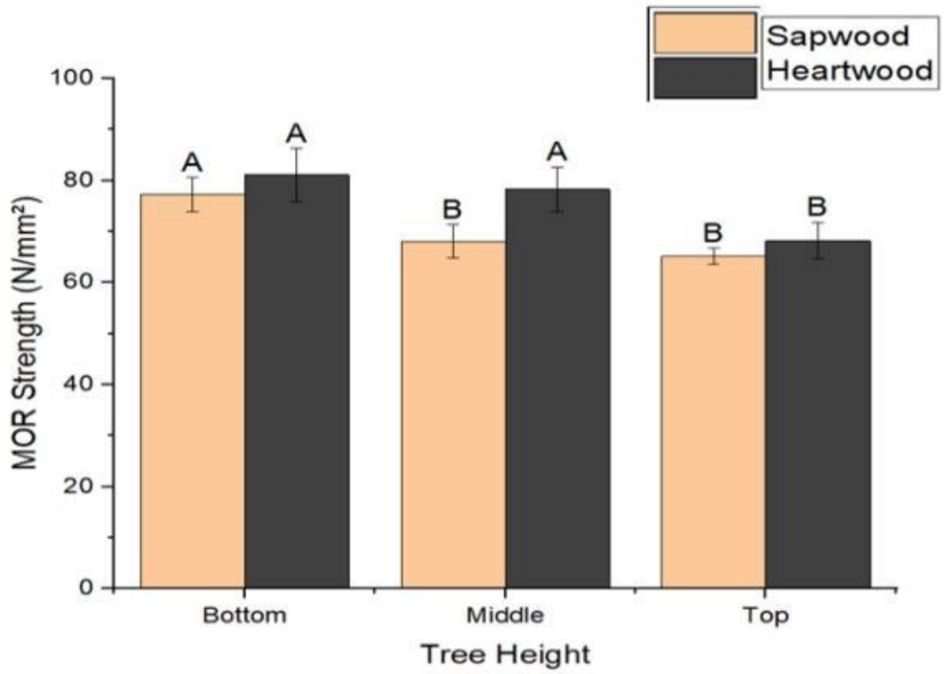


Figure 4.13. Interaction effect of wood type and tree height on modulus of rupture (MOR) (N/mm^2) of *Cordia africana*.

Nore: Error bars represent standard deviation. Means followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.2.2.2. Modulus of Elasticity (MOE) (N/mm^2) of *Cordia africana*as affected by wood type and tree height position

Modulus of elasticity (MOE) is a property of wood that describes how well it resists deformation by external loads within its elastic limit. The current experiment was conducted to determine how wood type (sapwood and heartwood) and height of the tree (lower, middle, and upper) affect the MOE of *Cordia africana*. The results are shown in Table 4.3 and Figure 4.14.

From Table 4.3, the modulus of elasticity (MOE) of *Cordia africana* at 12% moisture content differed based on the wood type and position in the stem. MOE ranged between 4619.62 and 6281.32 N/mm^2, where the stiffest MOE was found in the bottom heartwood and the least in top sapwood. MOE values reduced steadily from bottom to top in sapwood from 5708.12 N/mm^2 to 4619.62 N/mm^2, respectively, while in heartwood, it reduced steadily from 6281.32 N/mm^2 at the bottom to 4930.32 N/mm^2 at the top. At all height positions, heartwood had higher MOE compared to sapwood, an indication of stiffer mature wood. This difference could be related to differences in wood maturity, density, cell wall composition, and percentage of juvenile wood in the stem(Glass & Zelinka, 2021). The mean MOE was 5354.84 N/mm^2, indicating *C. africana* has good stiffness properties.

According to the Ethiopian Forest Products Utilization Laboratory Getachew Desalegn et al.(2015), the modulus of elasticity of *Cordia africana* with a density of 410 is kg/m^3 (MOE) of 6996 N/mm^2. Similarly, Hamza et al.(2004). reported mean basic density of about 400 kg/m 3 (SD = 0.07 g/cm 3) and MOE of about 2468 N/mm^2 for *Cordia africana* grown in Tanzania. In Moshi, Kilimanjaro, Tanzania, (In et al., 1999), reported a basic density of about 375 kg/m^3 and a MOE of 4711.3 N/mm^2, while (Mahonge, 2007), reported a MOE of 6003.83 N/mm^2 for agroforestry grown *Cordia africana* in Arumeru, Tanzania.

These results imply that the modulus of elasticity of *Cordia africana* is highly variable and largely depends on the density of the wood and the maturity of the wood in the stem (Glass & Zelinka, 2021). In light of the above-mentioned density and MOE of *Cordia africana* found in this study, it can be deduced that the mature heartwood and lower parts of the stem exhibit better mechanical properties than sapwood and the upper parts of the stem.

4.2.2.2.1. Two-way Analysis of variance (ANOVA) for modulus of elasticity (MOE) (N/mm^2) of *Cordia africana* as affected by wood type and tree height

Based on the results of the ANOVA, one may conclude that there is a statistically significant effect of wood type, tree height, and the interaction of both on the modulus of elasticity (MOE) of *Cordia africana* wood **(**Table 4.4). One of the factors "wood type" had a very highly significant effect on MOE ($p < 0.0001$), which means that the stiffness of wood differed for heartwood and sapwood and, this supported as studied in *Eucalapytus by* Bektaş et al., (2020). It may be connected with different densities and structures of wood types, which affect its mechanical properties (Zhang et al., 2024).The factor "tree height" also had a very highly significant effect ($p < 0.0001$), which means that MOE varied from bottom to top of the stem because of changes in properties of wood along the stem (Mahonge, 2007; Zhang et al., 2024).

4.2.2.2.2. Interaction effect of wood type and tree height on modulus of elasticity (MOE) (N/mm^2) of *Cordia africana*

Figure 4.14 shows the interaction effect of wood type and tree height on the MOE of *Cordia africana*. The MOE progressively decreased from bottom to top of the stem in heartwood and sapwood. Heartwood had higher MOE values compared to sapwood throughout the length of the stem. The highest value of MOE was attained at the bottom heartwood (6281.32 N/mm^2) whereas the lowest value of MOE was attained at top sapwood (4619.62 N/mm^2) and top heartwood (4930.32 N/mm^2).

From the point of view of Tukey's grouping, bottom heartwood (A) had significantly high MOE compared to other treatments. The second most rigid wood is bottom sapwood (B). The third and fourth ranks in terms of stiffness belonged to middle sapwood (C) and middle heartwood (C). Top heartwood (D) and top sapwood (E) turned out to be the least stiff materials.

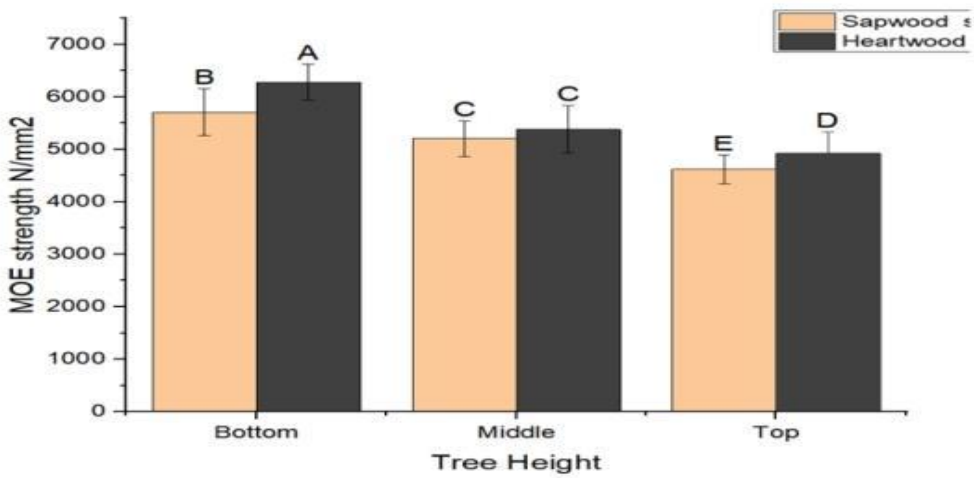


Figure 4.14: Interaction effect of wood type and tree height on modulus of elasticity (MOE) (N/mm^2) of *Cordia africana*.

Note: Error bars represent standard deviation. Means followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.2.3. Impact Bending Strength of *Cordia africana* as affected by wood type and tree height position.

Impact bending strength refers to the ability of the wood material to absorb energy and withstand rupture in the presence of sudden dynamic loadings without failure. Impact bending strength is thus an important property of the wood in terms of its shock resistance (Niemz et al., 2023). Impact bending strength of *Cordia africana* was determined for variations based on wood type and the height position of the tree. Descriptive statistics and analysis of variance and mean separations are provided in Table 4.3, while interaction effects are shown in Figure 4.15.

The impact strength of *Cordia africana* wood was affected by both wood type and tree height positions (Table 4.3). Impact strength varied between 63,011.11 N•m/m² and 78,055.56 N•m/m². It was observed that heartwoods were more impact resistant than sapwoods, and also wood from the lower stem had more impact strength than wood from the upper stem. The highest mean impact strength was in the bottom heartwood (78,055.56 N•m/m²), while the lowest mean impact strength was in the top sapwood (63,011.11 N•m/m²).

In both wood types, there is a progressive reduction of impact strength from the bottom to the top of the stem. In sapwood, the mean impact strength reduced from 71,666.67 N•m/m² at the bottom to 65,555.56 N•m/m² in the middle and to 63,011.11 N•m/m² at the top. Likewise, in heartwood, the mean impact strength reduced from 78,055.56 N•m/m² in the bottom to 72,416.67 N•m/m² in the middle and to 64,777.78 N•m/m² in the top. From these results, it can be concluded that wood from the lower stem has more resistance against sudden shock loads than wood from the upper stem. Table 4.33. Analysis of variance (ANOVA) for impact strength (N·m/m²) of *Cordia africana* as affected by wood type and tree height. The greater impact strength noted for the heartwood and lower parts of the stem is associated with the greater maturity of the wood tissue and its generally higher density, discussed in the density section. High-density wood is characterized by a larger share of cell wall content, which makes it better able to absorb energy and withstand crack propagation under impact loading. Such dependence between density and impact strength has been established for many hardwood species.

The coefficient of variation varied within 11%-21% range, implying low variability between the samples and high consistency of the measurement results.

The impact strength of the material measured in this work was relatively high in comparison with the average values reported for some hardwood species. According to Nenning et al., (2025) the median impact bending strength values for European beech (Fagus sylvatica), sessile oak (Quercus petraea), and white poplar (Populus alba) were 56 kJ/m², 48 kJ/m² and 43 kJ/m², respectively, with the maximum values being 147 kJ/m², 89 kJ/m² and 91 kJ/m², respectively. The stem wood densities were 727 kg/m³, 691 kg/m³, and 465 kg/m³, respectively. While *Cordia africana* has demonstrated relatively moderate average basic 469 basic densities and 559 oven-dry densities, the impact strength values observed in the experiment (63.01-78.06 kJ/m^2) lie within the range of hardness species and exceed the average values for beech, oak, and poplar. In other words, the results prove the good toughness and shock resistance of this species. This can be explained by the presence not only of relatively high density, but also by the favorable anatomical properties and fiber structure of the material. Thus, relatively high impact strength values observed in the current work are viewed as realistic and coincide with data from the literature for hardwoods. The work by Desalegn et al.(2015), which deals with the use of forest products from Ethiopia, gives the impact strength of *Cordia africana* as 6588 N•m/m². The figure is much less compared to that derived in this study, but there is a trend in the impact resistance capability of the species.

4.2.3.1. Two-way ANOVA Results for the impact strength of *Cordia africana* at 12% moisture

Based on ANOVA, it was evident that the impact strength of *Cordia africana* was significantly dependent on wood type and height of the tree (Table 4.4).

There was a significant effect of wood type on the impact strength (p<0.001), indicating that sapwood and heartwood have different levels of resistance against impact loading. Also, there was a highly significant effect of tree height (p<0.0001), suggesting that the impact strength changes along the stem from bottom to top position. Interestingly, there was no statistical interaction between wood type and tree height (p=0.208), meaning that impact strength shows the same level of dependency on tree height whether for sapwood or heartwood. Consequently, the trend of change along the stem was found to be constant irrespective of the wood type. To sum up, the impact strength of *Cordia africana* depends mainly on the individual effects of wood type and height of the tree, while their interaction has little influence on the property.

4.2.3.2. Interaction effect of wood type and tree height on impact strength (N·m/m²) of *Cordia africana*

Figure 4.15 shows the interaction effect between wood types and tree height on the impact strength of *Cordia africana*. Even though the interaction effect was insignificant according to the ANOVA output, the graphical representation indicates that the decreasing trend of impact strength in both sapwood and heartwood from the bottom to the top of the stem is similar.

It should be noted that heartwood showed greater impact strength than sapwood at different height levels. Impact strength for bottom heartwood was 78,055.56 N·m/m², while middle heartwood showed 72,416.67 N·m/m². The lowest impact strength was reported for top sapwood (63,011.11 N·m/m²). Impact strength of sapwood gradually reduced from 71,666.67 N·m/m² (bottom) to 65,555.56 N·m/m² (middle) and to 63,011.11 N·m/m² (top). In heartwood, the same decreasing trend was observed, showing that impact resistance is negatively correlated with tree height irrespective of wood type. Based on Tukey's grouping method, it can be stated that the bottom heartwood (A) and middle heartwood (A) have high impact strength and are statistically equal. The bottom sapwood (AB) had moderate performance and was statistically not different from the first highest group. The middle sapwood (BC) had a moderate value, and the top sapwood (C) and top heartwood (C) had low impact strength and were statistically equal. In conclusion, the data presented in the graph suggest that impact strength is high in heartwood and low in sapwood; moreover, it decreases from bottom to top. Thus, it can be concluded that the lower part of the stem has more toughness than the upper part.

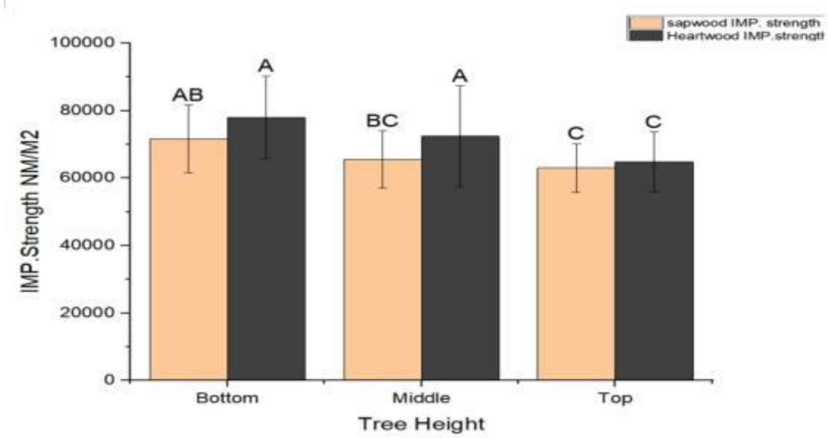


Figure 4.15. Interaction effect of wood type and tree height on impact strength (N·m/m²) of *Cordia africana.*

Note: Error bars represent standard deviation. Means followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.2.4. Janka radial hardness (N) of *Cordia africana* as affected by wood type and tree height position at 12% moisture content

Radial hardness can be described as the wood's resistance to indentation under a load that acts perpendicularly to the grain. Radial hardness for *Cordia africana* was determined based on the wood and tree heights, and the findings are shown in Table 4.3 and Figure 4.16.

The descriptive statistics of radial hardness (N) of *Cordia africana* at 12% moisture content based on wood type and stem height are shown in Table 4.3. The range of radial hardness was between 3265.78 and 3690.00 N, with the maximum value occurring in bottom heartwood (3690.00 N), while the minimum value occurred in top sapwood (3265.78 N). Radial hardness declined progressively from bottom to top along the stem in both wood types, thus showing that the stem is more resistant to indentation in the lower sections. This suported by study of (Mussa et al., 2025).Heartwood showed higher radial hardness values than sapwood for all the heights tested, which were about 228 N at the bottom, 276 N in the middle, and 228 N at the top.

In general, it was found that the wood type and the vertical position significantly affect the radial hardness of the *Cordia africana* trees. From the observations, the wood which had the highest radial hardness was bottom heartwood (3690.00 N), while the wood which had the lowest radial hardness was top sapwood (3265.78 N). Higher values of radial hardness were recorded in heartwood and in the lower part of the stem. This is due to high density and thickness of cell wall. Similar findings were reported by Desalegn et al.(2015),on *Cordia africana* where the radial hardness was 2213 N and the average density was 410 kg m^{-3}. The current study measured a higher density average of 469 kg m^{-3}, which might have resulted in the higher hardness values. According to PROTA (Louppe et al., 2008) , *Cordia africana* is an average-density hardwood having a density value between 440 and 580 kg m^{-3} with 12% moisture content and a side Brinell hardness of 23.5 N mm^{-2} and an end Brinell hardness of 40 N mm^{-2}. The density in the current study falls within the range provided by PROTA. Therefore, the wood specimens tested in this study have similar physical and mechanical properties as those of the species. Variation in the radial hardness in wood types and stem positions is probably linked to density and tissue maturity in the wood samples.

4.2.5. Two-Way ANOVA Results for Radial Hardness of *Cordia africana* at 12% Moisture Content

According to the findings of the two-way ANOVA test (Table 4.4) for radial hardness in *Cordia africana* wood at 12% moisture content, it can be seen that both wood type and tree height position significantly influence radial hardness, although there was no statistical significance in their interaction effect. Wood type had a very highly significant effect on radial hardness (F = 107.82, p < 0.0001), meaning that heartwood and sapwood have different degrees of radial hardness. This means that wood type is one of the most important factors affecting radial hardness in *Cordia africana* wood.

Likewise, tree height position had a significant effect on radial hardness (F = 23.89, p < 0.0001), which implies that radial hardness is influenced by the position of wood along the height of the tree. On the other hand, the effect of interaction between wood type and tree height was not statistically significant (F = 0.45, p = 0.6351). This suggests that the way radial hardness varies with respect to the tree height is the same for both sapwood and heartwood. This means that the two independent variables do not interact to influence radial hardness.

The entire model was statistically highly significant (F = 31.30, p < 0.0001), meaning that the combined effects of the wood type and tree height account for a considerable amount of variance in radial hardness. Nevertheless, there was still some degree of unexplained variation in the response variable, which suggests biological variability.

In summary, the results show that wood type and tree height independently affect the radial hardness of *C. africana* wood at 12% moisture content while their interaction is non-significant.

4.2.5.1. Interaction Effect of Wood Type and Tree Height on Radial Hardness of *Cordia africana*

The interaction diagram for radial hardness in *Cordia africana* at 12% moisture content (Table 36) depicts the interaction between wood species (sapwood, and heartwood) and tree height level (bottom, middle, and top) in the determination of variations in hardness. Based on the data obtained, there is a consistent trend that the radial hardness of heartwood is greater than sapwood throughout the tree height levels. Hardness differences comparable to those in this study have been observed in hardwood trees, in which the heartwood was found to be harder than the sapwood (Bektaş et al., 2020;Mussa et al., 2025).

For sapwood, the radial hardness value drops with increasing height level of trees from bottom (3461.56N) to middle (3368.00 N) and further to top (3265.78 N). This can be shown by the grouping of letters in which the bottom section is not significantly different from the middle in certain overlaps (BC and CD). In contrast, the top section (D) is significantly lower than the other two sections (AB).

On the contrary, heartwood had a higher value of radial hardness compared to sapwood, which was more or less constant with smaller variance. The bottom and the middle were in the same group (A), which indicated that there was no significant difference, while the upper was significantly lower (3493.42 N) (B) but still higher than sapwood. Overall, heartwood had higher radial hardness compared to sapwood without considering tree height. Also, there was a decreasing trend in radial hardness from the bottom to the top for both wood types, just like other hardwoods (Mussa et al., 2025;).The overlap in letters indicated a partial statistical similarity for some stem heights, while different letters indicated a significant difference between the treatments. Radial hardness was significantly affected by wood type and stem position as per the ANOVA results.

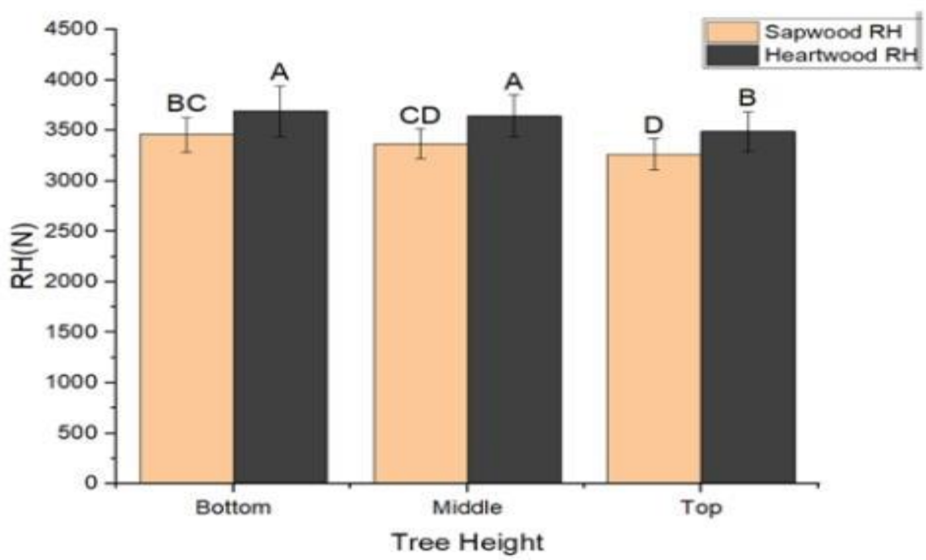


Figure 4.16. Interaction effect of wood type and tree height on radial hardness (N·m/m²) of *Cordia africana*.

Note: Error bars represent standard deviation. Means followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.

4.2.6. Janka Tangential Hardness (N) of *Cordia africana* as affected by wood type and tree height position at 12% mosture content

The tangential hardness is defined as the resistance of the wood to penetration by the load that is applied perpendicularly to the grain tangentially (Koczan et al., 2021). The tangential hardness of *Cordia africana* was determined based on the wood type and the height of the tree. Tangential Hardness results are shown in Table 4.3 and Figure 4.17.

Table 4.3 provides the descriptive statistics of tangential hardness of *Cordia africana* wood at 12% moisture content. The lowest tangential hardness value was recorded as 3220 N, and the highest value was 3588 N, where the highest hardness value was recorded in bottom heartwood while the lowest hardness value was recorded in top sapwood. In both heartwood and sapwood, there was a decreasing trend in tangential hardness from bottom to top of stem. It indicates that there was a decrease in mechanical strength with increasing tree height, which is also found for hardwood species (Kiaei & Farsi, 2016).The hardness value was greater in heartwood than in sapwood by about 200-300 N at all heights.

4.2.6.1. Two-Way ANOVA Results for Tangential Hardness of *Cordia africana* at 12% Moisture Content

The output in Table 4.4 indicates the outcome of the two-way analysis of variance for tangential hardness of the wood of *Cordia africana* with moisture content of 12%. Wood type and tree height significantly affected tangential hardness ($F = 68.42$, $p < 0.0001$ and $F = 6.77$, $p = 0.00135$, respectively), while their interaction was not found to be significantly different ($F = 0.32$, $p = 0.7290$). It is clear that there is a significant difference in the hardness of the heartwood and sapwood and also that the tangential hardness decreases from the base to the top of the stem. Such a significant difference in hardness between the heartwood and sapwood has been observed for other hardwood species in which the wood type affected the indentation resistance (Bektaş et al., 2020). Changes in the wood mechanical properties depending on the height of the stem have also been documented for hardwoods (Kiaei & Farsi, 2016).

4.2.6.2. Interaction Effect on Tangential Hardness of *Cordia africana* at 12% Moisture Content

Figure 4.17 shows the interaction effect of wood type and tree height on the tangential hardness of *Cordia africana*. Heartwood maintained a high tangential hardness compared to sapwood at all stem levels. Bottom heartwood (3587.56 N; Group A) had the highest tangential hardness, followed by middle heartwood (3488.22 N; Group AB) and top heartwood (3436.67 N; Group BC). Bottom sapwood (3322.00 N; Group CD), middle sapwood (3269.33 N; Group D), and top sapwood (3219.78 N; Group D) possessed low tangential hardness.

Tangential hardness tended to decrease gradually from the bottom to the top of the stem for both wood types. Letter group overlap (AB, BC, CD, and D) means that some adjacent treatments are not significantly different, whereas bottom heartwood (Group A) is significantly different from most sapwood treatments. This is consistent with the fact that heartwood maintains a higher tangential hardness than sapwood, while the same gradual decrease in both wood types supports the absence of a significant interaction effect in ANOVA.

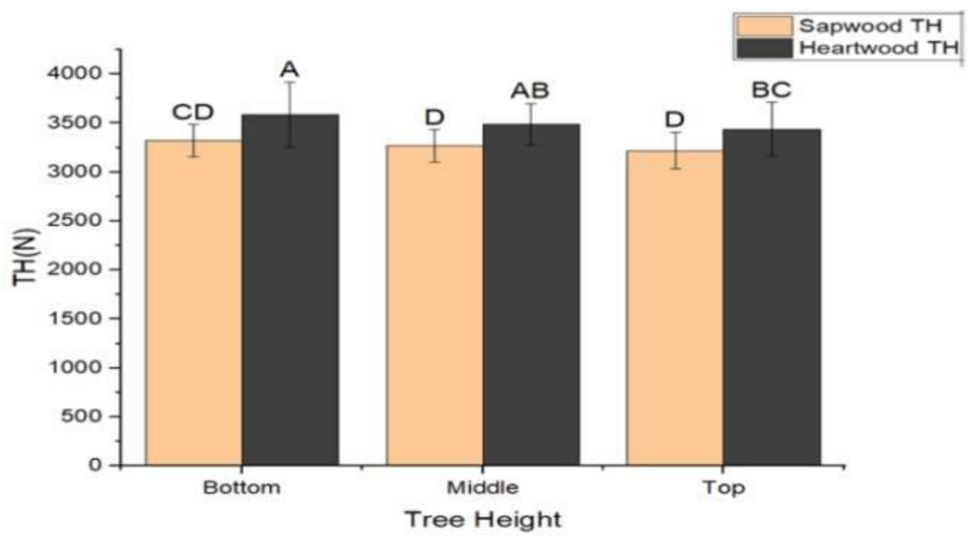


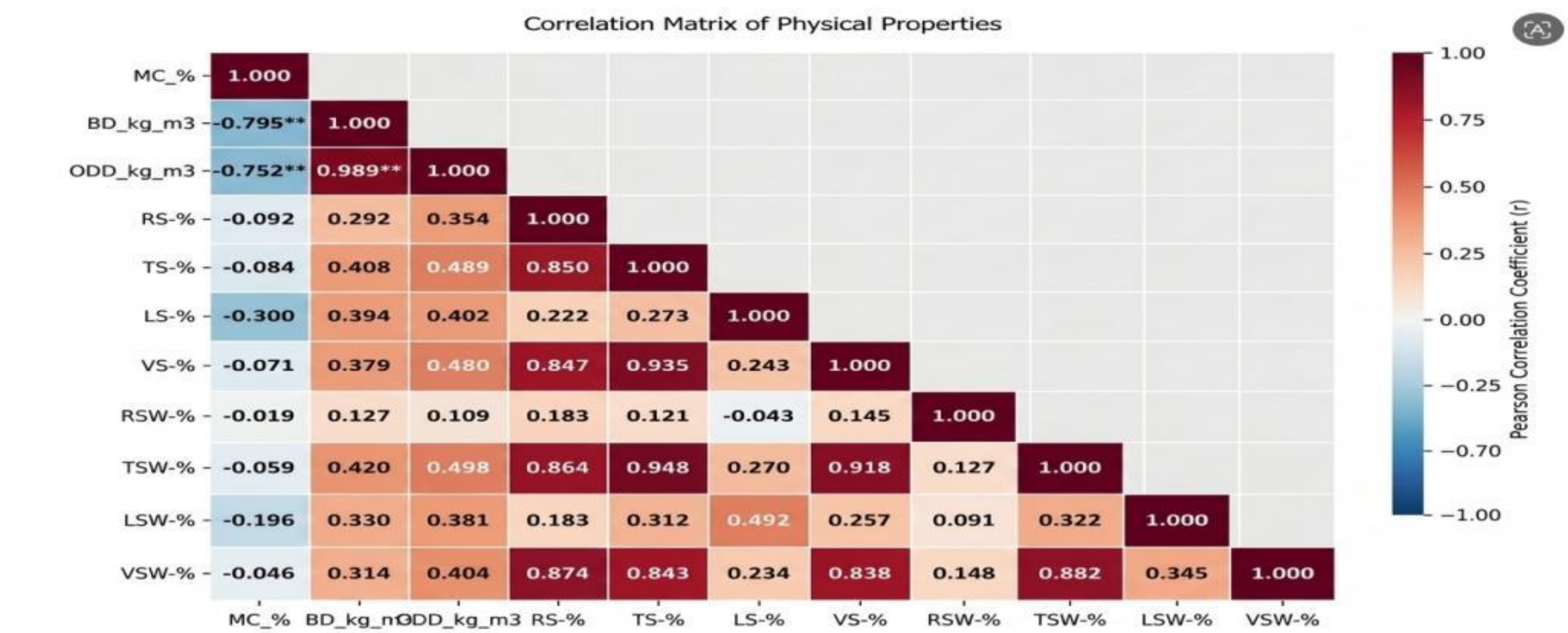
Figure 4.17. Interaction effect of wood type and tree height on tangential hardness (N) of *Cordia africana* at 12% moisture content.

Note: Means followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test. Error bars represent standard deviation.

Table 4.5. Pearson Correlations between physical properties of *Cordia africana*

Pearson Correlations between physical properties of *Cordia africana*.												
		MC(%)	BD(kg/m^3)	ODD (kg/m^3)	RS(%)	TS(%)	LS(%)	VS(%)	RSW(%)	TSW(%)	LSW(%)	VSW(%)
MC_%	Pearson Corr.	1	-0.79536*	-0.75222*	-0.09183	-0.06326	0.30089*	-0.07114	0.01962	-0.05814	0.19947*	0.04596
	p-value	--	<0.0001	<0.0001	0.13232	0.30032	<0.0001	0.244	0.74823	0.34128	9.82E-04	0.45199
BD_kg_m3	Pearson Corr.	0.79536*	1	0.9866*	0.29234*	0.40779*	-0.3944*	0.37994*	0.12734*	0.41968*	-0.33003*	0.3138*
	p-value	<0.0001	--	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.03651	<0.0001	<0.0001	<0.0001
ODD_kg_m3	Pearson Corr.	-0.75222*	0.9866*	1	0.35492*	0.48852*	-0.40244*	0.46038*	0.10899	0.49751*	-0.36134*	0.40414*
	p-value	<0.0001	<0.0001	--	<0.0001	<0.0001	<0.0001	<0.0001	0.07379	<0.0001	<0.0001	<0.0001
RS-%	Pearson Corr.	-0.09183	0.29234*	0.35492*	1	0.65072*	-0.22166*	0.84736*	0.1832*	0.66429*	-0.18319*	0.67362*
	p-value	0.13232	<0.0001	<0.0001	--	<0.0001	2.41E-04	<0.0001	0.00251	<0.0001	0.00251	<0.0001
TS-%	Pearson Corr.	-0.06326	0.40779*	0.48852*	0.65072*	1	-0.27242*	0.93512*	0.12134*	0.94896*	-0.31282*	0.84334*
	p-value	0.30032	<0.0001	<0.0001	<0.0001	--	<0.0001	<0.0001	0.04639	<0.0001	<0.0001	<0.0001
LS-%	Pearson Corr.	0.30089*	-0.3944*	-0.40244*	-0.22166*	-0.27242*	1	-0.24374*	-0.0434	-0.27069*	0.4926*	-0.23482*
	p-value	<0.0001	<0.0001	<0.0001	2.41E-04	<0.0001	--	<0.0001	0.47762	<0.0001	<0.0001	<0.0001
VS-%	Pearson Corr.	-0.07114	0.37994*	0.46038*	0.84736*	0.93512*	-0.24374*	1	0.14553*	0.91829*	-0.25705*	0.8376*
	p-value	0.244	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	--	0.01671	<0.0001	<0.0001	<0.0001
RSW-%	Pearson Corr.	0.01962	0.12734*	0.10899	0.1832*	0.12134*	-0.0434	0.14553*	1	0.12752*	-0.09157	0.1466*
	p-value	0.74823	0.03651	0.07379	0.00251	0.04639	0.47762	0.01671	--	0.03624	0.13341	0.01592
TSW-%	Pearson Corr.	-0.05814	0.41968*	0.49751*	0.66429*	0.94896*	-0.27069*	0.91829*	0.12752*	1	-0.32256*	0.8825*
	p-value	0.34128	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.03624	--	<0.0001	<0.0001

LSW-%	Pearson Corr.	0.19947*	-0.33003*	-0.36134*	-0.18319*	-0.31282*	0.4926*	-0.25705*	-0.09157	-0.32256*	1	-0.3451*
	p-value	9.82E-04	<0.0001	<0.0001	0.00251	<0.0001	<0.0001	<0.0001	0.13341	<0.0001	--	<0.0001
VSW-%	Pearson Corr.	0.04596	0.3138*	0.40414*	0.67362*	0.84334*	-0.23482*	0.8376*	0.1466*	0.8825*	-0.3451*	1
	p-value	0.45199	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.01592	<0.0001	<0.0001	--
2-tailed test of significance is used *: Correlation is significant at the 0.05 level												



$p < 0.05$; $p < 0.01$

Figure 4.18. Correlation map of physical properties

Significant relationships between the moisture content, density, shrinkage, and swelling characteristics of *Cordia africana* were determined using Pearson correlation analysis. As explained by Evans (1996), a relationship coefficient of 0.60 to 0.79 suggests a strong relationship, while 0.80 to 1.00 is indicative of a very strong relationship.

A very strong positive relationship was found between the basic density and the oven-dry density (r = 0.987, p < 0.0001). In addition, volumetric shrinkage was also strongly related to tangential shrinkage (r = 0.935) and radial shrinkage (r = 0.847), which implied that both radial and tangential shrinkage largely influence the total volumetric shrinkage. Likewise, tangential swelling had a very strong positive relationship with volumetric swelling (r = 0.883) and volumetric shrinkage (r = 0.918). There were also positive correlations that were strong between radial shrinkage and tangential shrinkage (r = 0.651), radial shrinkage and tangential swelling (r = 0.664), and radial shrinkage and volumetric swelling (r = 0.674). On the other hand, there was a strong negative correlation between basic density (r = -0.795) and oven-dry density (r = -0.752) with moisture content (p<0.0001), which means that denser wood had lower moisture content. The findings therefore prove that density is a factor in the dimensional stability of *C. africana* wood.

Table 4.6. Pearson correlation between MOR and MOE of *Cordia africana* wood

Variable	MOR (N/mm^2)	MOE (N/mm^2)
MOR (N/mm^2)	1	0.7165**
MOE (N/mm^2)	0.7165**	1

Note: ** indicates significance at p < 0.01 (2-tailed). Correlation coefficient (r) = 0.7165; p < 0.0001; n = 270.

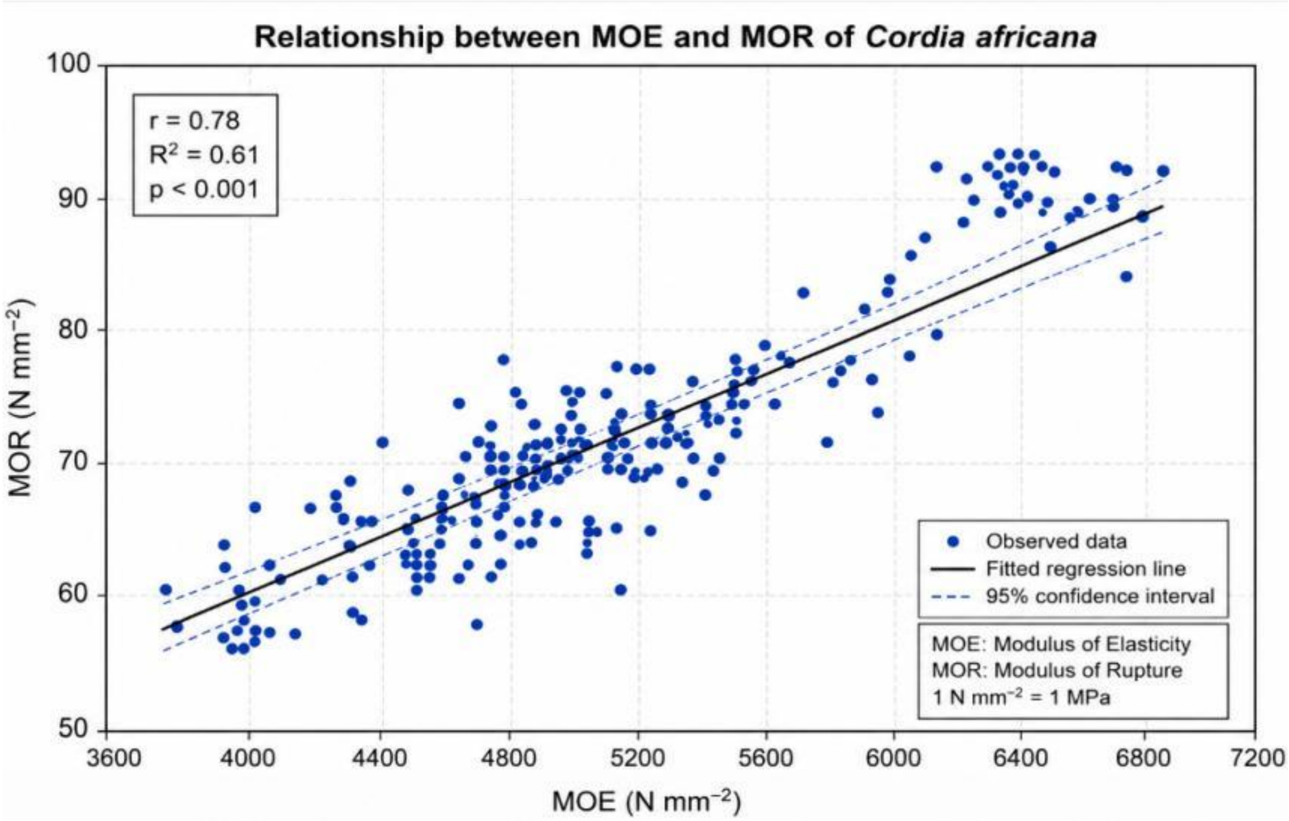


Figure 4.19. Correlation between MOR &MOE

Pearson correlation coefficient revealed a positive and highly significant relationship between the modulus of rupture and modulus of elasticity of *Cordia africana* ($r = 0.7165$, $p < 0.0001$). It implies that stiff wood samples were more likely to possess greater strength in bending. The high degree of correlation implies that MOE could be used as a predictor for MOR because they depend on similar characteristics of wood.

Table 4.7. Summary of Key Findings for Physical Properties of *Cordia africana* grown around Ahferom Woreda Tigray Ethiopia.

Property	Overall Mean	Wood Type Effect	Tree Height Effect	Interaction Effect	Highest Mean Value	Lowest Mean Value	Key Finding
Moisture Content (%)	120.10	Significant (*p*<0.001)	Significant (*p*<0.001)	Not Significant (*p*=0.641)	Sapwood Top (136.72%)	Heartwood Bottom (106.80%)	Moisture content increased from bottom to top and was consistently higher in sapwood than heartwood.
Basic Density (kg/m³)	469.78	Significant (*p*<0.001)	Significant (*p*<0.001)	Not Significant (*p*=0.258)	Heartwood Bottom (506.37)	Sapwood Top (432.46)	Density decreased significantly with stem height and was higher in heartwood than sapwood.
Oven-Dry Density (kg/m³)	510.75	Significant (*p*<0.001)	Significant (p<0.001)	Not Significant (*p*=0.076)	Heartwood Bottom (552.70)	Sapwood Top (468.89)	Oven-dry density followed the same trend as basic density, decreasing from bottom to top and remaining higher in heartwood.
Radial Shrinkage (%)	2.90	Significant (*p*<0.001)	Significant (*p*<0.001)	Significant (*p*<0.001)	Sapwood Bottom (3.26%)	Heartwood Top (2.66%)	Radial shrinkage decreased with tree height and was greater in sapwood than heartwood.
Tangential Shrinkage (%)	5.53	Significant (*p*<0.001)	Significant (*p*<0.001)	Significant (*p*=0.033)	Sapwood Bottom (6.10%)	Heartwood Top (5.10%)	Tangential shrinkage showed the largest dimensional change and decreased from bottom to top.

Longitudinal Shrinkage (%)	0.110	Significant (*p*=0.011)	Significant (*p*<0.001)	Significant (*p*=0.035)	Sapwood Top (0.128%)	Sapwood Bottom (0.091%)	Longitudinal shrinkage was very low compared with radial and tangential shrinkage and increased toward the top of the stem.

Overall Results

1. Moisture content increased from the bottom to the top of the tree, while density decreased in the same direction.
2. Sapwood was significantly lower in mean basic and oven dry density than heartwood.
3. Positions on the stem, such as sapwood and lower stem, showed higher radial and tangential shrinkage, which means higher dimensional movement in these parts.
4. Longitudinal shrinkage was negligible (<0.13 %) compared to radial and tangential shrinkage, confirming the high dimensional stability of wood along the grain direction.
5. Tree height was significant for all physical properties measured, while wood type was significant for moisture content, density and shrinkage properties.

Table 4.8. Summary of Key Findings for Mechanical Properties of *Cordia africana*

Property	Overall Mean	Wood Type Effect	Tree Height Effect	Interaction Effect	Highest Mean Value	Lowest Mean Value	Key Finding
Compression Strength (N/mm^2)	≈41.30	Significant (*p*<0.001)	Significant (*p*<0.001)	Significant	Heartwood Bottom (47.07)	Sapwood Top (36.01)	Compression strength was significantly higher in heartwood and decreased from bottom to top stem positions.

Modulus of Rupture (MOR) (N/mm^2)	≈73.03	Significant ($p<0.001$)	Significant ($p<0.001$)	Significant	Heartwood Bottom (81.11)	Sapwood Top (65.15)	Bending strength decreased with increasing stem height and was consistently higher in heartwood.
Modulus of Elasticity (MOE) (N/mm^2)	5353.85	Significant ($p<0.001$)	Significant ($p<0.001$)	Not Significant	Heartwood Bottom (6281.32)	Sapwood Top (4619.62)	Stiffness was greatest in bottom heartwood and declined progressively toward the top of the stem.
Impact Strength (J/m^2)	69,247.22	Significant ($p<0.001$)	Significant ($p<0.001$)	Significant	Heartwood Bottom (78,055.56)	Sapwood Top (63,011.11)	Impact resistance was higher in heartwood and decreased from bottom to top positions.
Radial Hardness (N)	3487.05	Significant ($p<0.001$)	Significant ($p<0.001$)	Significant	Heartwood Bottom (3690.00)	Sapwood Top (3265.78)	Radial hardness was greater in heartwood and lower at upper stem positions.
Tangential Hardness (N)	3387.26	Significant ($p<0.001$)	Significant ($p<0.01$)	Significant	Heartwood Bottom (3587.56)	Sapwood Top (3219.78)	Tangential hardness followed the same trend as radial hardness, decreasing with stem height and being higher in heartwood.

Table 4.9. Comparison of mean values the physical Properties in *Cordia africana* with selected five Ethiopian commercial timber hardwood Species studied.

Species	Study Area	MC (%)	BD (kg/m³)	ODD (kg/m³)	RS (%)	TS (%)	LS (%)	VS (%)	RSW (%)	TSW (%)	LSW (%)	VSW (%)	Reference
Cordia africana	Ahferom - Tigray(This study)	120.10	469.78)	510.75	2.904)	5.53	0.109	8.36	2.89	5.53	0.103	8.76	This study
cordia alliodora	Ethiopia.	54.5 at inital	350	-	4.08	6.33	0.60	10.61	-	-	-	-	(Desalegn, 2011)
Eucalyptus globulus	D/Birhan	—	541+66.47	-	4.06+1.41	8.44+2.78	1.42+0.80	+	-	-	-	-	.(Waktole et al., 2024)
Acacia melanoxylon	Chencha, SNNPR Ethiopia.	67.36 at initial	57 0g/cm³ at12%	-	1.97	3.8	-	6.19	-	-	-	-	(Mussa & Bekele, 2021a)
Cordia africana	Ethiopian forestry reports	71	410 at12%										(Desalegn et al., 2015
Grevillea robusta	Ethiopian forestry reports	108 at green initial	530 at12%	-	-	-	-	-	-	-	-	-	(Desalegn et al., 2015),
Olea welwitschii lF@	Ethiopian forestry reports	191 initialgreen MC%	820 at12%	-	-	-	-	-	-	-	-	-	(Desalegn et al., 2015),

Table 4.10. Comparison of mean values of density and Mechanical Properties in *Cordia africana* with the selected five Ethiopian commercial timber Hardwood Species studied.

Species	Study Area / Institution	BD Kg/m^3 at 12%	Compression Strength (N mm^{-2})	MOR (N mm^{-2})	MOE (N mm^{-2})	Impact Strength (N mm^{-2})	Radial hardness (N)	Tangential hardness (N)	Reference
Cordia africana	Ahferom -Tigray(This study)	469.78	41.30	(73.03)	5353.85	69,247.22	3487.05	3387.26	This study
Cordia africana	(EEFRI, Addis Ababa). reports	410	29	64	6996	6588	2213	-	(Desalegn et al., 2015),
Senegalia caffra	Northern Ethiopia	594.40	53.15	105.69	9,556.79	14,825.00	4,958.67	5,324.78	(Waktole et al., 2025)
Acacia melanoxylon	Chencha, SNNPR, Ethiopia.	609	62.71	147.98	13671.89	9880.81	5415.40	5373.1	(Yilma et al., 2021)
Casuarina equisetifolia	Bishoftu,Ethiopia	774	59	124	9400	12456	6391	6471	(Mussa et al., 2025b)
Hagenia abyssinica	(EEFRI, Addis Ababa).	560	43	86	9563	6436	-	3814	(Desalegn et al., 2015),
Grevillea robusta	(EEFRI, Addis Ababa). reports	530	41	83	8899	18094	-	6737	(Desalegn et al., 2015),

Chapter 5. Conclusions and recommendations

5.1. Conclusions

This study analyzed the physical and mechanical properties of *Cordia africana* wood from Ahferom, Tigray, Ethiopia, according to wood type (heartwood and sapwood) and stem height (bottom, middle, and top). It can be concluded that both wood type and stem height had significant effects on most physical and mechanical properties of wood.

For instance, heartwood always had significantly lower moisture content, higher density, greater dimensional stability, and better compression strength parallel to grain, modulus of rupture (MOR), modulus of elasticity (MOE), impact strength, and hardness compared to sapwood. Similarly, wood from the bottom stem showed significantly higher density and mechanical properties compared to wood from the middle and upper stems, while moisture content increased with increasing height of the stem. Moreover, radial, tangential, and volumetric shrinkage and swelling were significantly different for wood type and stem height, whereas longitudinal shrinkage and swelling were very small, showing good dimensional stability of the wood along the grain.

As compared to the previous studies, *Cordia africana* from Ahferom is reported to have similar physical and mechanical characteristics as most medium-density commercial hardwood species available in Ethiopia. Moderate density, acceptable values of strength, stiffness, toughness, hardness, and dimensional stability make it appropriate for the manufacture of furniture, interior joinery, doors, windows, flooring, and other value-added wood products.

The results of the study represent the first set of data on the physical and mechanical properties of *Cordia africana* from Ahferom. The results will be helpful for further research, forest management, wood industries, engineering, and policymakers regarding sustainable utilization of the timber resource.

5.2. Recommendations:

1. Matured wood bottom stem heartwood should be preferred for use in furniture, flooring, jointed structural applications, doors, windows, and other uses where strength and durability are required due to the higher density and good mechanical properties.
2. The wood processing industries are advised to sort the logs based on their stem height and wood type at the time of sawing and processing to maximize recovery and utilization of *Cordia africana*.
3. The results from this study can be used as the baseline information in creating a national database of wood properties for timber grading, design, and utilization in Ethiopia.
4. Further studies on the physical and mechanical properties of *Cordia africana* should be done to provide nationally referenced values for properties such as moisture content, density, shrinkage, swelling, dimensional stability, strength, stiffness, impact resistance, and hardness.
5. Future investigations ought to include the study of the anatomy, chemistry, and microstructure of *Cordia africana* wood, along with its physical and mechanical properties, to increase knowledge of the influencing factors on the quality of wood.

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Appendices

Appendix A: Justification for the Selection of Appendix Materials

The Appendices are meant to give supporting evidence for the study in an organized and concise way to keep the thesis statement. The full data set used in the experiment was comprised of results collected from three sampled trees, two kinds of wood (sapwood and heartwood), three heights of the trees (bottom, middle top), and fifteen samples for every treatment combination. Moreover, the physical and mechanical properties were statistically analyzed in the OriginPro2024 software. Adding the full data set and all statistics would make the appendix include more than 132 pages and create redundancy in the thesis.

To ensure the reduction of the thesis without affecting its scientific nature, only selected examples of supporting material have been included in the appendices. Examples of raw data for all physical and mechanical properties of Tree 1 are shown to give an understanding of how the specimen code has been used and the format of measurements and data presentation employed in the entire experiment. But it is worth noting that all statistical analyses done in this thesis have been carried out using full data collected from the three trees. The description of the statistics, two-way analysis of variance (ANOVA), interaction, Tukey's HSD multiple comparison output, tables and figures, and their interpretation have been included in chapter four. Thus, these are not repeated in the appendices. In this case, examples of statistical diagnostic outputs for normality, histogram distribution, box plot, and outliers for one representative physical property (Basic density) and one representative mechanical property MOE have been included as examples of the statistical assumptions used before carrying out two-way ANOVA test.

There are also representative pictures in the appendices that show the process of field sampling, the process of preparation of the laboratory specimens, the process of testing, the process of workshops, and some of the graphs produced through the testing machine software. Furthermore, there are also supporting documents such as the letters of cooperation and permissions from both Axum University and Mekelle University.

In accordance with this, the appendix is a representation of the processes involved in the experiment, but not an archive of all the experimental data. The author still has the complete data of the experiment and will provide the same on request.

Appendix B: Raw data for physical test

Tree No.	Wood type	Tree height	specimen no	MC_%	BD_kg_m3	ODD_kg_m3	RS-%	TS-%	LS-%	VS-%	RSW-%	TSW-%	LSW-%	VSW-%
1	SW	Bottom	1	116.9	483	526.49	3.25	6.05	0.1	9.22	3.36	6.44	0.1	8.89
1	SW	Bottom	2	117.4	485	536.81	3.3	6.05	0.07	9.27	3.21	6.39	0.07	8.43
1	SW	Bottom	3	116.3	485	526.99	3.35	6.05	0.07	9.29	3.47	6.44	0.07	8.98
1	SW	Bottom	4	117.1	488	536.63	3.25	6.05	0.1	9.24	3.36	6.23	0.1	8.99
1	SW	Bottom	5	115.8	485	536.18	3.4	6.05	0.1	9.34	3.52	6.44	0.1	9.15
1	SW	Bottom	6	114.4	492	531.01	3.25	5.95	0.1	9.1	3.36	6.33	0.1	9.4
1	SW	Bottom	7	116.3	485	524.52	3.35	6.1	0.07	9.26	3.47	6.44	0.07	9.25
1	SW	Bottom	8	113	501	541.61	3.4	6.05	0.07	9.34	3.52	6.44	0.07	9.47
1	SW	Bottom	9	111	501	547.06	3.4	5.95	0.1	9.14	3.52	6.21	0.1	9.04
1	SW	Bottom	10	117.4	483	535.15	3.3	6.3	0.1	9.51	3.36	6.14	0.1	8.45
1	SW	Bottom	11	117.8	487	531.08	3.25	5.95	0.07	9.07	3.36	6.33	0.07	9.66
1	SW	Bottom	12	115.8	487	528.02	3.35	6.05	0.07	9.26	3.47	6.44	0.07	9.17
1	SW	Bottom	13	117.4	483	532.38	3.25	6.1	0.07	9.21	3.36	6.5	0.07	9.66
1	SW	Bottom	14	112.5	494	546.81	3.25	5.95	0.1	9.1	3.31	6.33	0.1	9.12
1	SW	Bottom	15	116.7	475	525.62	3.3	5.95	0.07	9.11	3.36	6.17	0.07	9.12
1	SW	Middle	1	118.8	460	500.77	3.1	5.9	0.13	8.94	3.2	5.95	0.11	9.45
1	SW	Middle	2	123.2	467	511.35	3.15	5.55	0.1	8.62	3.15	5.72	0.1	8.76
1	SW	Middle	3	119.1	458	502.46	3	5.4	0.1	8.33	3.04	5.71	0.1	9.06
1	SW	Middle	4	121.8	475	520.5	3.15	5.45	0.13	8.55	3.15	5.71	0.11	9.27
1	SW	Middle	5	122	454	489.64	3	5.6	0.13	8.55	3.09	5.93	0.11	8.98
1	SW	Middle	6	122.8	475	514.47	3.1	5.5	0.1	8.52	3.2	5.77	0.1	9.28
1	SW	Middle	7	118	467	503.83	3.2	5.45	0.13	8.6	3.31	5.76	0.1	8.75
1	SW	Middle	8	123.1	448	478.06	3.25	5.45	0.1	8.61	3.26	5.66	0.1	8.34
1	SW	Middle	9	123.9	447	485.97	3.25	5.75	0.13	8.93	3.2	5.84	0.1	8.73
1	SW	Middle	10	120.4	458	496.42	3.15	5.55	0.13	8.65	3.2	5.88	0.1	9
1	SW	Middle	11	121.2	471	514.18	3.2	5.45	0.1	8.57	3.15	5.76	0.1	8.87

1	SW	Middle	12	123.8	467	502.45	3.2	5.5	0.13	8.65	3.31	5.82	0.11	9.02
1	SW	Middle	13	122	450	495.27	3.15	5.8	0.1	8.86	3.15	5.89	0.1	8.44
1	SW	Middle	14	119.3	475	516.86	3.1	5.5	0.1	8.52	3.15	5.82	0.1	8.63
1	SW	Middle	15	121.2	471	508.37	3.15	5.5	0.1	8.57	3.25	5.82	0.1	8.95
1	SW	Top	1	126.4	452	488.58	3.05	5.15	0.13	8.17	2.89	5.43	0.1	8.1
1	SW	Top	2	124.7	462	497.76	3	5.25	0.13	8.51	2.94	5.29	0.13	7.7
1	SW	Top	3	126.1	463	501.71	3.1	5.2	0.1	8.23	2.84	5.22	0.1	7.7
1	SW	Top	4	125.2	433	475.29	3	5.35	0.13	8.31	2.89	5.23	0.1	7.76
1	SW	Top	5	122.3	467	504.14	3.05	5.05	0.1	8.04	2.94	5.32	0.1	8.48
1	SW	Top	6	122.8	450	479.44	3.1	5.05	0.13	8.12	2.89	5.32	0.13	8.17
1	SW	Top	7	124.2	475	511.66	3.1	5.1	0.13	8.16	2.84	5.22	0.1	7.83
1	SW	Top	8	127	442	481.95	3.05	5.35	0.13	8.36	2.89	5.44	0.13	7.9
1	SW	Top	9	123.5	454	497.94	3	5.25	0.1	8.43	2.94	5.45	0.1	8.13
1	SW	Top	10	126.3	475	513.87	3.15	5.25	0.1	8.08	2.89	5.26	0.1	7.95
1	SW	Top	11	126.4	442	471.02	3	5.25	0.13	8.46	2.89	5.45	0.1	7.83
1	SW	Top	12	123.2	450	489.22	3.05	5.25	0.13	8.02	2.89	5.26	0.13	8.4
1	SW	Top	13	125	467	502.89	3.05	5.25	0.13	8.02	2.99	5.26	0.1	8.53
1	SW	Top	14	125.8	455	495.38	3	5.25	0.13	8.22	2.89	5.33	0.13	8.24
1	SW	Top	15	126.2	462	496.99	3.05	5.1	0.13	8.12	2.99	5.27	0.13	8.02
1	HW	Bottom	1	98.25	525	568.99	2.75	5.5	0.1	8.19	2.83	5.61	0.1	8.16
1	HW	Bottom	2	100	508	554.98	2.5	5.65	0.07	8.07	3.08	5.99	0.07	8.45
1	HW	Bottom	3	102.3	533	578.45	2.7	5.6	0.13	8.27	2.72	5.93	0.13	8.41
1	HW	Bottom	4	97.1	517	560.14	3	5.55	0.1	8.48	2.89	5.77	0.1	8.09
1	HW	Bottom	5	99.06	533	579.57	2.7	5.75	0.1	8.39	2.98	5.94	0.07	8.69
1	HW	Bottom	6	98.41	525	574.34	3	5.7	0.07	8.59	2.99	5.78	0.07	9.01
1	HW	Bottom	7	98.44	533	581.35	2.75	5.75	0.13	8.46	2.72	5.89	0.1	8.64
1	HW	Bottom	8	98.7	514	564.84	3.25	5.55	0.07	8.68	3.1	5.51	0.07	9.2
1	HW	Bottom	9	98.41	525	569.29	3.25	5.15	0.07	8.29	3.15	5.54	0.07	8.33
1	HW	Bottom	10	97.76	520	565.92	3.2	5.25	0.1	8.37	3.1	5.54	0.1	8.61
1	HW	Bottom	11	99.52	517	566.57	3.25	5.65	0.1	8.81	3	5.99	0.07	9.24
1	HW	Bottom	12	97.9	517	563.85	2.9	5.6	0.07	8.4	2.83	5.93	0.07	8.97
1	HW	Bottom	13	101.3	508	557.95	3.2	5.7	0.1	8.81	3.05	5.99	0.1	9.43
1	HW	Bottom	14	100.2	508	552.13	2.75	5.75	0.07	8.4	2.83	5.99	0.07	8.51
1	HW	Bottom	15	98.41	525	574.05	2.9	5.75	0.07	8.54	2.88	5.84	0.07	8.96
1	HW	Middle	1	95.16	517	551.19	2.75	5	0.13	7.74	2.83	5.79	0.1	7.88
1	HW	Middle	2	99	498	537.8	2.85	5.5	0.1	8.29	2.93	5.71	0.1	7.81

1	HW	Middle	3	93.81	525	569.91	2.85	5.6	0.07	8.35	2.83	5.83	0.07	8.34
1	HW	Middle	4	97.54	508	552.4	3.05	5.65	0.1	8.62	2.89	5.83	0.07	8.2
1	HW	Middle	5	98.2	508	557.4	2.75	5.55	0.1	8.24	2.72	5.77	0.07	9.4
1	HW	Middle	6	98.49	496	539.91	3.05	5.6	0.07	8.54	2.99	5.77	0.07	8.56
1	HW	Middle	7	95.57	508	556.14	2.85	5.25	0.13	8.07	2.88	5.54	0.13	9.35
1	HW	Middle	8	98.68	503	545.18	2.75	5.15	0.13	7.88	2.72	5.64	0.1	8.39
1	HW	Middle	9	96.72	508	549.44	2.95	5.55	0.1	8.43	2.94	5.88	0.07	7.94
1	HW	Middle	10	98.17	500	538.42	2.8	5.6	0.1	8.33	2.88	5.83	0.1	7.88
1	HW	Middle	11	97.48	496	537.78	2.85	5.5	0.1	8.29	2.78	5.77	0.1	8.24
1	HW	Middle	12	97.46	492	534.47	2.75	5.55	0.13	8.27	2.72	5.61	0.1	8.29
1	HW	Middle	13	97.5	500	544.11	2.95	5.25	0.07	8.11	2.94	5.7	0.07	8.88
1	HW	Middle	14	96.23	508	549.44	2.95	5.1	0.1	7.99	2.94	5.48	0.07	8.05
1	HW	Middle	15	100.2	491	533.69	3.05	5.2	0.13	8.21	2.94	5.7	0.1	8.69
1	HW	Top	1	106.3	463	505.36	2.8	5	0.1	7.75	2.88	5.16	0.1	8.62
1	HW	Top	2	106.3	463	489.17	2.85	5	0.13	7.83	2.78	5.26	0.13	7.61
1	HW	Top	3	105.8	462	489.64	2.75	5	0.1	7.7	2.78	5.26	0.1	8.28
1	HW	Top	4	108.1	461	485.5	2.7	5.1	0.13	7.79	2.77	5.37	0.1	7.32
1	HW	Top	5	113.8	458	484.58	2.7	5.35	0.1	8	2.77	5.55	0.07	7.59
1	HW	Top	6	109.6	458	484.53	2.85	5	0.13	7.83	2.78	5.16	0.1	7.42
1	HW	Top	7	111.1	458	483.24	2.8	5	0.1	7.75	2.83	5.26	0.07	8.25
1	HW	Top	8	112.4	450	478.42	2.75	5	0.13	7.74	2.72	5.26	0.13	7.21
1	HW	Top	9	111.5	457	496.18	2.7	5.3	0.13	7.98	2.77	5.33	0.1	8.34
1	HW	Top	10	111.6	453	482.28	2.7	5	0.13	7.69	2.77	5.26	0.1	7.35
1	HW	Top	11	107	463	503.95	2.85	5	0.1	7.8	2.88	5.26	0.1	8.71
1	HW	Top	12	113	450	489.12	2.8	5.2	0.13	7.98	2.88	5.33	0.13	8.53
1	HW	Top	13	113	449	476.79	2.75	5.3	0.13	8.03	2.83	5.6	0.1	7.11
1	HW	Top	14	108.2	458	497.31	2.75	5.25	0.13	7.98	2.83	5.17	0.1	8.09
1	HW	Top	15	112.5	467	503.49	2.7	5	0.1	7.66	2.77	5.26	0.07	7.85

Appendix C: Raw data for Mechanical Test

Tree No	Wood type	Tree height	Specimens no	CS strength (N/mm2)	MOR(N/mm2)	MOE (N/mm2)	IMP. strength Nm/M2	RH (N)	HT(N)
1	SW	Bottom	1	44.19	91.09	6418.26	87500	3340	3270
1	SW	Bottom	2	45.64	90.56	6274.88	80000	3490	3260

1	SW	Bottom	3	44.51	91.09	6422.84	81250	3550	3370
1	SW	Bottom	4	45.44	91.09	6023.94	82500	3250	3350
1	SW	Bottom	5	44.46	90.56	6316.92	88750	3590	3450
1	SW	Bottom	6	44.59	91.61	6424.85	87500	3570	3350
1	SW	Bottom	7	45.04	91.09	6517.00	81250	3550	3390
1	SW	Bottom	8	44.24	90.04	6086.16	81250	3450	3460
1	SW	Bottom	9	44.01	91.09	5836.53	87500	3550	3560
1	SW	Bottom	10	45.39	90.04	6062.89	78750	3550	3130
1	SW	Bottom	11	45.51	90.56	5960.67	88750	3550	3270
1	SW	Bottom	12	44.51	91.61	6334.07	88750	3350	3280
1	SW	Bottom	13	44.96	91.09	6149.50	90000	3380	3520
1	SW	Bottom	14	45.66	90.56	6566.64	87500	3450	3280
1	SW	Bottom	15	45.46	91.61	6086.16	85000	3550	3350
1	SW	Middle	1	42.01	73.76	4594.51	78750	3460	3260
1	SW	Middle	2	41.56	74.81	5169.50	80000	3580	3480
1	SW	Middle	3	41.19	76.39	4824.87	77500	3210	3160
1	SW	Middle	4	42.91	76.39	5463.50	80000	3210	3250
1	SW	Middle	5	44.96	72.19	5654.14	75000	3310	3550
1	SW	Middle	6	42.64	75.34	5047.56	75000	3450	3270
1	SW	Middle	7	43.41	74.81	4903.26	73750	3450	3370
1	SW	Middle	8	43.46	71.14	5414.50	75000	3360	3350
1	SW	Middle	9	43.04	72.71	5064.29	76250	3250	3250
1	SW	Middle	10	41.29	72.71	4887.75	76250	3270	3360
1	SW	Middle	11	43.59	76.39	5414.30	77500	3550	3450
1	SW	Middle	12	42.84	73.76	5579.79	80000	3460	3310
1	SW	Middle	13	43.19	74.29	5082.26	77500	3490	3350
1	SW	Middle	14	44.61	76.39	5369.92	77500	3350	3220
1	SW	Middle	15	41.56	75.34	5896.78	72500	3260	3120
1	SW	Top	1	38.84	68.51	4887.75	73750	3150	3180
1	SW	Top	2	37.41	72.19	4847.36	72500	3550	3300
1	SW	Top	3	37.14	72.71	4737.69	72500	3160	3450
1	SW	Top	4	37.44	69.56	4875.50	72500	3450	3150
1	SW	Top	5	37.09	68.51	4663.60	73750	3470	3320
1	SW	Top	6	37.39	67.99	4544.75	71250	3250	3260
1	SW	Top	7	40.06	71.14	4660.76	72500	3450	3550
1	SW	Top	8	37.89	70.09	5179.30	75000	3150	3390

1	SW	Top	9	37.56	72.19	4679.50	72500	3250	3300
1	SW	Top	10	36.61	71.14	4630.50	72500	3110	2950
1	SW	Top	11	38.94	68.51	4824.87	73750	3460	3050
1	SW	Top	12	38.09	67.99	5169.50	72500	3190	3160
1	SW	Top	13	38.89	71.14	4511.77	71250	3130	3290
1	SW	Top	14	36.64	70.61	4951.37	72500	3250	3250
1	SW	Top	15	37.14	71.14	4887.75	73750	3370	3150
1	HW	Bottom	1	53.36	93.71	6086.16	97500	3850	3850
1	HW	Bottom	2	53.69	92.66	6840.51	96250	3970	3700
1	HW	Bottom	3	53.36	93.61	6019.65	82500	4020	3740
1	HW	Bottom	4	54.14	93.19	6678.41	98750	4010	3670
1	HW	Bottom	5	53.69	93.71	6600.76	95000	4010	3460
1	HW	Bottom	6	54.11	93.61	6832.78	82500	3950	3950
1	HW	Bottom	7	54.64	93.19	6733.90	97500	3650	3990
1	HW	Bottom	8	53.44	93.19	5912.91	98750	3750	3950
1	HW	Bottom	9	54.44	93.19	6168.47	97500	3950	3360
1	HW	Bottom	10	53.69	93.51	6466.01	82500	4030	3950
1	HW	Bottom	11	53.41	93.71	6574.17	95000	3960	3550
1	HW	Bottom	12	54.39	93.19	6667.06	92500	4020	3490
1	HW	Bottom	13	53.24	93.51	6131.71	98750	4030	3950
1	HW	Bottom	14	53.71	93.19	6086.16	96250	3970	3850
1	HW	Bottom	15	53.44	93.61	6726.02	98750	4020	4450
1	HW	Middle	1	51.86	93.19	5586.49	93750	3950	3840
1	HW	Middle	2	45.64	92.14	5977.28	95000	3890	3850
1	HW	Middle	3	46.19	94.24	5974.32	92500	3950	3880
1	HW	Middle	4	51.01	93.19	5968.20	93750	3970	3870
1	HW	Middle	5	51.94	92.14	5955.73	95000	3950	3850
1	HW	Middle	6	50.61	93.71	5951.05	88750	3980	3400
1	HW	Middle	7	51.24	93.71	5750.29	92500	3960	3690
1	HW	Middle	8	50.99	94.24	5883.10	95000	3970	3950
1	HW	Middle	9	52.14	93.19	5784.23	85000	3750	3590
1	HW	Middle	10	50.81	91.61	5975.42	95000	3630	3380
1	HW	Middle	11	48.59	94.24	5883.10	92500	3630	3560
1	HW	Middle	12	51.34	92.66	5770.74	95000	3970	3700
1	HW	Middle	13	49.76	93.19	5812.51	92500	3760	3510
1	HW	Middle	14	51.89	93.71	5883.10	92500	3750	3620

1	HW	Middle	15	47.59	92.66	5852.78	92500	3750	3570
1	HW	Top	1	41.86	71.66	4890.93	76250	3560	3950
1	HW	Top	2	43.39	75.34	5039.46	80000	3800	4050
1	HW	Top	3	46.21	72.19	5231.84	78750	3650	3400
1	HW	Top	4	43.41	73.24	5249.57	78750	3760	3410
1	HW	Top	5	42.14	66.41	4639.29	77500	3820	3710
1	HW	Top	6	44.31	76.39	5241.04	73750	3850	3950
1	HW	Top	7	46.71	70.61	4831.28	78750	3780	3930
1	HW	Top	8	43.69	73.76	5244.42	76250	3740	4000
1	HW	Top	9	48.44	78.49	4994.94	80000	3720	3050
1	HW	Top	10	45.39	73.76	4622.13	73750	3670	3050
1	HW	Top	11	47.01	72.19	5145.00	73750	3750	3320
1	HW	Top	12	49.11	68.51	4855.72	73750	3590	3290
1	HW	Top	13	49.69	76.39	5664.01	75000	3504	3250
1	HW	Top	14	46.36	73.24	5559.92	76250	3490	3950
1	HW	Top	15	42.61	71.66	4890.93	80000	3720	3550

Appendix C: Stastically out put

Basic density

Notes

Description	Perform Normality Test
User Name	gg201
Operation Time	6/3/2026 00:48:51
Report Status	New Analysis Report
Data Filter	No

Input Data

	Data	Range
Data	[Book1]Sheet1!E"BD_kg_m3"	[1*:270*]
Group	[Book1]Sheet1!B"Wood type"	[1*:270*]
	[Book1]Sheet1!C"Tree height"	[1*:270*]

Descriptive Statistics

			N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
BD_kg_m3	Sapwood	Bottom	45	0	485.74074	9.30037	1.38642
		Middle	45	0	455.68519	12.0726	1.79968
		Top	45	0	432.46296	27.34977	4.07706
	Heartwood	Bottom	45	0	506.37037	13.38078	1.99469
		Middle	45	0	484.03704	17.71598	2.64094
		Top	45	0	454.38889	14.87044	2.21675

Shapiro-Wilk

			DF	Statistic	p-value	Decision at level(5%)
BD_kg_m3	Sapwood	Bottom	45	0.96735	0.23146	Can't reject normality
		Middle	45	0.9122	0.00232	Reject normality
		Top	45	0.95111	0.05594	Can't reject normality
	Heartwood	Bottom	45	0.94396	0.03012	Reject normality
		Middle	45	0.97751	0.5225	Can't reject normality
		Top	45	0.94122	0.02385	Reject normality

BD_kg_m3(Sapwood,Bottom): At the 0.05 level, the data was significantly drawn from a normally distributed population.

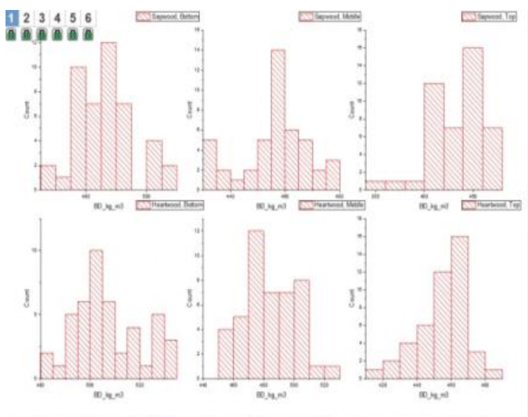
BD_kg_m3(Sapwood,Middle): At the 0.05 level, the data was not significantly drawn from a normally distributed population.

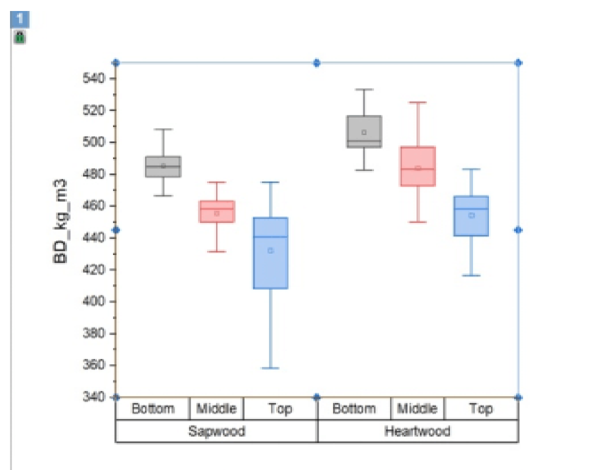
BD_kg_m3(Sapwood,Top): At the 0.05 level, the data was significantly drawn from a normally distributed population.

BD_kg_m3(Heartwood,Bottom): At the 0.05 level, the data was not significantly drawn from a normally distributed population.

BD_kg_m3(Heartwood,Middle): At the 0.05 level, the data was significantly drawn from a normally distributed population.

BD_kg_m3(Heartwood,Top): At the 0.05 level, the data was not significantly drawn from a normally distributed population.





Histogram graph ***Box plot graph***

Notes

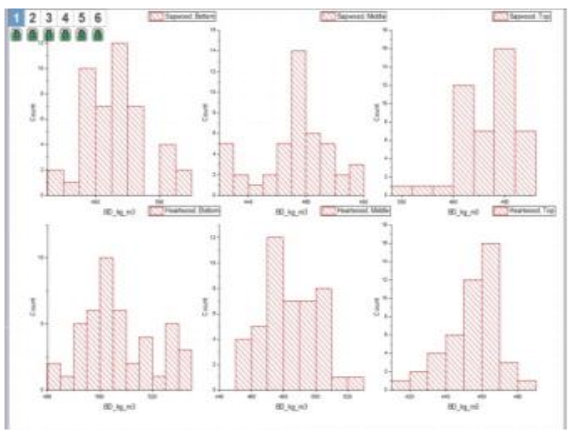
Description	Perform Descriptive Statistics
User Name	gg201
Operation Time	6/3/2026 00:56:40
Report Status	New Analysis Report
Data Filter	No

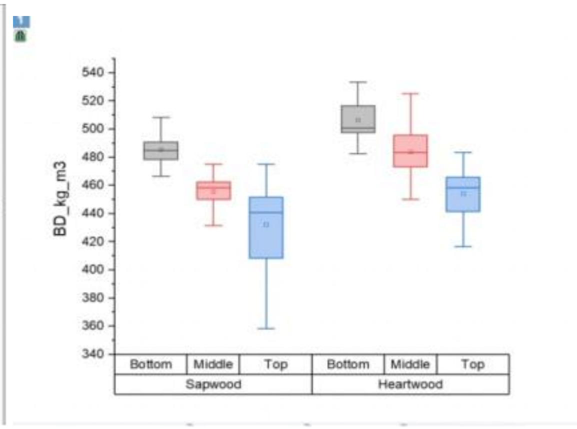
Input Data

	Data	Range
Data	[Book1]Sheet1!E"BD_kg_m3"	[1*:270*]
Group	[Book1]Sheet1!B"Wood type"	[1*:270*]
	[Book1]Sheet1!C"Tree height"	[1*:270*]

Descriptive Statistics

			N total	N missing	Mean	Standard Deviation	Skewness	Coefficient of Variation	Minimum	Maximum
BD_kg_m3	Sapwood	Bottom	45	0	485.74074	9.30037	0.48441	0.01915	466.66667	508.33333
		Middle	45	0	455.68519	12.0726	-0.61581	0.02649	431.66667	475
		Top	45	0	432.46296	27.34977	-0.62467	0.06324	358.33333	475
	Heartwood	Bottom	45	0	506.37037	13.38078	0.45858	0.02642	482.5	533.33333
		Middle	45	0	484.03704	17.71598	0.13985	0.0366	450	525
		Top	45	0	454.38889	14.87044	-0.71068	0.03273	416.66667	483.33333





Histogram graph

Box plot graph

Notes

Description	Perform Two-Way ANOVA
User Name	gg201
Operation Time	6/3/2026 01:01:50
Report Status	New Analysis Report
Data Filter	No

Input Data

	Data	Range
Dependent Variable	[Book1]Sheet1!E"BD_kg_m3"	[1*:270*]
Factor A	[Book1]Sheet1!B"Wood type"	[1*:270*]
Factor B	[Book1]Sheet1!C"Tree height"	[1*:270*]

Wood type

	N	Mean	SD	SEM	Variance	Missing	NonMissing
Sapwood	135	457.96296	28.30381	2.436	801.10558	0	135
Heartwood	135	481.59877	26.28991	2.26268	691.15933	0	135

Tree height

	N	Mean	SD	SEM	Variance	Missing	NonMissing
Bottom	90	496.05556	15.45543	1.62914	238.87016	0	90
Middle	90	469.86111	20.74692	2.18692	430.43461	0	90
Top	90	443.42593	24.50841	2.58341	600.66237	0	90

Overall

N	Mean	SD	SEM	Variance	Missing	NonMissing
270	469.78086	29.72441	1.80897	883.54071	0	270

Interaction

		N	Mean	SD	SEM	Variance	Missing	NonMissing
Sapwood	Bottom	45	485.74074	9.30037	1.38642	86.49691	0	45
	Middle	45	455.68519	12.0726	1.79968	145.74776	0	45
	Top	45	432.46296	27.34977	4.07706	748.00996	0	45
Heartwood	Bottom	45	506.37037	13.38078	1.99469	179.04531	0	45
	Middle	45	484.03704	17.71598	2.64094	313.85592	0	45
	Top	45	454.38889	14.87044	2.21675	221.13005	0	45

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	P Value
Wood type	1	37708.95319	37708.95319	133.53928	<0.0001
Tree height	2	124645.37551	62322.68776	220.70426	<0.0001
Interaction	2	769.54218	384.77109	1.3626	0.25779
Model	5	163123.87088	32624.77418	115.5346	<0.0001
Error	264	74548.58025	282.38099		
Corrected Total	269	237672.45113			

At the 0.05 level, the population means of Wood type are significantly different.

At the 0.05 level, the population means of Tree height are significantly different.

At the 0.05 level, the interaction between Wood type and Tree height is not significant.

Wood type

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Heartwood Sapwood	23.6358	2.04534	16.34254	<0.0001	0.05	1	19.60848	27.66312

Tree height

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Middle Bottom	-26.19444	2.50502	14.78811	<0.0001	0.05	1	-32.09879	-20.2901
Top Bottom	-52.62963	2.50502	29.71213	<0.0001	0.05	1	-58.53398	-46.72528
Top Middle	-26.43519	2.50502	14.92402	<0.0001	0.05	1	-32.33953	-20.53084

Interactions

Wood type	Tree height	Wood type	Tree height	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Sapwood	Middle	Sapwood	Bottom	-30.05556	3.54264	11.99812	<0.0001	0.05	1	-40.22568	-19.88543
Sapwood	Top	Sapwood	Bottom	-53.27778	3.54264	21.26839	<0.0001	0.05	1	-63.4479	-43.10766
Sapwood	Top	Sapwood	Middle	-23.22222	3.54264	9.27027	<0.0001	0.05	1	-33.39234	-13.0521
Heartwood	Bottom	Sapwood	Bottom	20.62963	3.54264	8.23531	<0.0001	0.05	1	10.45951	30.79975
Heartwood	Bottom	Sapwood	Middle	50.68519	3.54264	20.23343	<0.0001	0.05	1	40.51506	60.85531
Heartwood	Bottom	Sapwood	Top	73.90741	3.54264	29.5037	<0.0001	0.05	1	63.73729	84.07753
Heartwood	Middle	Sapwood	Bottom	-1.7037	3.54264	0.68012	0.99679	0.05	0	-11.87383	8.46642
Heartwood	Middle	Sapwood	Middle	28.35185	3.54264	11.31801	<0.0001	0.05	1	18.18173	38.52197

Heartwood	Middle	Sapwood	Top	51.57407	3.54264	20.58828	<0.0001	0.05	1	41.40395	61.7442
Heartwood	Middle	Heartwood	Bottom	-22.33333	3.54264	8.91543	<0.0001	0.05	1	-32.50345	-12.16321
Heartwood	Top	Sapwood	Bottom	-31.35185	3.54264	12.5156	<0.0001	0.05	1	-41.52197	-21.18173
Heartwood	Top	Sapwood	Middle	-1.2963	3.54264	0.51748	0.99914	0.05	0	-11.46642	8.87383
Heartwood	Top	Sapwood	Top	21.92593	3.54264	8.75279	<0.0001	0.05	1	11.7558	32.09605
Heartwood	Top	Heartwood	Bottom	-51.98148	3.54264	20.75091	<0.0001	0.05	1	-62.1516	-41.81136
Heartwood	Top	Heartwood	Middle	-29.64815	3.54264	11.83549	<0.0001	0.05	1	-39.81827	-19.47803

Wood type's Grouping Letters Table

	Mean	Groups	
Heartwood	481.59877	A	
Sapwood	457.96296		B

Means that do not share a letter are significantly different.

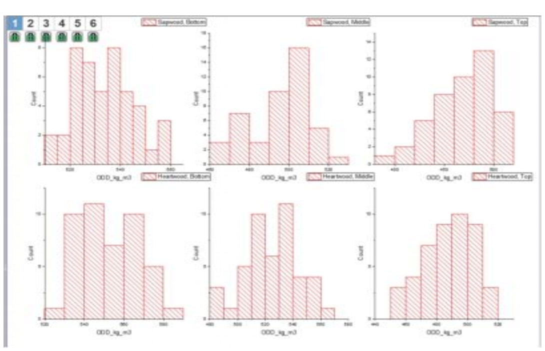
Tree height's Grouping Letters Table

	Mean	Groups		
Bottom	496.05556	A		
Middle	469.86111		B	
Top	443.42593			C

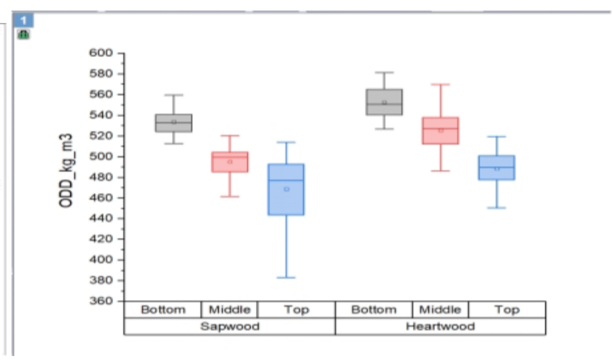
Means that do not share a letter are significantly different.

Interactions 's Grouping Letters Table

Wood type	Tree height	Mean	Groups			
Heartwood	Bottom	506.37037	A			
Sapwood	Bottom	485.74074		B		
Heartwood	Middle	484.03704		B		
Sapwood	Middle	455.68519			C	
Heartwood	Top	454.38889			C	
Sapwood	Top	432.46296				D



Histogram graph



Box plot graph

Notes

Description	Perform Descriptive Statistics
User Name	gg201
Operation Time	6/3/2026 01:32:56

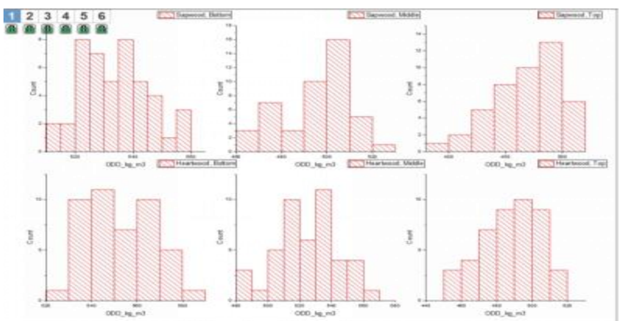
Report Status	New Analysis Report
Data Filter	No

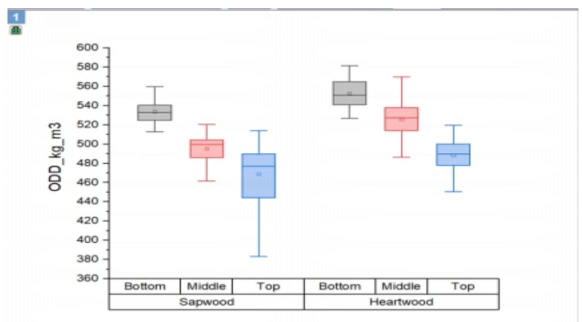
Input Data

	Data	Range
Data	[Book1]Sheet1!F"ODD_kg_m3"	[1*:270*]
Group	[Book1]Sheet1!B"Wood type"	[1*:270*]
	[Book1]Sheet1!C"Tree height"	[1*:270*]

Descriptive Statistics

			N total	N missing	Mean	Standard Deviation	Skewness	Coefficient of Variation	Minimum	Maximum
ODD_kg_m3	Sapwood	Bottom	45	0	533.80947	11.32035	0.42367	0.02121	512.92729	559.58442
		Middle	45	0	495.30643	14.48833	-0.62658	0.02925	461.40069	520.50462
		Top	45	0	468.88539	30.00668	-0.76045	0.064	383.16781	513.86943
	Heartwood	Bottom	45	0	552.70481	14.51773	0.30014	0.02627	526.88631	581.34934
		Middle	45	0	525.44048	19.61964	-0.031	0.03734	486.49736	569.90791
		Top	45	0	488.3772	15.65097	-0.44303	0.03205	450.52389	519.66952





Histogram graph   ***Box plot graph***

Notes

Description	Perform Two-Way ANOVA
User Name	gg201
Operation Time	6/3/2026 01:38:11
Report Status	New Analysis Report
Data Filter	No

Input Data

	Data	Range
Dependent Variable	[Book1]Sheet1!F"ODD_kg_m3"	[1*:270*]
Factor A	[Book1]Sheet1!B"Wood type"	[1*:270*]
Factor B	[Book1]Sheet1!C"Tree height"	[1*:270*]

Wood type

	N	Mean	SD	SEM	Variance	Missing	NonMissing
Sapwood	135	499.33376	33.50515	2.88366	1122.59517	0	135
Heartwood	135	522.17416	31.24465	2.68911	976.22815	0	135

Tree height

	N	Mean	SD	SEM	Variance	Missing	NonMissing
Bottom	90	543.25714	16.05661	1.69252	257.81468	0	90
Middle	90	510.37346	22.88329	2.41211	523.64497	0	90
Top	90	478.63129	25.73504	2.71271	662.29227	0	90

Overall

N	Mean	SD	SEM	Variance	Missing	NonMissing
270	510.75396	34.29892	2.08737	1176.41626	0	270

Interaction

		N	Mean	SD	SEM	Variance	Missing	NonMissing
Sapwood	Bottom	45	533.80947	11.32035	1.68754	128.15032	0	45
	Middle	45	495.30643	14.48833	2.15979	209.91171	0	45
	Top	45	468.88539	30.00668	4.47313	900.40095	0	45
Heartwood	Bottom	45	552.70481	14.51773	2.16417	210.76439	0	45
	Middle	45	525.44048	19.61964	2.92472	384.9301	0	45
	Top	45	488.3772	15.65097	2.33311	244.953	0	45

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	P Value
Wood type	1	35213.64854	35213.64854	101.62129	<0.0001
Tree height	2	187962.05311	93981.02656	271.2151	<0.0001
Interaction	2	1799.41113	899.70556	2.59641	0.07644
Model	5	224975.11278	44995.02256	129.84887	<0.0001
Error	264	91480.86013	346.51841		
Corrected Total	269	316455.9729			

At the 0.05 level, the population means of Wood type are significantly different.

At the 0.05 level, the population means of Tree height are significantly different.

At the 0.05 level, the interaction between Wood type and Tree height is not significant.

Wood type

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Heartwood Sapwood	22.8404	2.26575	14.25632	<0.0001	0.05	1	18.37909	27.3017

Tree height

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Middle Bottom	-32.88368	2.77496	16.75863	<0.0001	0.05	1	-39.42428	-26.34309
Top Bottom	-64.62585	2.77496	32.93551	<0.0001	0.05	1	-71.16644	-58.08525
Top Middle	-31.74216	2.77496	16.17688	<0.0001	0.05	1	-38.28276	-25.20157

Interactions

Wood type	Tree height	Wood type	Tree height	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Sapwood	Middle	Sapwood	Bottom	-38.50304	3.92439	13.87516	<0.0001	0.05	1	-49.76908	-27.23699
Sapwood	Top	Sapwood	Bottom	-64.92408	3.92439	23.39639	<0.0001	0.05	1	-76.19013	-53.65804

Sapwood	Top	Sapwood	Middle	-26.42105	3.92439	9.52123	<0.0001	0.05	1	-37.68709	-15.155
Heartwood	Bottom	Sapwood	Bottom	18.89534	3.92439	6.80923	<0.0001	0.05	1	7.62929	30.16138
Heartwood	Bottom	Sapwood	Middle	57.39837	3.92439	20.68439	<0.0001	0.05	1	46.13233	68.66442
Heartwood	Bottom	Sapwood	Top	83.81942	3.92439	30.20562	<0.0001	0.05	1	72.55337	95.08547
Heartwood	Middle	Sapwood	Bottom	-8.36899	3.92439	3.0159	0.27381	0.05	0	-19.63504	2.89705
Heartwood	Middle	Sapwood	Middle	30.13404	3.92439	10.85927	<0.0001	0.05	1	18.868	41.40009
Heartwood	Middle	Sapwood	Top	56.55509	3.92439	20.3805	<0.0001	0.05	1	45.28904	67.82114
Heartwood	Middle	Heartwood	Bottom	-27.26433	3.92439	9.82512	<0.0001	0.05	1	-38.53038	-15.99828
Heartwood	Top	Sapwood	Bottom	-45.43228	3.92439	16.37222	<0.0001	0.05	1	-56.69832	-34.16623
Heartwood	Top	Sapwood	Middle	-6.92924	3.92439	2.49706	0.48979	0.05	0	-18.19529	4.33681
Heartwood	Top	Sapwood	Top	19.49181	3.92439	7.02417	<0.0001	0.05	1	8.22576	30.75786
Heartwood	Top	Heartwood	Bottom	-64.32761	3.92439	23.18145	<0.0001	0.05	1	-75.59366	-53.06156
Heartwood	Top	Heartwood	Middle	-37.06328	3.92439	13.35632	<0.0001	0.05	1	-48.32933	-25.79723

Wood type's Grouping Letters Table

	Mean	Groups	
Heartwood	522.17416	A	
Sapwood	499.33376		B

Means that do not share a letter are significantly different.

Tree height's Grouping Letters Table

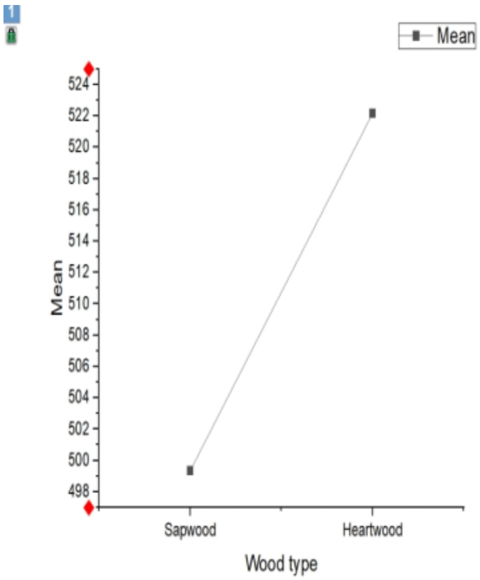
	Mean	Groups		
Bottom	543.25714	A		
Middle	510.37346		B	
Top	478.63129			C

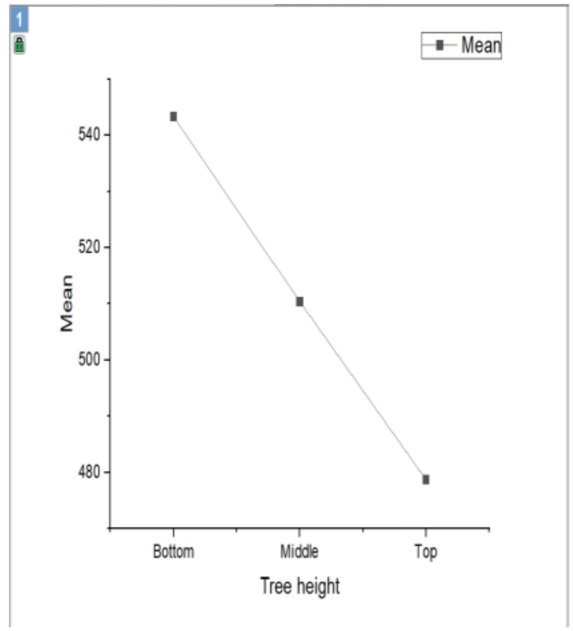
Means that do not share a letter are significantly different.

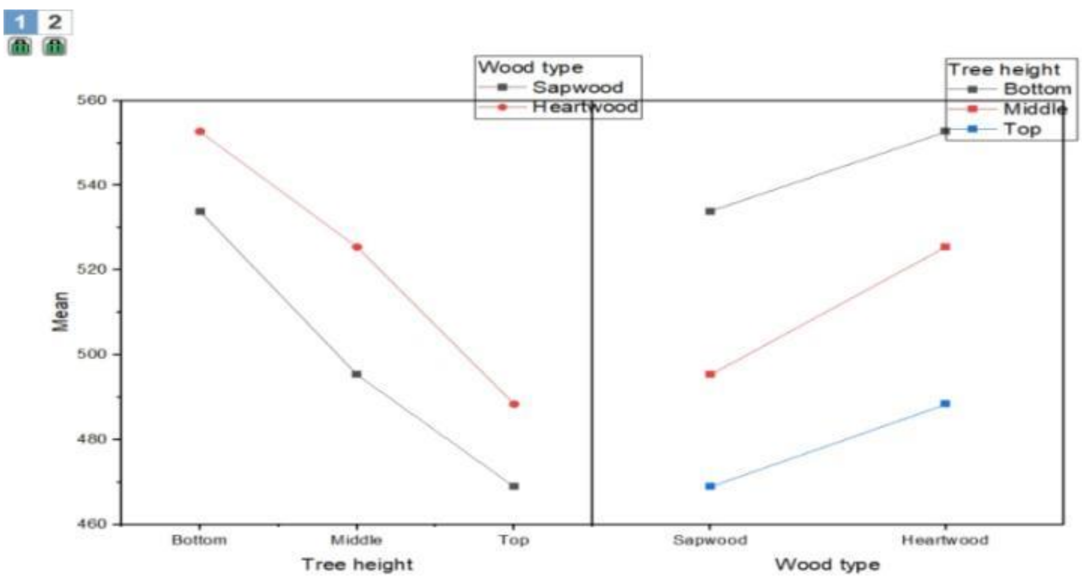
Interactions 's Grouping Letters Table

Wood type	Tree height	Mean	Groups			
Heartwood	Bottom	552.70481	A			
Sapwood	Bottom	533.80947		B		
Heartwood	Middle	525.44048		B		
Sapwood	Middle	495.30643			C	
Heartwood	Top	488.3772			C	
Sapwood	Top	468.88539				D

Means that do not share a letter are significantly different.







MOE strength to the radial

Notes

Description	Perform Normality Test
User Name	gg201
Operation Time	6/4/2026 11:23:42
Report Status	New Analysis Report
Data Filter	No

Input Data

	Data	Range

Data	[Book1]"Mechanical Properties"!F"MOE"	[1:269]
Data	[Book1]"Mechanical Properties"!F"MOE"	[1:269]
Group	[Book1]"Mechanical Properties"!B"Wood Type"	[1*:270*]
	[Book1]"Mechanical Properties"!B"Wood Type"	[1*:270*]
Group	[Book1]"Mechanical Properties"!C"Tree Height"	[1*:270*]
	[Book1]"Mechanical Properties"!C"Tree Height"	[1*:270*]

Descriptive Statistics

			N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
MOE	Sapwood	Bottom	45	0	5708.12245	443.34574	66.09008
		Middle	45	0	5205.40899	335.71954	50.04611
		Top	45	0	4619.62455	269.96849	40.24453
	Heartwood	Bottom	45	0	6281.32346	334.26873	49.82984
		Middle	45	0	5378.27439	453.95552	67.67169
		Top	45	0	4930.31958	397.13367	59.20119

Shapiro-Wilk

			DF	Statistic	p-value	Decision at level(5%)
MOE	Sapwood	Bottom	45	0.95388	0.07131	Can't reject normality
		Middle	45	0.97073	0.30775	Can't reject normality
		Top	45	0.98237	0.7162	Can't reject normality
	Heartwood	Bottom	45	0.94668	0.03807	Reject normality
		Middle	45	0.93295	0.01194	Reject normality
		Top	45	0.96083	0.13133	Can't reject normality

MOE(Sapwood,Bottom): At the 0.05 level, the data was significantly drawn from a normally distributed population.

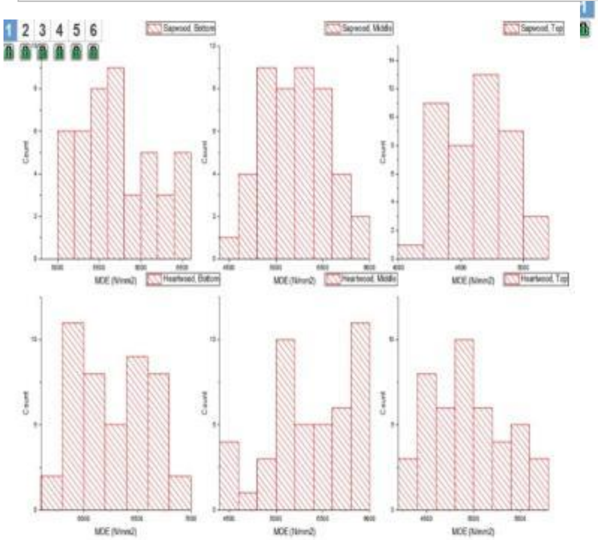
MOE(Sapwood,Middle): At the 0.05 level, the data was significantly drawn from a normally distributed population.

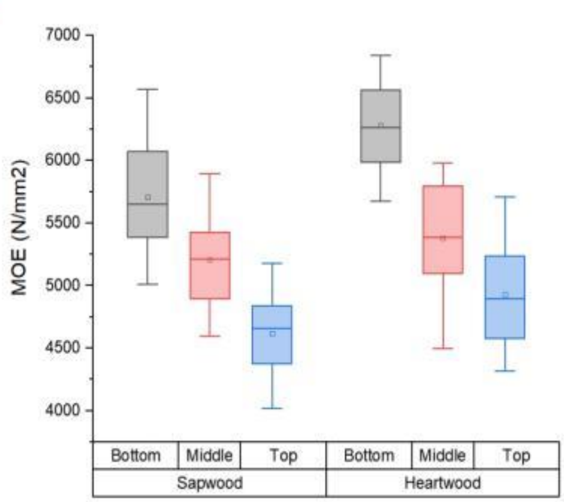
MOE(Sapwood,Top): At the 0.05 level, the data was significantly drawn from a normally distributed population.

MOE(Heartwood,Bottom): At the 0.05 level, the data was not significantly drawn from a normally distributed population.

MOE(Heartwood,Middle): At the 0.05 level, the data was not significantly drawn from a normally distributed population.

MOE(Heartwood,Top): At the 0.05 level, the data was significantly drawn from a normally distributed population.





Notes

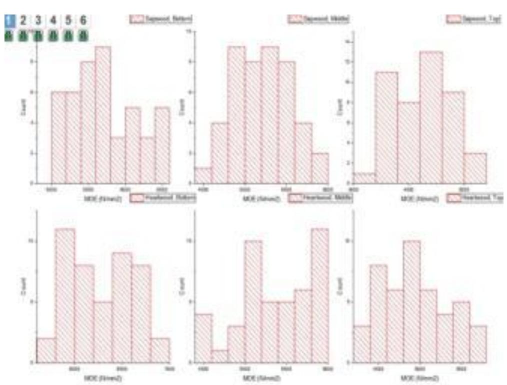
Description	Perform Descriptive Statistics
User Name	gg201
Operation Time	6/4/2026 11:29:28
Report Status	New Analysis Report
Data Filter	No

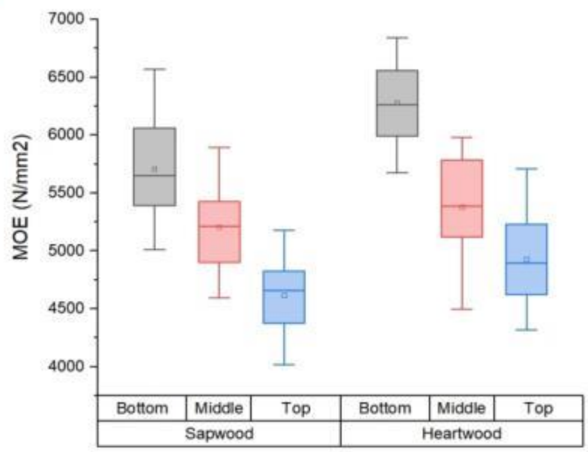
Input Data

	Data	Range
Data	[Book1]"Mechanical Properties"!F"MOE"	[1:269]
Data	[Book1]"Mechanical Properties"!F"MOE"	[1:269]
Group	[Book1]"Mechanical Properties"!B"Wood Type"	[1*:270*]
	[Book1]"Mechanical Properties"!B"Wood Type"	[1*:270*]
Group	[Book1]"Mechanical Properties"!C"Tree Height"	[1*:270*]
	[Book1]"Mechanical Properties"!C"Tree Height"	[1*:270*]

Descriptive Statistics

			N total	Mean	Standard Deviation	Skewness	Coefficient of Variation	Minimum	Maximum
MOE	Sapwood	Bottom	45	5708.12245	443.34574	0.32751	0.07767	5008.57955	6566.64474
		Middle	45	5205.40899	335.71954	0.1633	0.06449	4594.50617	5896.78082
		Top	45	4619.62455	269.96849	0.03802	0.05844	4017.32877	5179.3
	Heartwood	Bottom	45	6281.32346	334.26873	0.02864	0.05322	5672.69231	6840.51136
		Middle	45	5378.27439	453.95552	-0.36872	0.08441	4496.64634	5977.27941
		Top	45	4930.31958	397.13367	0.1963	0.08055	4316.08333	5707.73438





Notes

Description	Perform Two-Way ANOVA
User Name	gg201
Operation Time	6/4/2026 11:34:49

Report Status	New Analysis Report
Data Filter	No

Input Data

	Data	Range
Dependent Variable	[Book1]"Mechanical Properties"!F"MOE"	[1:269]
Dependent Variable	[Book1]"Mechanical Properties"!F"MOE"	[1:269]
Factor A	[Book1]"Mechanical Properties"!B"Wood Type"	[1*:270*]
Factor A	[Book1]"Mechanical Properties"!B"Wood Type"	[1*:270*]
Factor B	[Book1]"Mechanical Properties"!C"Tree Height"	[1*:270*]
Factor B	[Book1]"Mechanical Properties"!C"Tree Height"	[1*:270*]

Wood Type

	N	Mean	SD	SEM	Variance	Missing	NonMissing
Sapwood	135	5177.71866	569.92278	49.05114	324811.97244	0	135
Heartwood	135	5529.97248	688.62695	59.26757	474207.07864	0	135

Tree Height

	N	Mean	SD	SEM	Variance	Missing	NonMissing
Bottom	90	5994.72295	485.25901	51.15079	235476.30962	0	90
Middle	90	5291.84169	406.39297	42.83758	165155.24542	0	90
Top	90	4774.97206	372.03169	39.21558	138407.5798	0	90

Overall

	N	Mean	SD	SEM	Variance	Missing	NonMissing
	270	5353.84557	655.10332	39.86832	429160.36614	0	270

Interaction

		N	Mean	SD	SEM	Variance	Missing	NonMissing
Sapwood	Bottom	45	5708.12245	443.34574	66.09008	196555.44128	0	45
	Middle	45	5205.40899	335.71954	50.04611	112707.61077	0	45
	Top	45	4619.62455	269.96849	40.24453	72882.98536	0	45
Heartwood	Bottom	45	6281.32346	334.26873	49.82984	111735.58297	0	45
	Middle	45	5378.27439	453.95552	67.67169	206075.61119	0	45
	Top	45	4930.31958	397.13367	59.20119	157715.15237	0	45

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	P Value
Wood Type	1	8375585.64585	8375585.64585	58.5929	<0.0001
Tree Height	2	6.74697E7	3.37348E7	235.998	<0.0001
Interaction	2	1861312.46126	930656.23063	6.51057	0.00174
Model	5	7.77066E7	1.55413E7	108.72201	<0.0001
Error	264	3.77376E7	142945.39732		
Corrected Total	269	1.15444E8			

At the 0.05 level, the population means of Wood Type are significantly different.
At the 0.05 level, the population means of Tree Height are significantly different.
At the 0.05 level, the interaction between Wood Type and Tree Height is significant.

Wood Type

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Heartwood Sapwood	352.25382	46.01858	10.82524	<0.0001	0.05	1	261.64223	442.8654

Tree Height

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Middle Bottom	-702.88126	56.36102	17.63673	<0.0001	0.05	1	-835.7244	-570.03812
Top Bottom	-1219.75089	56.36102	30.60605	<0.0001	0.05	1	-1352.59403	-1086.90775
Top Middle	-516.86963	56.36102	12.96932	<0.0001	0.05	1	-649.71277	-384.02649

Interactions

Wood Type	Tree Height	Wood Type	Tree Height	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
Sapwood	Middle	Sapwood	Bottom	-502.71346	79.70652	8.91952	<0.0001	0.05	1	-731.53321	-273.89371
Sapwood	Top	Sapwood	Bottom	-1088.4979	79.70652	19.31296	<0.0001	0.05	1	-1317.31765	-859.67815
Sapwood	Top	Sapwood	Middle	-585.78444	79.70652	10.39343	<0.0001	0.05	1	-814.60419	-356.96469
Heartwood	Bottom	Sapwood	Bottom	573.20101	79.70652	10.17017	<0.0001	0.05	1	344.38126	802.02076
Heartwood	Bottom	Sapwood	Middle	1075.91447	79.70652	19.08969	<0.0001	0.05	1	847.09472	1304.73422
Heartwood	Bottom	Sapwood	Top	1661.69891	79.70652	29.48312	<0.0001	0.05	1	1432.87916	1890.51866
Heartwood	Middle	Sapwood	Bottom	-329.84806	79.70652	5.85241	6.6538E-4	0.05	1	-558.66781	-101.02831
Heartwood	Middle	Sapwood	Middle	172.8654	79.70652	3.06711	0.25599	0.05	0	-55.95435	401.68515
Heartwood	Middle	Sapwood	Top	758.64984	79.70652	13.46054	<0.0001	0.05	1	529.83009	987.46959
Heartwood	Middle	Heartwood	Bottom	-903.04907	79.70652	16.02258	<0.0001	0.05	1	-1131.86882	-674.22932
Heartwood	Top	Sapwood	Bottom	-777.80287	79.70652	13.80037	<0.0001	0.05	1	-1006.62262	-548.98312
Heartwood	Top	Sapwood	Middle	-275.08941	79.70652	4.88085	0.00844	0.05	1	-503.90916	-46.26966
Heartwood	Top	Sapwood	Top	310.69503	79.70652	5.51259	0.0017	0.05	1	81.87528	539.51478
Heartwood	Top	Heartwood	Bottom	-1351.00388	79.70652	23.97054	<0.0001	0.05	1	-1579.82363	-1122.18413
Heartwood	Top	Heartwood	Middle	-447.95481	79.70652	7.94795	<0.0001	0.05	1	-676.77456	-219.13506

Wood Type's Grouping Letters Table

	Mean	Groups	
Heartwood	5529.97248	A	
Sapwood	5177.71866		B

Means that do not share a letter are significantly different.

Tree Height's Grouping Letters Table

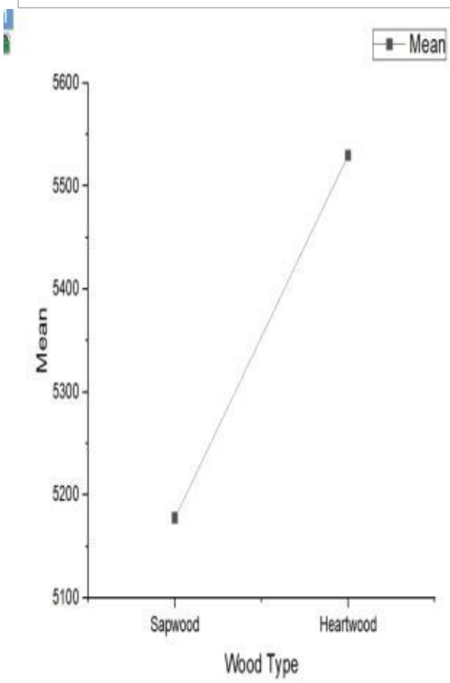
	Mean	Groups		
Bottom	5994.72295	A		
Middle	5291.84169		B	
Top	4774.97206			C

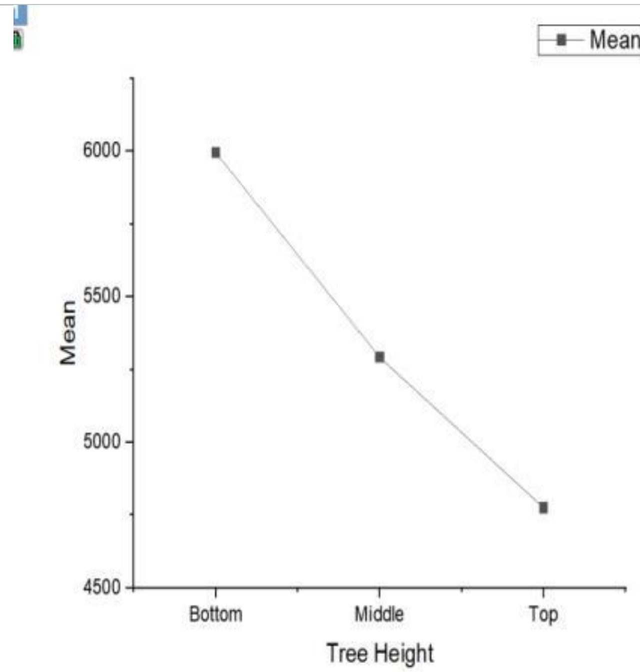
Means that do not share a letter are significantly different.

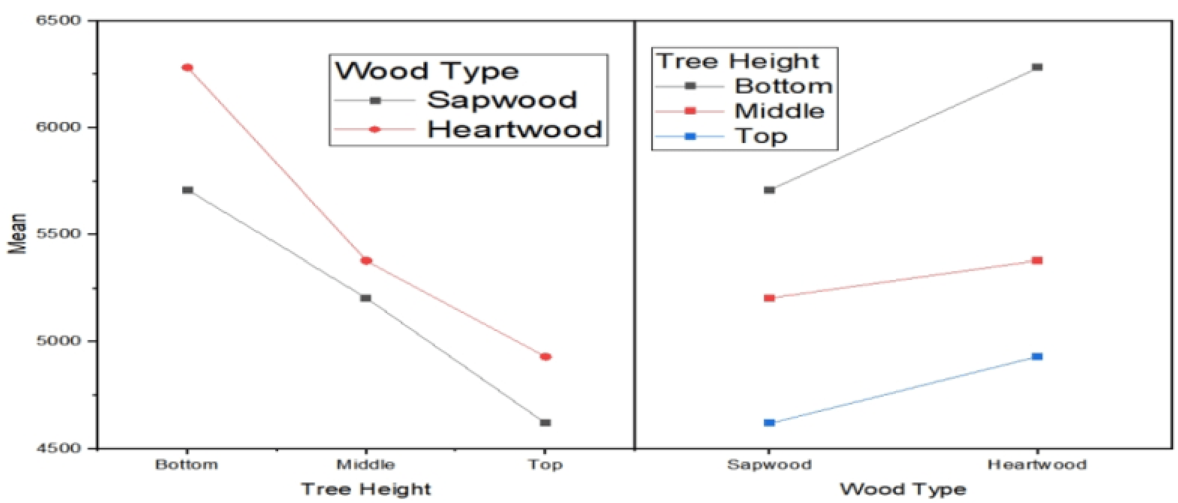
Interactions 's Grouping Letters Table

Wood Type	Tree Height	Mean	Groups				
Heartwood	Bottom	6281.32346	A				
Sapwood	Bottom	5708.12245		B			
Heartwood	Middle	5378.27439			C		
Sapwood	Middle	5205.40899			C		
Heartwood	Top	4930.31958				D	
Sapwood	Top	4619.62455					E

Means that do not share a letter are significantly different.







Appendix D: photos

(a) *Cordia africana*, Potential site

(b) Water releasing from the cut log

(C) In the sawmill

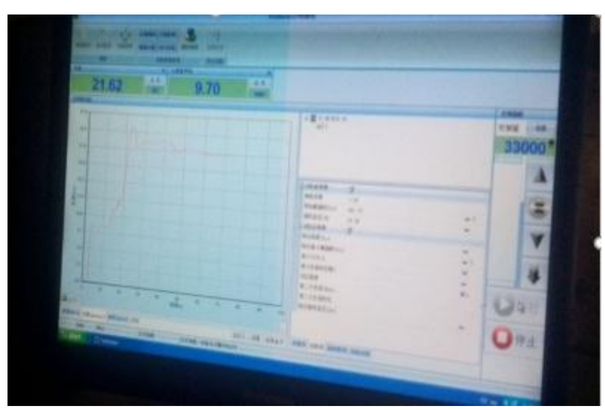
(d) Boards/lumbers

(e) Specimens

(f)Weighing specimens
For physical test

(g) Oven dry machine

(h) Weighing specimens
for mechanical test



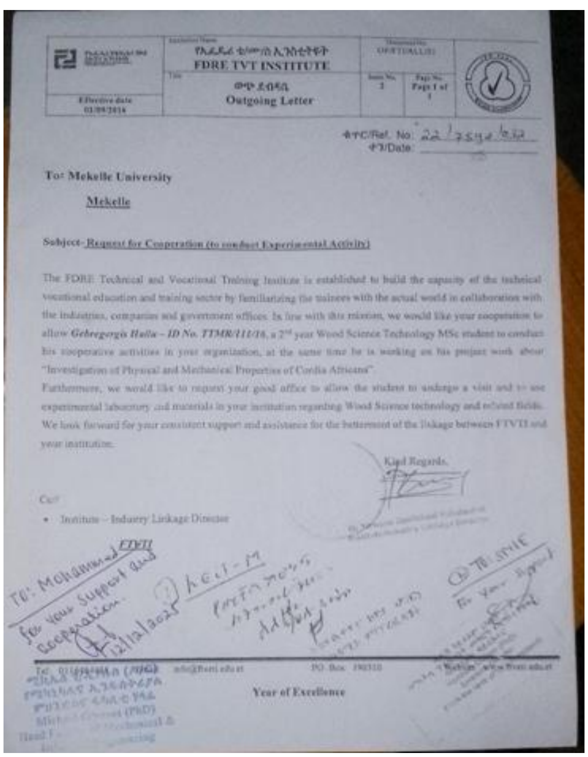
Computer interface of the Universal Testing Machine during mechanical testing of *Cordia africana* wood specimens.

The Figure is a load-displacement curve for *Cordia africana* wood that was drawn in the process of conducting the compression strength parallel to the grain test. In the first stage of deformation, the load almost linearly increased with an increase in displacement up to 21.62 kN, where the displacement was 9.70 mm. After reaching the maximum load, the load started decreasing slowly due to gradual crushing of wood fibers parallel to the grain. This implies that the specimen was still able to bear loads even after failing, which**is** characteristic of wood subjected to compression parallel to the grain. Sample calculations of compression strength from the computer recorded when testing.

$$\sigma_c = \frac{P_{max}}{bd}$$

$\sigma_c = P_{max}/bd$ = 21,620 N/(20 mm × 20 mm) = 21,620 N/400 mm² = 54.05 N/mm² (54.05 MPa).

Appendix E: Letter of Request and Approval for Conducting the Experiment



FDRE TVT INSTITUTE

Outgoing Letter

To: Mekelle University

Mekelle

Subject- Request for Cooperation (to conduct Experimental Activity)

The FDRE Technical and Vocational Training Institute is established to build the capacity of the technical vocational education and training sector by familiarizing the trainees with the actual world in collaboration with the industries, companies and government offices. In line with this mission, we would like your cooperation to allow *Gebregergis Haila – ID No. TTMR/111/16*, a 2nd year Wood Science Technology MSc student to conduct his cooperative activities in your organization, at the same time he is working on his project work about "Investigation of Physical and Mechanical Properties of Cordia Africana".

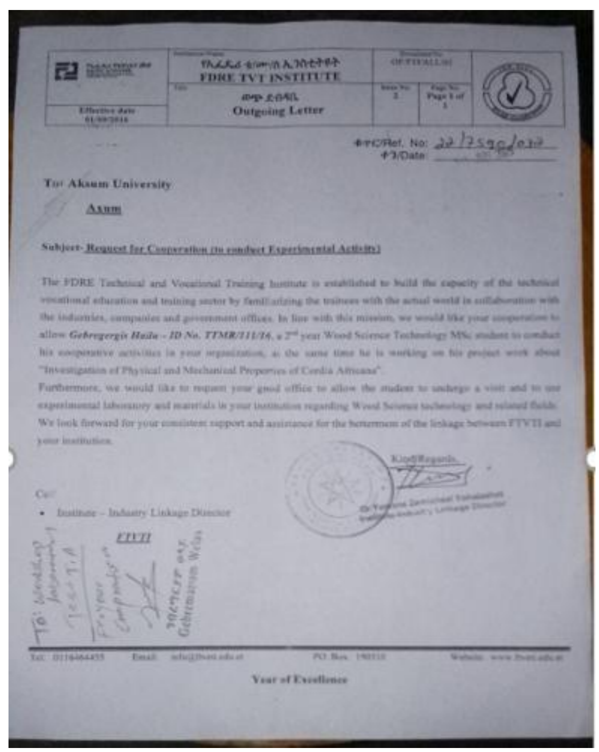
Furthermore, we would like to request your good office to allow the student to undergo a visit and to use experimental laboratory and materials in your institution regarding Wood Science technology and related fields. We look forward for your consistent support and assistance for the betterment of the linkage between FTVTI and your institution.

Kind Regards,

Cc:

- Institute – Industry Linkage Director

Year of Excellence



FDRE TVT INSTITUTE

Outgoing Letter

To: Aksum University

Axum

Subject- Request for Cooperation (to conduct Experimental Activity)

The FDRE Technical and Vocational Training Institute is established to build the capacity of the technical vocational education and training sector by familiarizing the trainees with the actual world in collaboration with the industries, companies and government offices. In line with this mission, we would like your cooperation to allow *Gebregergis Haila – ID No. TTMR/111/16*, a 2nd year Wood Science Technology MSc student to conduct his cooperative activities in your organization, at the same time he is working on his project work about "Investigation of Physical and Mechanical Properties of Cordia Africana".

Furthermore, we would like to request your good office to allow the student to undergo a visit and to use experimental laboratory and materials in your institution regarding Wood Science technology and related fields. We look forward for your consistent support and assistance for the betterment of the linkage between FTVTI and your institution.

Kind Regards,

Cc:

- Institute – Industry Linkage Director

Year of Excellence