Sokoine University of Agriculture

MSc Dissertation

Growth, Yield and Wood Properties of Teak (*Tectona grandis*) Provenances at Longuza Forest Plantation, Muheza District, Tanzania

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GROWTH, YIELD AND WOOD PROPERTIES OF TEAK (*TECTONA GRANDIS*) PROVENANCES AT LONGUZA FOREST PLANTATION, MUHEZA DISTRICT, TANZANIA

Dissertation is Submitted to Sokoine University of Agriculture in fulfilment of the requirements for the Master Degree of Science in Forestry

By

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EXTENDED ABSTRACT

A comprehensive study was conducted at Longuza Forest Plantation in Tanzania to enhance the production of Teak (*Tectona grandis*) in response to increasing demand for improved Teak provenances for productive plantations. The study aimed to evaluate the growth performance and wood properties of 12 provenances established in 2011, comprising 41 families. The experiment used a randomized complete block design with 8 replications, each plot containing 6 trees. The growth performance assessment included survival, diameter at breast height (Dbh), height (Ht), basal area (BA), volume (Vol), and mean annual increment (MAI). Additionally, the study examined stem straightness and the physical properties. Statistical analysis was carried out using SAS® software version 9.4, NPAR1WAY and rank procedures. The results showed non-significant differences ($p > 0.05$) in survival among provenances but highly significant differences ($p < .0001$) for Dbh, Ht, Vol, BA, and MAI, the average values for these parameters were 68.70 ± 5.64 %, 21.35 ± 4.04 cm, 18.65 ± 2.2 m, 304.83 ± 135.37 m^3 ha^{-1}, 9.96 ± 3.60 m^2 ha^{-1}, and 27.71 ± 12.30 m^3 ha^{-1} yr^{-1} respectively. The study identified superior performing provenances, including the East Africa Longuza seed stand, East Africa Longuza Provenance Trial, and East Africa Longuza Progeny Trial. Furthermore, the results revealed significant variation in stem straightness among provenances with the average score of 1.9 ± 0.8. Provenances like East Africa Mtibwa, CSIRO Thailand, and East Africa Longuza seed stand showed superior stem straightness. However, no substantial variations in physical properties were observed among the provenances. The average basic density was 0.571 ± 0.059 g cm^{-3}, with mean ranging from 0.469 ± 0.053 in CSIRO Thailand to 0.545 ± 0.071 g cm^{-3} in East Africa Longuza Progeny Trial. Based on the findings, the study recommends planting East Africa Longuza seed stand, East Africa Longuza Provenance Trial, and East Africa Longuza Progeny Trial in pilot plantations at Longuza and in areas with similar climatic and soil conditions. Furthermore, the study revealed that stem straightness is the crucial feature for wood quality determination. Provenances with superior stem straightness and favourable wood basic density, like East Africa Mtibwa, CSIRO Thailand and East Africa Longuza seed stand, are also preferred.

Keywords: Teak, Family, Provenance, Survival, Growth, Wood quality

MUHTASARI KUU

Utafiti wa kina ulifanyika katika Shamba la Miti Longuza nchini Tanzania ukiwa na lengo la kuongeza uzalishaji wa miti ya Misaji (*Tectona grandis*) ili kukabiliana na ongezeko la mahitaji yake na uboreshaji kwa mashamba yenye tija. Utafiti ulilenga kutathmini ukuaji na ubora wa mbao zitokanazo na miti hii ya Misaji utokanao na mbegu mbalimbali kutoka maeneo 12 ulimwenguni iliyojumuisha familia 41 iliyoanzishwa shamba la mti Longuza mnamo mwaka 2011 ikiwa na umri wa miaka 11 hadi sasa. Jaribio lilitumia muundo kamili wa bloku na replikesheni 8, likiwa na idadi ya miti 6 katika kila ploti. Tathmini ilijumuisha vipengele kama vile uhai wa miti, kipenyo cha mti katika urefu wa mita 1.3 (Dbh), Urefu (Ht), Basal area (BA), Ujazo (Volume), na ongezeko la ujazo kwa mwaka (MAI). Zaidi ya hayo, utafiti ulichunguza unyoofu wa shina la mti na vielelezo mbalimbali vya mbao vitokanavyo na miti hii ya Misaji. Uchambuzi wa takwimu ulifanyika kwa kutumia toleo la programu ya SAS® 9.4, na upangaji kulingana na jinsi ilivyo onesha ubora katika vipengele vilivyo ainishwa ili kuweza kutambua asili ipi ni bora zaidi. Matokeo yalionyesha tofauti zisizo muhimu ($p > 0.05$) katika uhai wa miti kwenye asili mbalimbali ya mbegu za Misaji, lakini tofauti kubwa sana ($p < .0001$) ilionekana katika vipengele vya Dbh, Ht, Vol, BA, na MAI, vikiwa na wastani wa 68.70 ± 5.64 %, 21.35 ± 4.04 cm, 18.65 ± 2.2 m, 304.83 ± 135.37 m^3 ha^{-1}, 9.96 ± 3.60 m^2 ha^{-1}, na 27.71 ± 12.30 m^3 ha^{-1} yr^{-1} kwa mtiririko huo. Utafiti ulibaini aina ya mbegu za miti ya Misaji zilizo fanya vizuri katika ukuwaji ikiwa ni pamoja na East Africa Longuza seed stand, East Africa Longuza Provenance Trial, and East Africa Longuza Progeny Trial. Zaidi ya hayo, matokeo yalionesha tofauti kubwa katika unyoofu wa shina la miti katika aina hizo za miti ya Misaji kutoka maeneo mbalimbali kwa wastani wa 1.9 ± 0.8, mbegu hizo ni pamoja na East Africa Mtibwa, CSIRO Thailand, and East Africa Longuza seed stand. Hata hivyo, hakuna tofauti kubwa iliyoonekaana katika besiki densiti. Wastani wa wiani ulikuwa 0.571 ± 0.059 g cm^{-3}, kutoka 0.469 ± 0.053 katika CSIRO Thailand hadi 0.545 ± 0.071 g cm^{-3} katika East Africa

Longuza Progeny Trial. Kulingana na matokeo ya utafiti huu inapendekezwa kupanda aina za mbegu zifuatazo, East Africa Longuza seed stand, East Africa Longuza provenance trial, and East Africa Longuza progeny trial kwa kiwango kikubwa katika shamba la miti Longuza na katika maeneo mbalimbali yenye hali ya hewa na udongo sawa. Zaidi ya hayo, utafiti umeonesha kuwa unyoofu wa shina la miti ni kipengele muhimu kwa uamuzi wa ubora wa miti. Asili hizi za mbegu ya miti zenye unyoofu mzuri na besiki densiti nzuri kama vile East Africa Mtibwa, CSIRO Thailand and East Africa Longuza seed stand, zinapendekezwa pia katika matumizi.

Maneno muhimu: Misaji, Familia, Asili, Uhai wa mti, Ukuaji, Ubora wa mbao

DECLARATION

I, **ANTHONY PHANUEL OPIYO** do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and it has neither been submitted nor being concurrently submitted in any other institution.

Anthony Phanuel Opiyo Date
(MSc. Candidate)

The declaration above is confirmed by;

Prof. Shabani. A.O. Chamshama Date
(Supervisor)

LIST OF MANUSCRIPTS

Manuscript 1: Growth Performance of *Tectona grandis* Provenances trial in Tanzania.

Manuscript 2: Variation in Stem Straightness and Wood Basic Density of *Tectona grandis* Provenances at Longuza Forest Plantation, Tanzania.

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DEDICATION

The work is dedicated to my parents Mr. and Mrs. Opiyo who gave me a good foundation for my life and education.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
BA	Basal area
BD	Basic density
cm	Centimetre
cm^3	Centimetre cubic
Dbh	Diameter at breast height
DMRT	Duncan Multiple Range Test
g cm^{-3}	Gram per cubic centimetre
GLM	General Linear Model
ha	Hectare
Ht.	Height
ISO	International Organization for Standards
m	Metre
m^3	Metre cubic
MAI	Mean Annual Increment
NPAR1WAY	Non-Parametric Way
^oC	Degree Celsius
SAS	Statistical Analysis System
SUA	Sokoine University of Agriculture
TAFORI	Tanzania Forestry Research Institute
TFS	Tanzania Forest Services Agency
Vol	Volume
Yr	Year

CHAPTER ONE

1.0 General Introduction

1.1 Background Information

Teak (*Tectona grandis* Linn. f.) is renowned as one of the world's most valuable timber tree species due to its exceptional wood properties. It is native to regions of India, Myanmar, Thailand, and the Lao People's Democratic Republic, covering a large area of about 29 million hectares (ha) of which almost half is located in Myanmar (Kollert and Cherubini, 2012). Teak wood is highly valued for its durability, strength, dimensional stability, resistance to termites and weathering, as well as its aesthetic qualities (Van Zyl, 2005). These characteristics have made it a preferred choice for various applications, including furniture, shipbuilding, and decorative building components (Myint and Naing, 2012).

Teak holds a prominent position in the global wood market due to its versatility and diverse applications (Turnbull *et al.,* 2012). Teak is now grown in approximately 70 countries worldwide, with the majority of the plantations in Asia (80%), with remarkable producers including India, Indonesia, Myanmar, and Lao PDR. Africa accounts for (10%) of Teak cultivation with countries like Tanzania, Benin, Ghana, and Nigeria where Teak was introduced in the 20^{th} century (Verhaegen *et al.,* 2010).

In tropical America, approximately 6% of global Teak plantations are located, with countries such as Costa Rica, El Salvador, Guatemala, Nicaragua, Panama, Ecuador, and Brazil being prominent contributors. Additionally, Oceania accounts for 4% of Teak cultivation (Kollert and Kleine, 2017). Furthermore, the quality of Teak in plantations is primarily determined by tree dimensions particularly their diameter and the straightness of their stems. Moreover, Basic density (BD) emerges as a critical determinant of

Teak quality from a physical properties' perspective (Kollert and Kleine, 2017).

1.2 Problem Statement and Study Justification

1.2.1 Problem statement

Natural Teak forests have been diminishing rapidly in their native areas, primarily due to increasing demand and resource depletion (Kollert and Kleine, 2017). To address this, there has been an increase in provenance trials aimed at identifying superior genetic materials capable of producing high-quality Teak including growth performance and stem straightness in a shorter period of time (Graudal and Moestrup, 2017). Provenances from various regions may display diverse growth patterns that are influenced by varying environmental factors such as temperature, rainfall, and soil composition (Parihar *et al.,* 2016). In 2011, a Teak provenance trial was established at Longuza Forest Plantation, focusing on evaluating the adaptability and performance of 12 different provenances consisting of 41 families. The primary objective was to gather data for selection of the most suitable seed sources for future planting and ensure high quality planting material.

1.2.2 Study justification

The study's main goal is to evaluate the growth performance, productivity, and wood properties of various Teak provenances. The findings obtained will contribute to the improving genetic pool of Teak seed improving Teak production, conserving genetic diversity, and providing a foundation for informed decisions regarding Teak plantation management, informed selection of superior planting materials of exceptional quality for plantation programmes and woodlots by government agencies, private sector and individuals.

1.3 Objectives

1.3.1 Main objective

To assess the performance of *Tectona grandis* provenances at Longuza Forest Plantation, Muheza district, Tanzania.

1.3.2 Specific objectives

i. To assess the survival, growth and productivity of *Tectona grandis* provenances at Longuza Forest Plantation.
ii. To assess the stem quality of *Tectona grandis* provenances at Longuza Forest Plantation.
iii. To assess BD of *Tectona grandis* provenances at Longuza Forest Plantation.

1.4 Research Questions

The study will answer the following questions

1. To assess the survival, growth and productivity of *Tectona grandis* provenances at Longuza Forest Plantation:
    i. What are the survival rates of different *Tectona grandis* provenances at Longuza Forest Plantation?
    ii. How does the growth (height and diameter) of *Tectona grandis* trees vary among different provenances at Longuza Forest Plantation?
    iii. What is the productivity, in terms of volume, MAI and BA of *Tectona grandis* provenances at Longuza Forest Plantation?

2. To assess the stem quality of *Tectona grandis* provenances at Longuza Forest Plantation:
    i. How does the stem straightness vary among *Tectona grandis* provenances at Longuza Forest Plantation?
    ii. What are the key factors contributing to variations in stem straightness among *Tectona grandis* provenances at Longuza Forest Plantation?
    iii. How does stem straightness affect wood quality among *Tectona grandis* provenances at Longuza Forest Plantation?

3. To assess wood properties of *Tectona grandis* provenances at Longuza Forest Plantation:
    i. What is the BD of *Tectona grandis* from different provenances at Longuza Forest Plantation?

ii. How do the physical properties (BD) of *Tectona grandis* vary among provenances at Longuza Forest Plantation?
iii. What are the key factors contributing to variations in BD among *Tectona grandis* provenances at Longuza Forest Plantation?

1.5 Study Limitations

Given that the study's focus lies on evaluating the performance of different *Tectona grandis* provenances, it is noteworthy that the observed variation among these provenances may be attributable to factors encompassing genetics. Distinguishing and attributing the precise impact of each of these factors presents a challenging task.

1.6 Dissertation Structure

This dissertation follows a structured format, comprising five main chapters designed in the format of publishable manuscripts. Chapter one comprises the introduction, showing the comprehensive background information of the study. It addresses the problem statement, provides justification for the research, and outlines the study's objectives, research questions, and inherent limitations. Chapter two, presented as Manuscript one, explains the growth performance of *Tectona grandis* provenances in Tanzania. Chapter three, presented as Manuscript two, focuses on the variation in stem straightness and wood basic density of *Tectona grandis* provenances at Longuza Forest Plantation, Tanzania. Chapter four provides the general discussion of the study’s findings. Chapter five summarizes the study's key contributions and presents general conclusions drawn from the research findings. Additionally, it offers valuable recommendations for the future management of Teak, particularly in Tanzania.

References

Graudal, L., & Moestrup, S. (2017). The genetic variation in natural and planted teak forests: Characterisation, use and conservation for the future. International Union of Forest Research Organizations 36: 19–29.

Kollert, W. & Cherubini, L. (2012). *Teak Resources and Market Assessment 2010. Planted Forests and Trees.* Working Paper No.47. Food and Agriculture Organization, Rome. 206pp.

Kollert, W., & Kleine, M. (2017). *The Global Teak Study. Analysis, Evaluation and Future Potential of Teak Resources.* International Union of Forest Research Organizations, Vienna Austria. 36pp.

Myint, W. & Naing, Y. M. (2012). *A Follow-up Study on Provenance Trial of Teak.* Forest Research Institute, India. 16pp.

Parihar, U. S., Chakravarty, N. V., & Kaushik, S. (2016). Impact of silvicultural practices on growth, yield and wood properties of Teak (*Tectona grandis* L.f.): A review. *Forest Ecology and Management,* 378: 147-160

Turnbull, J. W., Midgley, S. J., & Cossalter, C. (2012). Domestication of tropical trees: an overview. *forests, Trees and Livelihoods* 7(2): 111-117

Van Zyl, L. (2005). Stem form, height and volume models for Teak in Tanzania*.* Dissertation for Award of MSc Degree at University of Stellenbosch, Stellenbosch, 141pp.

Verhaegen, D., Fofana, I. J., Logossa, Z. A., & Ofori, D. (2010). What is the genetic origin of Teak (*Tectona grandis* L.) introduced in Africa and in Indonesia? *Tree Genetics and Genomes, 6,* 717–733.

CHAPTER TWO

Manuscript One

Growth Performance of *Tectona grandis* Provenances trial in Tanzania

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Abstract

Teak (*Tectona grandis* L.f.) is of significant economic importance. It was introduced to Tanzania in the early 20th century for commercial purposes. However, there is limited available information regarding the growth performance of teak seeds obtained from various localities. The study aimed to assess the performance of teak provenances at Longuza Forest Plantation, Tanzania. The study employed a randomized complete block design with eight replications, each consisting of six trees, to evaluate 12 provenances of 11-year- old teak trees from 41 families. These trees were planted in the same area with similar climatic conditions. The assessment parameters included survival, diameter at breast height (1.3 m above the base) over bark (Dbh), total tree height (Ht), basal area at breast height (BA), total tree above ground volume (Vol) and the mean annual increment (MAI). The statistical analysis was performed using SAS® software version 9.4 and its Rank procedures. There were no significant ($p > 0.05$) differences in survival among the tested provenances. However, highly significant ($p < 0.0001$) differences were observed for Dbh, Ht, Vol, BA and MAI among the provenances and families, with mean (± SD) values of survival, Dbh, Ht, Vol, BA and MAI of 68.70 ± 5.64%, 21.35 ± 4.04 cm, 18.65 ± 2.2 m, 304.83 ± 135.37 m^3/ha, 9.96 ± 3.60 m^2/ha and 27.71 ± 12.30 m^3/ha/yr, respectively. The findings revealed the superior performance of the East Africa Longuza seed, East Africa Longuza provenance trial and East Africa Longuza progeny trial provenances. There were significant variations in all tested parameters except survival. The Tanzanian provenances showed superior performance in both growth and productivity. Thus, it was recommended to plant these provenances on a large scale in Longuza and other areas with similar climatic and soil conditions.

Keywords: Teak, Family, Provenance, Survival, Growth, Productivity

† *The content presented in this chapter has been published in the journal of Agriculture and Natural Resources*

2.1 Introduction

Teak (*Tectona grandis* L.f.) belongs to the Lamiaceae family and it is one of the three species in the genus Tectona, with the other two species being *T. hamiltoniana* and *T. philippinensis,* which are endemics with relatively small native distributions in Myanmar and the Philippines, respectively (Minn *et al.,* 2016). Generally, teak grows naturally in soils with a pH range of 6.5–7.5, a distinct dry season and an annual rainfall in the range 1,200–1,500 mm (Palanisamy *et al.,* 2009). The species is native to India, Myanmar, Thailand and the Lao People's Democratic Republic; in addition, it is grown as an exotic tree in numerous tropical nations across Asia, Africa, South America and Central America (Khanduri and Vanlalremkimi, 2008).

Teak (*Tectona grandis*) is not native to Tanzania but has been introduced and cultivated in various regions of the country due to its economic importance and desirable timber properties (Rance and Monteuuis, 2004). Teak was introduced to Tanzania in early 20th century for commercial purposes because of its excellent wood quality and high demand in local and international markets Verhaegen *et al.* (2010). Teak is mainly concentrated in the coastal areas of the country, including Tanga and Mtwara (Madoffe and Maghembe, 1988).

Teak is primarily grown and managed in plantations in Tanzania by both private companies and government agencies and its cultivation contributes significantly to the country's economy as the teak timber from harvested trees is highly sought after for its quality and is used in various applications, including furniture production, construction, and boat building (Chamuya, 2007). In addition, the export of teak timber generates foreign exchange earnings for Tanzania (Kagosi *et al.,* 2015).

The growing global demand for teak wood, along with the depletion of accessible natural resources, resulted in the extensive development of teak plantations in the early 1970s, with the goal of producing large volumes of superior-quality teak lumber in the shortest feasible time (Keogh, 2001). The global effort to maximize the production of teak prompted the establishment of multiple provenance trials between 1905 and 1936, with the main teak provenances including *T. grandis* from India and Thailand (Rance and Monteuuis, 2004).

Various international teak provenance trials have revealed diversity among provenances (Graudal and Moestrup, 2017) which can be attributed to climatic, soil and atmospheric conditions (Rance and Monteuuis, 2004). Furthermore, a series of trials recognized the clear existence of provenance variations for many traits assessed, including survival, growth and productivity (Kjaer *et al.,* 1999). Despite the generally productive nature of teak in Tanzania, there remains a scarcity of information regarding the growth performance of teak seeds obtained from different localities. Similarly, Myint and Naing (2012) noted that *T. grandis* encompasses a range of provenances, with limited knowledge and documentation regarding specific provenance growth performance due to the extensive and irregular distribution of the species.

Consequently, this study aimed to elucidate the growth performance of teak provenances in the Longuza Forest Plantation, Tanzania. The findings from this study should provide valuable insights for decision-makers, forest managers, other teak cultivation entities and individuals regarding the selection of superior-quality seeds with a high yield and desirable wood properties. Additionally, the results should facilitate the appropriate matching of provenances with planting sites and support the effective establishment of teak planting programs or plantations, ensuring high yield and exceptional wood quality.

2.2 Materials and Methods

2.2.1 The study area

The study was conducted in Tanzania Forestry Research Institute (TAFORI) trial plots situated within the Longuza Forest Plantation, located in Northeastern Tanzania (40°55'– 50°10' S, 38°40'–39°00' E) at an elevation range above sea level of 160–560 m, in the foothills of the Eastern Usambara Mountains, in close proximity to the Amani Nature Reserve and approximately 52 km from Tanga City (Fig. 2.1). The topography of the area is characterized by moderate slopes with a gradient range of 10–15%, frequently intersected by numerous perennial and periodic streams. The soil composition predominantly consists of dark brown and red soils, with some areas containing clay soil. The area experiences two distinct seasons: the long rainy season (March–May) and the short rainy season (October–December). The mean values for the annual rainfall and temperature in the area are approximately 1,500 mm and 27°C, respectively (Zahabu *et al.,* 2018).

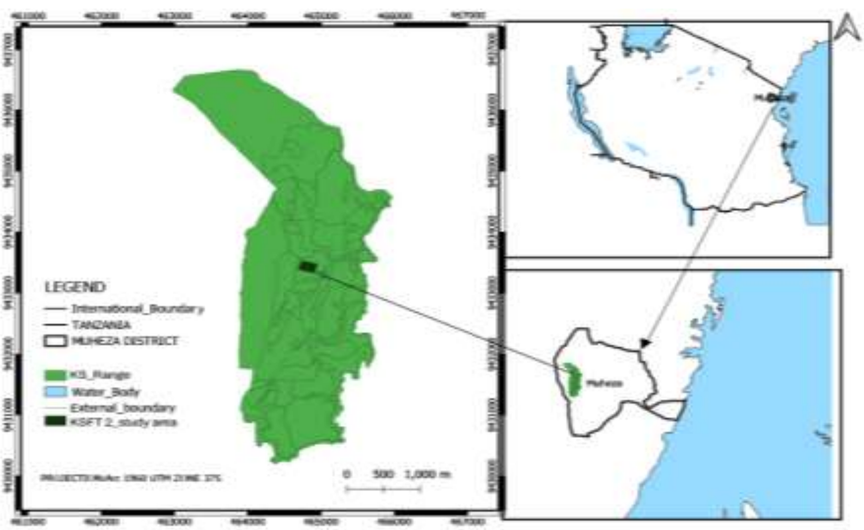

Figure 2.1: Maps showing study area in Longuza Forest Plantation
Source: Author (2022)

2.2.2 Experimental design

The trial was established on 2 May 2011 in plantations aged 11 yr. The plots were arranged using a complete randomized block design consisting of 8 replications, 16 blocks and 256 plots. Each plot contained 6 trees, spaced at 2.5 m × 2.5 m, resulting in a total of 96 trees per block and 192 trees per replication. To mitigate edge effects, the trial was bordered by two rows of the same species, ensuring consistency with the prevailing species composition within the trial. The experimental layout and map of the trial can be observed in Figures 2.2 and Appendix 1 respectively.

Rep	1	Block	1	Plots	to	16	Rep	5	Block	1	Plots	129 to	144
Rep	1	Block	2	Plots	to	32	Rep	5	Block	2	Plots	145 to	160
Rep	2	Block	1	Plots	to	48	Rep	6	Block	1	Plots	161 to	176
Rep	2	Block	2	Plots	to	64	Rep	6	Block	2	Plots	177 to	192
Rep	3	Block	1	Plots	to	80	Rep	7	Block	1	Plots	193 to	208
Rep	3	Block	2	Plots	to	96	Rep	7	Block	2	Plots	209 to	224
Rep	4	Block	1	Plots	to	112	Rep	8	Block	1	Plots	225 to	240
Rep	4	Block	2	Plots	to	128	Rep	8	Block	2	Plots	241 to	256

Figure 2.2: Study area trial layout
Source: TAFORI (2011)

2.2.3 Teak provenance seed origins

The teak provenance seeds used in this trial were sourced from various locations, representing different seed origins as represented by 41 families. The origins of the 12 teak provenance seeds are provided in Appendix 2 (Rance and Monteuuis, 2004; Hansen *et al.,* 2017; Kollert and Kleine, 2017).

2.2.4 Data collection

All teak trees were assessed for their height, survival and diameter at breast height (1.3 m above the base) over bark (Dbh). Survival was monitored by recording the initial condition of the planted seedlings, based on measuring the seedling height, root collar diameter and health status. Then, the percentage survival rate was computed using Equation 1:

Survival rate = (Number of surviving trees / Initial number of trees) × 100……………... *equation 1*

Height measurements for all trees in each plot were obtained using a Suunto hypsometer. The Dbh was measured using a diameter tape. The collected Dbh data were used to determine BA based on Equation 2:

$$BA = \left(\frac{\pi \times Dbh^2}{4}\right) \times 0.0001$$ ………….………………….............*equation 2*

where BA is the basal area (measured in square meters per hectare), π is approximately 3.14159 and Dbh is the diameter over bark at breast height (1.3 m above the tree base).

The total tree aboveground volume (Vol; measured in cubic meters) was estimated according to Zahabu *et al.* (2018) using Equation 3:

$$Vol = 0.00014 \times (Ht \times Dbh^2) \times 0.8793$$ ....*equation 3*

where Ht is the total tree height (measured in meters) and Dbh is the diameter over bark at breast height (1.3 m above the tree base).

The mean annual increment was determined using Equation 4:
Mean annual increment = Final volume / Number of years…………………………………………………….....*equation 4*

2.2.5 Data analysis

The statistical analysis was conducted using the SAS® software version 9.4 (SAS Institute Inc., 2023). Prior to the main analysis, the normality of the data distribution was assessed using the Shapiro-Wilk test. Descriptive statistics were calculated to determine the means of the variables under study (survival percentage, Dbh, HT, BA, Vol and MAI). To address issues of variance stabilization, symmetry and normality, the arcsine transformation was applied to the survival data. Then, analysis of variance (ANOVA) was performed on the treatment means for each research variable. This allowed for the assessment of significant differences among the various provenances. In cases where significant differences were observed, Duncan's multiple range test (DMRT) was applied as a post hoc test. The DMRT helped determine which pairs of group means showed significant variation. Furthermore, to provide a comprehensive assessment of overall performance for each provenance, an ordinal ranking mechanism was established. This ranking mechanism facilitated the differentiation of provenances based on their relative performance.

2.3 Results

Significant differences at a high level ($p < 0.0001$) were observed among provenances, replications, families and their interactions, as indicated in Appendix 4. The DMRT results, presented in Appendix 5, provided insights into the mean growth performance (DBH and Ht) and productivity (BA, Vol and MAI). The CSIRO Thailand provenance tended to show the highest survival rate, whereas the East Africa Longuza seed outperformed in terms of Dbh, Ht, Vol, BA and MAI.

2.3.1 Survival

The mean (± SD) survival rate for the teak provenances at age 11 yr was 68.70±5.64% with the range being from 67.44±7.73% for Sumalindo to 70.55±4.89% for CSIRO Thailand. The statistical analysis indicated no significant variations ($p > 0.05$) in the survival performance rates among the provenances within the study (Appendix 4). CSIRO Thailand had the highest survival rate of 70.55±4.89%, followed by East Africa Kihuhwi seed stand with 69.90±3.24% and East Africa Mtibwa with 69.88±5.11%. Among the tested provenances, Sumalindo had the lowest average survival rate of 67.44±7.73%. These findings are summarized in Appendix 5.

2.3.2 Diameter at breast height

There were highly significant ($p < 0.0001$, Appendix 4) differences in diameter growth among the teak provenances and families studied. The overall average Dbh was 21.35±4.04 cm. The mean Dbh values varied across the provenances from 18.32±3.7 cm for CSIRO Laos to 24.26±4.34 cm for East Africa Longuza seed, with the latter demonstrating superior performance in Dbh. Conversely, CSIRO Laos had lower Dbh performance compared to other provenances (Appendix 5).

2.3.3 Total tree Height

The variation in height performance among provenances was highly ($p < 0.0001$) significant. The mean height values varied significantly across the tested sources of variation from 16.91±2.6 m for CSIRO Laos to 20.10±2.4 m for East Africa Longuza seed stand, with an overall average of 18.73±2.3 m, as presented in Appendix 4. East Africa Longuza seed stand had the highest mean height (20.10±2.4 m), followed by East Africa Longuza provenance trial (19.89±2.18 m) and East Africa Longuza progeny trial (19.82±2.46 m), placing them in the higher group. In contrast, CSIRO Laos had the lowest mean height (16.91±2.6 m) and was significantly lower than East Africa Longuza seed stand, as shown in Appendix 5.

2.3.4 Basal area

The mean (± SD) BA of all plots was 9.96±3.60 m^2/ha. The mean values ranged from 7.32±3.01 m2/ha for CSIRO Laos to 12.70±4.24 m^2/ha for East Africa Longuza seed stand. There was a significantly variation in BA among the teak provenances in this study, as evidenced by the p value (< 0.0001) reported in Appendix 4. Among the provenances tested, East Africa Longuza seed stand had the highest BA (12.70±4.24 m^2/ha), followed by East Africa Longuza provenance trial (12.43±4.24 m^2/ha) and East Africa Longuza progeny trial (12.14±4.47 m^2/ha). On the other hand, CSIRO Laos has the lowest BA (7.32±3.01 m^2 /ha), as shown in Appendix 5.

2.3.5 Volume

The variation in mean total tree volume among provenances and families was highly significant ($p < 0.0001$) as indicated in Appendix 4. The mean Vol (± SD) was 304.83±135.37 m^3/ha ranging between 202.82±107.01 m^3/ha for CSIRO Laos to 410.69±164.70 m^3/ha for East Africa Longuza seed. Appendix 5 showed that East Africa Longuza seed stand had the highest mean Vol (410.69±164.70 m^3/ha), followed by East Africa Longuza provenance trial (398.54±165.19 m^3/ha) and East Africa Longuza progeny trial (390.62±173.78 m^3/ha). CSIRO Laos had the lowest mean Vol (202.82±107.01 m^3/ha).

2.3.6 Mean annual increment

Highly ($p < 0.0001$) significant differences were observed in the MAI values among the teak provenances, indicating variations in growth performance (Appendix 4). The overall mean MAI was 27.71±12.30 m^3/ha/yr, ranging between 18.44±9.72 m^3/ha/yr for CSIRO Laos and 37.34±14.97 m^3/ ha/yr for East Africa Longuza seed stand (Appendix 5).

2.3.7 Ordinal ranking

The provenances were ranked based on their performance in terms of growth (Dbh and Ht) and productivity (Volume, MAI and BA), as there were no significant differences in survival rates between provenances. According to Appendix 6, East Africa Longuza seed stand, East Africa Longuza provenance trial and East Africa Longuza progeny trial demonstrated superior performance in both growth and productivity. On the other hand, CSIRO Thailand, Chikweti Niasa-Lichinga and CSIRO Laos had the lowest performance in both aspects. Appendix 7 shows the ordinal ranking of the families based on their performance in the study.

2.4 Discussion

The results from the teak provenance studies have indicated high variability in performance regarding growth and productivity (Goh *et al.,* 2013). Variations at age 11 yr could be attributed to genetic variations among provenances, environmental factors and management practices (Kurniasari *et al.,* 2020). Tanzania provenances (land races) showed better growth performance than those from other countries, implying compatibility with the natural climatic conditions (Černý *et al.,* 2023). In addition, the superior performance of local land races has been shown in other species (Mwihomeke *et al.,* 2002). Some provenances, such as those from Indonesia, demonstrated superior growth in Dbh and Ht (Appendix 6), indicating their potential for high-yield plantations and quality wood production. These findings were similar to those reported by Kaosa-ard *et al*. (1992).

2.4.1 Survival

Results from other studies revealed that the survival rate for the majority of teak plantations was more than 75%. For example, Sett *et al.* (2023) reported survival rates in the range 62–80%, in survival performance for teak aged 15 yr in Myanmar. Similarly, Silva *et al*. (2014) found no significant variations in survival among teak trees aged 11 yr from three provenances in Brazil. The current results indicated a mean survival rate of 68.70 ± 5.64%, probably due to mortality caused by termites, as observed in the 1711 (CSIRO Laos) and 202 (Refocosta seed) families.

2.4.2 Diameter at breast height (Dbh)

The Dbh trends in teak provenances observed in the current study were consistent with findings at a similar age reported by various researchers. For example, Pandey *et al*. (2011) evaluated the growth performance of teak trees aged 11 yr from 16 provenances in India and found significant differences in Dbh, with mean values in the range 10.6–20.7 cm. Additionally, a study by Rojas-Sandoval *et al*. (2012), found significant variations in Dbh among the growth performance results for teak trees from 14 provenances aged 11 yr in Costa Rica.

2.4.3 Total tree Height

The total tree height findings from the current study corresponded with other research conducted in different regions. Notably, studies conducted by Goh *et al.* (2013) in Sabah, Pandey *et al.* (2011) in India and Silva *et al.* (2014) in Brazil reported Ht variation in the range 15.19–18.02 m among teak provenances at age 11 yr. Furthermore, a study by Malimbwi (2016) on teak trees aged 11–12 yr at Longuza revealed a similar mean height range of 12–20 m. Provenances that are better adapted to specific climatic conditions are more likely to show superior growth performance and consequently, greater height compared to others (Kurniasari et al., 2020). Additionally, management practices, such as thinning and pruning, can influence teak tree height growth (Palanisamy *et al.,* 2009).

2.4.4 Basal area

The BA results in the current study were consistent with other studies examining the growth performance of teak provenances aged 11 yr, such as Medeiros *et al.* (2018) and Drescher (2004) in Brazil and Tewari *et al.* (2014) in India. These studies revealed significant variations in BA among different teak provenances that could be attributed to a combination of genetic characteristics, environmental conditions and management approaches (Kurniasari *et al.,* 2020).

2.4.5 Volume

The tree volume results in the current study concurred with those reported by Goh *et al.* (2013) in Sabah, Khanduri et al. (2008) in

India and Rahmawati *et al*. (2022) in Indonesia, who examined the growth and volume production of teak provenances at ages in the range 8–11 yr. These studies revealed similar mean value ranges in volume production among different teak provenances. Genetic diversity within teak provenances, environmental factors and site characteristics can affect growth patterns and wood volume accumulation (Kurniasari *et al.,* 2020).

2.4.6 Mean annual increment

Similar MAI findings to the current ones have been reported in various studies, such as by Singh and Shukla (2007) in Thailand and Vaides-López *et al.* (2019) in central America, who investigated the growth performance of different teak provenances and observed significant variations in MAI among provenances. The observed variations in MAI and growth performance among teak provenances highlight the critical role played by genetic diversity and environmental dynamics in shaping the growth patterns of teak (Kurniasari *et al.,* 2020).

2.4.7 Ordinal ranking

The ordinal ranking findings from the current study showed that among the best-five provenances, four (East Africa Longuza seed, East Africa Longuza provenance trial, East Africa Longuza progeny trial and East Africa Kihuhwi seed stand) were from Tanzania and one (Sumalindo) was from Indonesia. Likewise, *Černý et al.* (2023) in Nicaragua, and Kokutse *et al.* (2009) in Togo identified local provenances had high performance compared to introduced ones. The good local performance could be attributed to the influence of genetic factors and adaptation to the local environment (Chaix *et al.,* 2011). In contrast, the current results for Chikweti Niasa- Lichinga from Mozambique, CSIRO Thailand and CSIRO Laos from Thailand produced the lowest performance levels among the current tested provenances.

2.5 Conclusion

The assessment conducted on a teak provenance trial aged 11 yr old revealed significant variations in all the measured parameters, except for survival, providing relevant information regarding teak growth and development. The variations suggested discernible differences in the performance of the tested provenances; provenances showed superior or inferior performance compared to others in terms of the measured parameters. These variations could be attributed to factors such as genetic differences, environmental conditions or a combination of both. However, the study found no significant differences in survival rates among the tested provenances, indicating that the overall survival of teak trees was relatively consistent across the different provenances, implying that the tested provenances had comparable levels of resilience or adaptability to the local environment. These findings underscored the importance of selecting suitable site-specific provenances for teak plantation establishment and management. Based on the current results, the following provenances showed high performance in growth and productivity: East Africa Longuza seed, East Africa Longuza Provenance Trial and East Africa Longuza Progeny Trial; thus, they should be planted on a large scale in Longuza and other areas with similar climatic and soil conditions. In addition, the findings provide useful information for economic growth through the timber industry in Tanzania. By focusing on provenances with superior growth characteristics, Tanzania can make improvements in both sustainable forest management and economic development.

2.6 Recommendations

The study recommends that the following provenances which showed high performance in growth and productivity be planted on a large scale in Longuza and other areas with similar climatic and soil conditions: East Africa Longuza seed stand, East Africa Longuza provenance trial and East Africa Longuza progeny trial. The findings also offer opportunities for economic growth through the timber industry in Tanzania. By focusing on provenances with superior growth characteristics, Tanzania can make improvements in both sustainable forest management and economic development.

References

Černý, J., Haninec, P., Novosadová, K., Patočka, Z., Haninec, P., Maděra, P. 2023. Provenance affects the growth and mortality of teak (*Tectona grandis* L.f) plantations cultivated in central Nicaragua. J. For. Sci. 69: 1–10. doi: 10.17221/115/2022-JFS

Chaix, G., Monteuuis, O., Garcia, C., Alloysius, D., Gidiman, J., Bacilieri, R., Goh, D.K.S. 2011. Genetic variation in major phenotypic traits among diverse genetic origins of Teak (*Tectona grandis* L.f.) planted in Taliwas, Sabah, East Malaysia. Ann. For. Sci. 68: 1015–1026. doi.org/10.1007/s13595-011-0109-8

Chamuya, N.-K.A. 2007. Alternative Pricing Mechanism of Teak Forest Plantation Saw-Logs in Tanzania. M.Sc. thesis, Sokoine University of Agriculture. Morogoro, Tanzania.

Drescher, R. 2004. Growth and yield of *Tectona grandis* Linn F in young plantations in two regions in Mato Grosso–Brazil. Ph.D. thesis, Federal University of Santa Maria. Mato Grosso, Brazil. [in Portuguese]

Goh, D.K.S., Bacilieri, R., Chaix, G., Monteuuis, O. 2013. Growth variations and heritabilities of teak CSO-derived families and provenances planted in two humid tropical sites. Tree Genet. Genomes 9: 1329–1341. doi.org/10.1007/s11295-013-0642-8

Graudal, L., Moestrup, S. 2017. The genetic variation in natural and planted teak forests: Characterisation, use and conservation for the future. In: Kollert, W., Kleine, M. (Eds.). The Global Teak Study: Analysis, Evaluation and Future Potential of Teak Resources, Vol. 36. International Union of Forest Research Organizations. Vienna, Austria, pp. 36: 19–29.

Hansen, O.K., Changtragoon, S., Ponoy, B., Lopez, J., Richard, J., Kjær, E.D. 2017. Worldwide translocation of teak—Origin of landraces and present genetic base. Tree Genet. Genomes 13: 87. doi.org/10.1007/ s11295-017-1170-8.

Kagosi, P.J., Laswai, F., Kapinga, C., Babili, H. 2015. Practices and challenges of selling systems for teak (*Tectona grandis*) at Mtibwa tree plantation in Tanzania. Journal of Continuing Education and Extension 6: 902–910.

Kaosa-ard, A. 1992. Teak international provenance trial I: Growth and stem quality. Seminar on 50st anniversary of Huay-Tak Teak Plantation. Lampang, Thailand.

Keogh, R. 2001. New horizons for teak (*Tectona grandis* Linn. F.) plantations: The consortium support model approach of Teak 2000. In: The Proceeding of the Third Regional Seminar on Teak, Potentials and Opportunities in Marketing and Trade of Plantation Teak: Challenge for the New Millennium. Yogyakarta, Indonesia, pp. 31–56.

Kollert, W., Kleine, M. 2017. The Global Teak Study. Analysis, Evaluation and Future Potential of Teak Resources. International Union of Forest Research Organizations. Vienna, Austria.

Khanduri, V.P., Lalnundanga, Vanlalremkimi, J. 2008. Growing stock variation in different teak (*Tectona grandis*) forest stands of Mizoram, India. J. For. Res. 19: 204–208. doi.org/10.1007/s11676-008-0043-2

Kjaer, E.D., Kaosa-ard, A., Suangtho, V. 1999. Domestication of teak through tree improvement: Options, potential gains and critical factors. In: Proceeding of International Seminar on Sire Technology and Productivity of Teak Plantation. FORSPA Publication. Humlebæk, Denmark, pp. 161–190.

Kokutse, A.D., Adjonou, K., Kokou, K., Gbeassor, M. 2009. Comparative performance of Tanzanian teak versus local teak planted in Togo. Bois et Forêt des Tropiques 302: 43–52.

Kurniasari, E., Indrioko, S., Ratnaningrum, Y.W.N. 2020. Selection of adaptive teak provenance in Gunungkidul. IOP Conf. Ser. Earth Environ. Sci. 449: 012028. doi: 10.1088/1755-1315/449/1/012028

Madoffe, S.S., Maghembe, J. 1988. Performance of teak (*Tectona grandis* L. f.) provenances seventeen years after planting at Longuza, Tanzania. Silv. Genet. 37: 175–178.

Malimbwi, R.E. 2016. Development of yield tables for seven Tanzania Forest Service Agency Forest plantations in Tanzania. Yield Tables for *Tectona grandis* Forest Plantations. Report. Department of Forest Resources Assessment and Management, Sokoine University of Agriculture. Morogoro, Tanzania.

Medeiros, R.A., de Paiva, H.N., D'Ávila, F.S., Leite, H.G. 2018. Growth and yield of teak stands at different spacing. Pesq. Agropec. Bras. 53: 1109–1118. doi.org/10.1590/S0100-204X2018001000004

Minn, Y., Gailing, O., Finkeldey, R. 2016. Genetic diversity and structure of teak (*Tectona Grandis* L. f.) and dahat (*Tectona hamiltoniana* Wall.) based on chloroplast microsatellites and amplified fragment length polymorphism markers. Genet. Resour. Crop Evol. 63: 961–74. doi. org/10.1007/s10722-015-0293-8.

Mwihomeke, S.T., Mugasha, A.G., Chamshama, S.A.O., Mgangamundo, M.A., Kumburu, O.C., Lupala, Z. 2002. Early performance of *Casuarina junghuhniana* provenances/land races at Lushoto, Tanzania. South. Afr. For. J. 194: 7–14. doi.org/10.1080/20702620. 2002.10434587

Myint, W., Naing, Y.M. 2012. A Follow-up Study on Provenance Trial of Teak. Forest Research Institute. Nay Pyi Taw, Myanmar.

Palanisamy, K., Hegde, M., Yi, J.S. 2009. Teak (*Tectona grandis* Linn. F.): A renowned commercial timber species. J. For. Sci. 25: 1–24.

Pandey, D., Kumar, R., Sharma, R. 2011. Variation in growth performance and wood properties of *Tectona grandis* from different provenances in India. Journal of Forestry Research 22: 73–79. doi: 10.1007/s11676- 011-0113-6

Rahmawati, R.B., Widiyatno, W., Hardiwinoto, S., Budiadi, B., Nugroho, W.D., Wibowo, A., Rodiana, D. 2022. Effect of spacing on growth, carbon sequestration, and wood quality of 8-year-old clonal teak plantation for sustainable forest teak management in Java Monsoon Forest, Indonesia. Biodiversitas 23: 4180–188. doi: 10.13057/biodiv/ d230840

Rance, W., Monteuuis, O. 2004. Teak in Tanzania I. Overview of the context. Paper report. Campus international de Baillarguet. Montpellier, France.

Rojas-Sandoval, J., Duque, A., Boshier, D.H. 2012. Provenance variation in growth performance and wood density in teak (*Tectona grandis* Linn f.) at 11 years of age in Costa Rica. New Forests 43: 249–263. doi: 10.1007/s11056-011-9274-4

SAS Institute Inc. 2023. SAS® 9.4M8 Language Reference: Concepts, 6th ed. SAS Institute Inc. Cary, NC, USA.

SettEi Sandi, LeeHye-Jin, KimYang-Gil, KimYe-Ji, LeeDayoung, KimSunjeong, HahnYoon-Ji, YeoTae-Lim and KangKyu-Suk 2023. Assessing the performance on phenotypic traits of teak (*Tectona grandis* L.f.) provenances across two trial sites in Myanmar Silvae Genetica 72, no.1 (2023): 92-104. https://doi.org/10.2478/sg- 2023-0009.

Silva, J.N., Gonçalves, J.L.M., Santos, A.F., Azevedo, C.P.M., Cruz, C.D. 2014. Selection of teak (*Tectona grandis*) provenances in Brazil based on survival, growth, and wood quality traits. New Forests 45: 313–331. doi: 10.1007/s11056-013-9402-2

Singh, M.P., Shukla, R.P. 2007.Growth performance of six different teak (*Tectona grandis*) provenances under irrigated and rainfed conditions in central India. New Forests 33: 297–311.

Tanzania Forest Research Institute. 2011. Camcore Test Code 63-50-02C East Africa. Establishment report. Muheza, Tanzania.

Tewari, V.P., Álvarez González, J.G., García, O. 2014. Developing a dynamic growth model for teak plantations in India. For. Ecosyst. 1: 9.

Vaides-López, E., Hernández, A.A., Fernández, R.M. 2019. Site characteristics that determine the growth and productivity of teak (*Tectona grandis* L.f.) of young plantations in Guatemala. Costa Rican Agronomy 43: 135–148. dx.doi.org/10.15517/rac.v43i1.35684

Verhaegen, D., Fofana, I.J., Logossa, Z.A., Ofori, D. 2010. What is the genetic origin of teak (*Tectona grandis* L.f) introduced in Africa and in Indonesia? Tree Genet. Genomes 6: 717–733. doi.org/10.1007/s11295- 010-0286-x

Zahabu, E., Mugasha, W.M., Katani, J.Z., Malimbwi, R.E., Mwangi, J.R., Chamshama, S.A. O. 2018. Allometric Biomass and Volume Models for *Tectona Grandis* Plantations. Sokoine University of Agriculture. Morogoro, Tanzania.

CHAPTER THREE

Manuscript Two

Variation in Stem Straightness and Wood Basic Density of *Tectona grandis* Provenances at Longuza Forest Plantation, Tanzania

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Abstract
Stem straightness and physical properties are crucial characteristics that influence the wood quality, commercial value and utilization of *Tectona grandis* (Teak) timber. However, limited research has examined the variability in stem straightness and physical properties within different Teak provenances. The extent of variation in stem straightness and wood basic density within various Teak provenances remains inadequately explored particularly in Tanzania, leading to this study. The study aimed to assess the wood quality based on stem straightness and wood basic density variations of Teak across 12 provenances established in 2011. The experiment was laid out in a randomized complete block design with 8 replications. Each plot contained 6 trees. Stem straightness was measured using a non-destructive method, with stem scoring method 1 being best and 4 worst. Wood basic density was determined through standardized laboratory testing procedures using extracted core samples. Statistical analysis was performed using SAS® software version 9.4. The results showed significant variation in stem straightness ($p < 0.01$), with some provenances displaying consistently straighter stems compared to others. Stem straightness was best in East Africa Mtibwa, CSIRO Thailand and East Africa Longuza seed stand provenances. Variations in wood basic density was not observed across the different provenances ($p > 0.05$). The average basic density of the wood across all provenances was 0.517 ± 0.059 g cm^{-3}, with a mean value range of 0.469 ± 0.053 in CSIRO Thailand to 0.545 ± 0.071 g cm^{-3} in East Africa Longuza Progeny Trial. Based on the findings it was revealed that stem straightness is the crucial feature for wood quality determination. Provenances with superior stem straightness and favourable wood basic density, like East Africa Mtibwa, CSIRO Thailand and East Africa Longuza seed stand, are preferred. This emphasis on stem straightness, rather than wood basic density, is crucial for maximizing wood quality and economic value in Teak plantations.

Keywords: Provenance, Stem straightness, Physical properties, Wood quality

3.1 Introduction

Teak (*Tectona grandis*) is a highly valued tropical hardwood known for its exceptional strength, durability, and aesthetic values. Its versatility and wide range of applications make it a popular choice for various purposes, including furniture, flooring, boat building, and construction (Kaosa-ard and Cox, 1998; Parihar *et al.,* 2016). The quality and suitability of Teak wood are influenced by several factors, including stem straightness and physical properties (Adi *et al.,* 2016). Stem straightness is a crucial characteristic in Teak trees as it determines the quality and usability of the harvested timber (Kollert and Kleine, 2017). A straight stem ensures minimal wastage during sawing and provides higher-quality boards and veneers (Fisher *et al.,* 2002). Moreover, it facilitates efficient processing and enhances the overall value of the timber. In addition to stem straightness, the physical properties of Teak wood play a vital role in determining its suitability for specific applications. Physical properties such as basic density have a positive correlation with mechanical properties of wood that influence the strength, durability, and workability of the wood (Amoah *et al.,* 2019; Hidayati *et al.,* 2015).

Although, the most common parameters measured in provenance trials are height and diameter, as easily obtainable measures of growth, wood density is often measured as a wood quality parameter (Nabais *et al.,* 2018). Understanding the variation in stem straightness and physical properties among different Teak provenances is of significant importance for determination of wood quality, and optimizing the use of Teak wood in different industries, ensuring its quality and long-term performance (Fisher *et al.,* 2002).

Several researchers around the world have undertaken research on stem straightness and physical properties variations of Teak. These studies used both destructive and non-destructive approaches, providing valuable insights into the field. Remarkable studies include the work of Madoffe and Maghembe (1988), Pedersen *et al.* (2007), Moya and Marin (2011), and Hidayati *et al.* (2014) at different ages of 10, 17 and 30 years old. Despite these significant research efforts, it remains clear that the level of knowledge concerning the stem straightness and wood basic density of Teak is currently insufficient to provide recommendations for the selection of a seed source when establishing plantations beyond its natural range, as noted by Kjær *et al*. (n.d.). Furthermore, the research specifically focusing on 11-year-old Teak provenances, particularly within the context of Tanzania, remains relatively scarce. This underscores the need for further exploration and analysis in this specific field to enhance our knowledge of Teak's stem straightness and physical properties variations in Tanzania.

The study aims to address these aspects by conducting a comprehensive assessment of stem straightness and wood basic density variation in a diverse range of Teak provenances. The findings of this study will serve as a valuable resource for stakeholders in the Teak industry, in choosing suitable provenance for breeding programmes, timber industries and end uses. This information will also enable decision-making and sustainable utilization of Teak resources that supports both conservation and economic goals.

3.2 Materials and Methods

3.2.1 The study area

The study was conducted in Tanzania Forestry Research Institute (TAFORI) trial plots situated within the Longuza Forest Plantation, located in the Northeastern of Tanzania, between latitudes 40°55' and 50°10' South, and longitudes 38°40' and 39°00' East. The study area is elevated between 160 and 560 m above sea level, positioned on the foothills of the Eastern Usambara Mountains, in close proximity to the Amani Nature Reserve. It is approximately 52 km away from Tanga City (Figure 3.1). The topography of the area is characterized by a moderate slope with a gradient ranging from 10% to 15%, frequently intersected by numerous perennial and periodic streams. The soil composition predominantly consists of dark brown and red soils, with some areas containing clay soil. The area experiences two distinct seasons: the long rainy season (March to May) and the short rainy season (October to December). The area's mean annual rainfall and temperature are approximately 1,500 mm and 27°C, respectively (Zahabu *et al*., 2018).

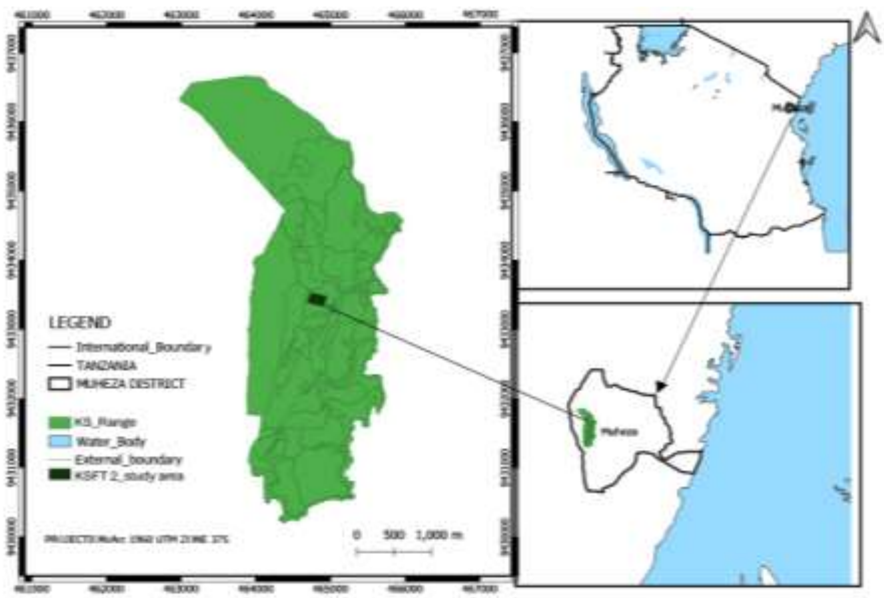


Figure 3.1: Maps showing study area in Longuza Forest Plantation
Source: Author (2022)

3.2.2 Experimental design

The trial was established on May 2, 2011. The plots were arranged using a complete randomized block design consisting of 8 replications, 16 blocks, and 256 plots. Each plot accommodated 6 trees, spaced at 2.5 m × 2.5 m, resulting in a total of 96 trees per block and 192 trees per replication. To mitigate edge effects, the trial was bordered by two rows of the same species, ensuring consistency with the prevailing species composition within the trial.

The experimental layout of the trial is shown in Figure 3.2 and the map layout in Appendix 1.

Rep	1	Block	1	Plots	to	16	Rep	5	Block	1	Plots	129 to	144
Rep	1	Block	2	Plots	to	32	Rep	5	Block	2	Plots	145 to	160
Rep	2	Block	1	Plots	to	48	Rep	6	Block	1	Plots	161 to	176
Rep	2	Block	2	Plots	to	64	Rep	6	Block	2	Plots	177 to	192
Rep	3	Block	1	Plots	to	80	Rep	7	Block	1	Plots	193 to	208
Rep	3	Block	2	Plots	to	96	Rep	7	Block	2	Plots	209 to	224
Rep	4	Block	1	Plots	to	112	Rep	8	Block	1	Plots	225 to	240
Rep	4	Block	2	Plots	to	128	Rep	8	Block	2	Plots	241 to	256

Figure 3.2: Study area trial layout
Source: Tanzania Forest Research Institute (2011)

3.2.3 Teak provenance seed origins

The Teak provenance seeds used in this trial were sourced from various locations, representing different seed origins represented by 41 families. The origins of the 12 Teak provenance seeds are provided in Appendix 2.

3.2.4 Data collection

The stem form of all living Teak within the study area was evaluated with respect to their straightness, branching patterns, and the presence of slight bends and crookedness using the scoring method,1 being the best and 4 the worst (Appendix 8). From each plot, one tree free from observable defects was selected for basic density determination. Cores were then extracted from the selected trees using a wood increment borer. Based on ISO 13061-1: 2014, the collected samples were immersed in clean water to restore them to their green volume condition. Once the samples had regained this state, the law of flotation was applied to determine their green volume. Subsequently, the samples were dried in an oven (102±3 ^{0}C) until a constant weight was attained. After allowing the samples to cool in a desiccator they were reweighed and the measurements were recorded. The basic density was calculated by dividing oven dry weight by green volume.

3.2.5 Data analysis

The analysis was conducted using SAS software. Stem straightness was evaluated using Wilcoxon Scores (Rank Sums) under NPAR1WAY Procedure for the variable "Score," and the Kruskal-Wallis Test was employed to determine significant differences among the groups. If significant differences were observed, the Dunn test was used to identify the specific locations of these differences. A Generalized Linear Model (GLM) procedure was used to analyse basic density where ANOVA was used to assess significance. In cases where significant differences were found, Duncan's Multiple Range Test (DMRT) was performed to identify specific group differences.

3.3 Results

3.3.1 Stem straightness

Findings of this study show that, there is significant variation in stem straightness among the Teak provenances studied ($p < 0.01$, Table 3.1). The average score for stem straightness across all provenances was 1.9 ± 0.8, indicating moderate straightness. About 66.98 % of the trees score 1 and 2, while 33.02% scored by 3 and 4. Provenances showed diverse mean score values, with the East Africa Mtibwa provenance having the lowest (1.8 ± 0.76) and CSIRO Laos provenance having the highest (2.27 ± 0.8) scores respectively (Table 3.2). Appendix 9 displays the mean straightness score of families within the study.

Table 3.1: Results of the Kruskal-Wallis Test and ANOVA for variables measured in the site

Variable	DF	p-value	Significant Differences
Stem Straightness	11	<0.0141'*'	Yes
Basic Density	11	>0.2375	No

Significance codes: (0.01 '*')

Table 3.2: Dunn Test results conducted for stem straightness parameter measured at the site

S/n	Country	Provenance name	Mean Score	Dunn Test
1	Tanzania	East Africa Mtibwa	1.81±0.76	b
2	Thailand	CSIRO Thailand	1.82±0.80	b
3	Tanzania	East Africa Longuza seed stand	1.82±0.79	b
4	Costa Rica	DeGuate- Tailandia	1.84±0.80	ab
5	Tanzania	East Africa Longuza Provenance Trial	1.88±0.86	ab
6	Tanzania	East Africa Longuza Progeny Trial	1.92±0.90	ab
7	Colombia	Refocosta seed stand	1.96±0.88	ab
8	Tanzania	East Africa Kihuhwi Seed stand	2.02±0.79	ab
9	Venezuela	SKCV Bulk	2.09±0.81	ab
10	Mozambique	Chikweti Niasa-Lichinga	2.12±0.60	ab
11	Indonesia	Sumalindo	2.16±1.06	ab
12	Thailand	CSIRO Laos	2.27±0.83	a

Mean values of the same letter in a Dunn test column indicate no significant differences ($p > 0.05$)

3.3.2 Wood basic density

Statistical analysis indicated no significant differences ($p > 0.05$) in mean wood basic densities among the provenances studied as shown in Table 3.1. Table 3.3 presents the results of the mean basic density variation between different provenances studied at Longuza forest plantation. The average basic density of the wood across all provenances was 0.517 ± 0.059 g cm^{-3}, with mean range of 0.469 ± 0.053 CSIRO Thailand to 0.545 ± 0.071 g cm^{-3} East Africa Longuza Progeny Trial.

Table 3.3: Basic density values of different Teak provenances at the site at 11-year-old

S/n	Country	Provenance name	BD (g cm^{-3})
1	Tanzania	East Africa Longuza Progeny Trial	0.545±0.071
2	Tanzania	East Africa Longuza seed stand	0.536±0.042
3	Tanzania	East Africa Longuza Provenance Trial	0.532±0.073
4	Tanzania	East Africa Kihuhwi Seed stand	0.531±0.063
5	Colombia	Refocosta seed stand	0.525±0.079
6	Costa Rica	DeGuate- Tailandia	0.521±0.065
7	Mozambique	Chikweti Niasa-Lichinga	0.520±0.050
8	Indonesia	Sumalindo	0.511±0.036
9	Tanzania	East Africa Mtibwa	0.508±0.043
10	Venezuela	SKCV Bulk	0.506±0.068
11	Thailand	CSIRO Laos	0.505±0.061
12	Thailand	CSIRO Thailand	0.469±0.053

3.4 Discussion

3.4.1 Stem straightness

The observed straightness of CSIRO Thailand Teak provenance in this study agrees with other studies. Verhaegen *et al.* (2010) and Palanisamy *et al.* (2009) reported that Teak provenances from Thailand (CSIRO Thailand) tend to show slightly slower growth rates compared to other provenances. However, they compensate for this by producing trees characterized by excellent persistence, including a clear bole and demonstrating favourable stem form. In contrast as per the findings of this study, Palanisamy *et al.* (2009) and Kaosa-ard (1992) showed that Teak provenances originating from Indonesia (Sumalindo), show impressive survival rates and good health, coupled with rapid growth. However, these Indonesian provenances showed suboptimal stem form characteristics, which may be considered a limitation in certain contexts. Additionally, Persson (1971) Madoffe and Maghembe (1988), Pedersen *et al.* (2007), identified Tanzanian land races, particularly East Africa Mtibwa, having superior stem straightness. These findings correspond with what has been observed in this study, as East

Africa Mtibwa provenance is superior and CSIRO Laos provenance least, as mean score 1 was for the best and 4 worst.

Wide provenance variations in Teak provenances have also been shown in other studies. Tripathi *et al*. (2015) and Rao *et al.* (2001), for example, examined the stem straightness of Teak trees from various provenances in India. According to the study, stem straightness varied widely across provenances with some having significantly straighter stems than others. Similarly, Hasanah *et al.* (2016) assessed the stem straightness of Teak trees from various provenances in Indonesia. The researchers identified significant differences in stem straightness amongst provenances. Depending on factors such as soil conditions, climate, genetics, or geographical sources of Teak trees, may show variation in stem straightness (Bhat and Priya, 2004).

3.4.2 Basic density

Wood basic density values obtained from this study on Teak trees range from 0.47 ± 0.053 to 0.55 ± 0.071 g cm^{-3}, with an average of 0.517 ± 0.059 g cm^{-3}, which is consistent with findings from multiple studies. For instance, Wanneng *et al.* (2014) found that the basic density of 10-year-old Teak planted in Laos and Solomon Islands was 0.53 g cm^{-3} and 0.54 g cm^{-3}, respectively. Zahabu *et al*. (2011) conducted a study on wood basic density of Teak in Tanzania. The results revealed that basic density values ranged from 0.40 to 0.60 g cm^{-3} in Teak trees of 10-20 years old. Another study by Sharma *et al.* (2019) observed Teak wood basic density ranging from 0.30 to 0.89 g cm^{-3}, with an average of 0.62 g cm^{-3}. Similarly, Ratnasingam and Ioras (2009) assessed Teak wood samples from different regions in Malaysia, reporting basic density values ranging from 0.47 to 0.76 g cm^{-3}, with an average of 0.64 g cm^{-3}. Putri *et al.* (2015) conducted a study in Indonesia, measuring Teak wood basic density from various regions and reported a range of 0.50 to 0.70 g cm^{-3}. Furthermore, Zahabu *et al*. (2014), and Mugasha *et al*. (2012) analyzed Teak wood basic density in Tanzania, revealed an average range of 0.36 to 0.60 g cm^{-3} and 0.42 to 0.65 g cm^{-3} respectively, with the highest value observed in trees from Tanga.

The lack of significant differences in wood basic density among Teak provenances found in this study has also been reported in several other studies. For instance, Prisantoso *et al.* (2017) conducted a study in Thailand, analysing the basic density of Teak wood from five distinct provenances, and observed no significant variations among them. Similarly, Mohanty *et al.* (2018) analyzed Teak wood from 18 different provenances in India and found no significant differences in basic density between them. In another study by Josh *et al.* (2002) in India, no significant difference in basic density was observed among eight Teak provenances analyzed. In line with these findings, Kebede *et al.* (2021) investigated the variation in wood basic density of Teak trees from six different provenances in Ethiopia. The study revealed no significant differences in basic density among the various provenances, with the average basic density ranging from 0.42 to 0.49 g cm^{-3}. These results indicate that the basic density of Teak wood may not vary significantly across different provenances in these particular studies.

Additionally, the lack of significant differences in basic density among various Teak provenances may be attributed to multiple factors. One possible reason is that the genetic variability between different provenances might not be substantial enough to cause notable variations in basic density (Rachman *et al.,* 2019). Furthermore, similarities in site climatic conditions, soil compositions and management practices across different provenances may lead to this outcome as observed in this study (Bhat and Priya, 2004).

3.5 Conclusion

The study showed substantial variances in stem straightness, but not in wood basic density across the Teak provenances tested. This indicates that the overall basic density of Teak trees was relatively consistent across the different provenances. Factors such as genetic variability, site conditions, and management practices are likely to contribute to the lack of significant variation in basic density between provenances. Thus, the study concludes for Teak plantation management, wood quality and economic value purposes, the focus should primarily be on stem straightness rather than wood basic density.

3.6 Recommendations

Based on the study's findings of substantial variances in stem straightness but not in wood basic density across Teak provenances, it is recommended to use the Teak provenances with straight stems namely as East Africa Mtibwa, CSIRO Thailand, and East Africa Longuza seed stand to maximize wood quality and economic value in Teak plantations.

References

Adi, D. S., Sudarmanto, S., Ismadi, I., Gopar, M., Darmawan, T., Amin, Y., & Witjaksono, W. (2016). Evaluation of the wood quality of platinum Teak wood. *Teknologi Indonesia 39*(1): 36-44.

Amoah, M., & Inyong, S. (2019). Comparison of some physical, mechanical and anatomical properties of smallholder plantation Teak (*Tectona grandis* Linn. f.) from dry and wet localities of Ghana. *Journal of the Indian Academy of Wood Science* 16: 125-138.

Bhat, K. M., & Priya, P. B. (2004). Influence of provenance variation on wood properties of Teak from the Western Ghat region in India. *Iawa Journal 25*(3): 273–282.

Fisher, R. F., McBride, J. R., and Shea, K. R. (2002). Predicting lumber recovery and stem quality for sawmilling: A Review. *Wood and Fiber Science 34*(4): 587 – 611.

Hasanah, U., Sumantyo, J. T. S., & Hidayat, A. (2016). Variation of stem straightness in progeny trial of Teak (*Tectona grandis* L.f.) provenance from Indonesia. *Journal of Forestry Research 27*(5): 1035–1041.

Hidayati, F., Sulistyo, J., Lukmandaru, G., Listyanto, T., Praptoyo, H., & Pujiarti, R. (2015). Physical and mechanical properties of 10-year-old superior and conventional Teak planted in Randublatung Central Java Indonesia. *Jurnal Ilmu Dan Teknologi Kayu Tropis 13*(1): 11–21.

Joshi, G., & Lohani, U. C. (2002). Variation in wood density and fibre length in *Tectona grandis* provenances. *Indian Forester 128*(5): 529-535.

Kaosa-ard, A. (1992). *Teak international provenance trial I: Growth and stem quality*. Seminar on 50 Anniversary of Huay-Tak Teak Plantation, Lampang (Thailand), 5-8 Aug 1992.

Kaosa-ard, A., & Cox, J. R. (1998). Growth and potential end uses of Teak (*Tectona grandis* Linn. f.) plantations in Northern

Thailand. *Forest Ecology and Management 107*(3): 115 – 129.

Kebede, M., Rasmussen, M. O., Nielsen, L. R., & Meilby, H. (2021). Variation in growth, wood basic density and fibre properties of Teak (*Tectona grandis* Linn. f.) from six provenances in Ethiopia. Southern Forests: *A Journal of Forest Science 83*(1): 41-50.

Kjær, E. D., Graudal, L. O. V., Ditlevsen, B., & Hansen, J. K. (n.d.). *Choice of quality planting stock of Teak the question of a" genetic business plan.*

Kollert, W., & Kleine, M. (2017). *The Global Teak Study. Analysis, Evaluation and Future Potential of Teak Resources.* International Union of Forest Research Organizations, Vienna Austria. 36pp.

Madoffe, S. S., & Maghembe, J. A. (1988). Performance of Teak (*Tectona grandis* Lf) provenances seventeen years after planting at Longuza, Tanzania. *Silvae Genetica 37*(6): 175–178.

Mohanty, S., Panda, M. P., Behera, B. K., & Tewari, A. (2018). Genetic variability, correlation and path coefficient analysis of *Tectona grandis* Linn. provenances in Central India. *Journal of Forestry Research 29*(6): 1537 – 1545.

Moya, R., & Marin, J. D. (2011). Grouping of *Tectona grandis* (L.f) clones using wood color and stiffness. *New Forest* 42: 329 – 345.

Mugasha, A. G., Eid, T., Bollandsås, O. M., Malimbwi, R. E., Chamshama, S. A. O., Zahabu, E., & Luoga, E. J. (2012). Variation in wood basic density of *Tectona grandis* in Tanzania: implications for carbon stocks. Southern Forests: *Journal of Forest Science* 74(1): 11 – 18.

Nabais, C., Hansen, J. K., David-Schwartz, R., Klisz, M., López, R., & Rozenberg, P. (2018). The effect of climate on wood density: What provenance trials tell us? *Forest Ecology and Management* 408:148–156.

Nocetti, M., Rozenberg, P., Chaix, G., & Macchioni, N. (2011). Provenance effect on the ring structure of Teak (*Tectona grandis* Lf) wood by X-ray microdensitometry. *Annals of Forest Science 68:* 1375–1383.

Palanisamy, K., Hegde, M., & Yi, J.-S. (2009). Teak (*Tectona grandis* Linn. F.): A renowned commercial timber species. *Journal of Forest and Environmental Science 25*(1): 1–24.

Parihar, U. S., Chakravarty, N. V., & Kaushik, S. (2016). Impact of silvicultural practices on growth, yield and wood properties of Teak (*Tectona grandis* L.f.): A review. *Forest Ecology and Management 378*: 147-160.

Pedersen, A. P., Hansen, J. K., Mtika, J. M., & Msangi, T. H. (2007). Growth, stem quality and age-age correlations in a Teak provenance trial in Tanzania. *Silvae Genetica, 56*(3–4), 142–147.

Persson, A. (1971). Observation from a progeny trial of *Tectona grandis Linn. F. at Longuza, Tanga Region (Tanzania). Silvic. Research Note Tanzania* 1971: 1 – 24.

Prisantoso, A. B., Sungthong, R., & Fukuda, K. (2017). Wood quality of Teak (*Tectona grandis* L.f.) from five provenances in Thailand. *Journal of Tropical Forest Science 29*(1): 64-73.

Putri, S. E., Syafii, W., & Widiyanto, S. (2015). The basic density of Teak (*Tectona grandis* L.f.) from different provenances in Indonesia. *Journal of Tropical Forest Science, 27*(3): 328 – 333.

Rachman, N. A., Syahputra, I., & Nugroho, W. D. (2019). Non-destructive measurement of Teak tree height and diameter to estimate stem volume and biomass. *IOP Conference Series: Earth and Environmental Science* 236(1): 012038

Rao, P. S., Venkaiah, K., Murali, V., Murti, S. S. N., & Sattar, S. A. (2001). Evaluation of international Teak provenance trial plot in North-East Andhra Pradesh. *Indian Forester 127*(4): 415–422.

Ratnasingam, J., & Ioras, F. (2009). Variability in the physical properties of plantation-grown Teakwood (*Tectona grandis*

Linn. f.) from Malaysia. *European Journal of Wood and Wood Products 67*(1): 97-102.

Sharma, R. K., Kumar, A., Gupta, A. K., & Mohapatra, K. P. (2019). Variation in wood basic density of *Tectona grandis* (Teak) in India. *Journal of Forestry Research 30*(5): 1515-1521.

Tripathi, S. K., & Roy, P. S. (2015). Provenance variation in growth and stem form traits of Teak (*Tectona grandis* Linn. f.) in India. *International Journal of Forestry Research 2015*: 424303.

Verhaegen, D., Fofana, I. J., Logossa, Z. A., & Ofori, D. (2010). What is the genetic origin of Teak (*Tectona grandis* L.) introduced in Africa and in Indonesia? *Tree Genetics and Genomes* 6: 717–733.

Wanneng, P. X., Ozarska, B., & Daian, M. S. (2014). Physical properties of *Tectona grandis* grown in Laos. *Journal of Tropical Forest Science* 26(3): 389–396.

Zahabu, E., Kajembe, G. C., & Luoga, E. J. (2014). Variability in wood basic density of Teak (*Tectona grandis* L.f.) in Tanzania. *Tanzania Journal of Forestry and Nature Conservation 83*(2): 71-80.

Zahabu, E., Kajembe, G. C., Luoga, E. J., & Malimbwi, R. E. (2011). The effect of age on wood basic density of Teak (*Tectona grandis* L.f.) in Tanzania. *Tanzania Journal of Forestry and Nature Conservation 80*(1): 13-23.

Zahabu, E., Mugasha, W. M., Katani, J. Z., Malimbwi, R. E., Mwangi, J. R., & Chamshama, S. A. O. (2018). *Allometric Biomass and Volume Models for Tectona Grandis Plantations.* Sokoine University of Agriculture, Morogoro, Tanzania. 11pp.

CHAPTER FOUR

General Discussion

4.1 Growth Performance and Productivity

The study findings revealed substantial variations in the growth performance and productivity of Teak trees across different provenances. This variation can be attributed to a combination of genetic diversity and climatic factors (Maneerat *et al.,* 2009). Tanzanian provenances demonstrated superior growth performance, indicating their compatibility with local climatic conditions. This finding aligns with the concept of indigenous genetic adaptations, where local land races tend to perform better in their native environments (Pedersen, 2010). The average survival rate of Teak trees in the study was 68.70 ± 5.64 %, which, while lower than in some other studies, still reflects the resilience of Teak plantations. However, termite-induced mortality may contribute to this lower survival rate, highlighting the importance of pest management in Teak plantations (Robertson and Reilly, 2004; Borges *et al.,* 2015). The observed variations in growth performance and survival rates among different provenances emphasize the need for careful selection of seed sources when establishing Teak plantations. Provenances adapted to specific climatic conditions tend to display superior growth, suggesting that matching provenances with their respective environments can enhance plantation success (Graudal and Moestrup, 2017).

4.2 Diameter at Breast Height and Height Growth

Findings showed differences in Dbh among the studied Teak provenances, where several provenances showed larger diameters compared to others. Similarly, Ht growth among these Teak provenances displayed variability, with some achieving greater Ht than others. These differences in Dbh and Ht growth highlight the complex nature of Teak's growth patterns. The interplay between genetic diversity and local climatic conditions may significantly influence these characteristics (Paudel *et al.,* 2017). Gaining insight into these variations can help in selecting provenances that align with particular growth objectives.

4.3 Basal Area and Volume Production

The study revealed notable variations in BA, Vol production, and MAI among different Teak provenances. These differences may be influenced by genetic traits and local climate conditions (Zhen *et al.,* 2019). These findings emphasize the importance of carefully choosing the appropriate Teak provenance based on specific plantation objectives. For example, if the goal is timber production, selecting provenances with superior BA and Vol production is advisable. On the other hand, for short-rotation plantations, those with a high MAI would be more suitable. Additionally, the study underscores the significance of considering genetic diversity and environmental factors when planning Teak plantations.

4.4 Stem Straightness and Physical Properties

The study also examined stem straightness, with different provenances showing varying characteristics. Some provenances showed slower growth rates but compensated with excellent stem straightness, while others displayed rapid growth but suboptimal stem form characteristics (Verhaegen *et al.,* 2010). Soil conditions, climate, and genetics may contribute to these variations (Zhen *et al.,* 2019). BD values of Teak were consistent with findings from several studies, falling within a specific range of 0.469 ± 0.053 g cm^{-3} to 0.545 ± 0.071 g cm^{-3}. The study found no significant differences in BD among Teak trees from different provenances, which may be attributed to factors such as genetic similarity, similar environmental conditions, and soil compositions (Bhat *et al.,* 2021). These findings can guide decisions on which provenances to choose based on the intended use of the timber. The consistent BD values suggest a level of uniformity among Teak trees from different provenances, which can be advantageous for timber processing and utilization.

References

Bhat, K. M., Manoj, K. P., Sharma, J. K., & Suresh Kumar, G. (2021). Inter-provenance variation in stem straightness of Teak (*Tectona grandis* L.f.) in Karnataka, India. *International Journal of Current Microbiology and Applied Sciences* 10(1): 2370–2380.

Borges, R. C. F., Santos, M. D. M., Macedo, M. A., Martins, I., Nascimento, A. G., Café-Filho, A. C., Boiteux, L. S., Fonseca, M. E. N., Inácio, C. A., & Mello, S. C. M. (2015). A trunk canker disease of *Tectona grandis* induced by Lasiodiplodia theobromae in Brazil. *New Disease Reports* 31(26): 2044–0588.

Graudal, L., & Moestrup, S. (2017). The genetic variation in natural and planted Teak forests: Characterisation, use and conservation for the future. *International Union of Forest Research Organizations 36*: 19–29.

Kjær, E. D., Graudal, L. O. V., Ditlevsen, B., & Hansen, J. K. (n.d.). *Choice of quality planting stock of Teak the question of a" genetic business plan.*

Maneerat, S., & Noshiro, S. (2009). Variation in basic density of Teak *Tectona grandis* Linn.f. from different provenances in Thailand. *Journal of Tropical Forest Science 21*(3): 244-250

Oo, M. Z., & Lwin, K. (2004). Growth Performance of Teak Provenance Trials Established in Bago Yoma: Evaluation at the 5th Year After Planting. *Forest Research Institute, Forest Department, Myanmar* 2004: 330–353.

Paudel, R. K., Baral, K. K., & Oli, B. N. (2017). Variability in growth and stem straightness of Teak (*Tectona grandis* Linn. f.) provenances in Nepal. Banko Janakari: *A Journal of Forestry Information for Nepal, 27*(2), 23–29.

Pedersen, A. P. (2010). *Teak Silviculture Manual. Part II: Producing Teak Plants*. Ministry of Forestry, Solomon Islands Government and EU. Unpublished manuscript, 25pp.

Robertson, R. M., & Reilly, D. F. (2004). Performance of a 16-year-old stand of Teak (*Tectona grandis* L) in the Darwin area in relation to that in other trials in the Northern Territory. Northern Territory. Government, Australia.11pp.

Verhaegen, D., Fofana, I. J., Logossa, Z. A., & Ofori, D. (2010). What is the genetic origin of Teak (*Tectona grandis* L.) introduced in Africa and in Indonesia? *Tree Genetics and Genomes* 6: 717–733.

Zhen, F., Zhang, S., Zhang, Y., & Song, X. (2019). Evaluation of stem straightness of Teak (*Tectona grandis* L.f.) clones in the three gorges reservoir area, China. *Forests* 10(2): 151.

CHAPTER FIVE

Key Contributions, Conclusions and Recommendations

5.1 Key Contributions of the Study

The present study has made several key contributions. In the first objective (Chapter two):

i. The study has shown the performance of different Teak provenances and identify superior provenances in terms of growth and productivity. In addition, the study has discussed the necessity of choosing the provenance that corresponds with the climate and soil condition of the area.

ii. The finding that Tanzanian provenances demonstrated superior growth performance aligns with the concept of indigenous genetic adaptations. This serves as empirical evidence of how local land races tend to perform better in their native environments. This validation contributes to the broader understanding of the importance of using local seed sources in Teak plantation programmes.

iii. The study provides information that contributes to the understanding of how genetic diversity and local climatic conditions influence these growth characteristics, assisting in the selection of Teak provenances for specific planting programmes.

iv. The study provides information that guides decisions on selecting provenances based on plantation objectives, such as timber production or short-rotation plantations. It emphasizes the importance of considering genetic diversity and environmental factors when planning for Teak plantations programmes.

The second objective (Chapter three) has managed to enhance our understanding on the variability in stem straightness and BD between Teak provenances:

i. This study has contributed essential insights for forest and plantation managers by comprehensively analyzing the variations in stem straightness and BD across different Teak provenances. These insights help in the precise selection of the most appropriate provenances aimed to specific objectives which can lead to more efficient and sustainable forest management practices.

ii. The study provided valuable information into the factors contributing to these variations and suggested guidance to Teak plantation management and wood product industries, emphasizing the importance of prioritizing stem straightness for improved wood quality and economic purposes.

5.3 Conclusions

The main objective of this study was to assess the performance of *Tectona grandis* provenances at Longuza Forest Plantation, Tanzania. The obtained results have led to the following conclusions.

i. The study revealed significant variations among the Teak provenances studied in terms of Dbh, Ht, BA, Vol, and MAI. Tanzanian land race provenance showed remarkable growth performance among these provenances.
ii. Furthermore, the results of the study indicated that there were no significant differences in survival rates among the tested Teak provenances.
iii. Additionally, the study revealed significant variations in stem straightness among the different Teak provenances at the study site.

iv. Moreover, the study indicated that there were no significant variations in BD among the different Teak provenances at the study site.

5.4 Recommendations

Based on the conclusions drawn from the study objectives, several recommendations can be made:

i. Given that the Tanzanian land race provenance demonstrated remarkable growth performance in terms of Dbh, Ht, BA, Vol, and MAI, it is advisable to prioritize these provenances East Africa Longuza seed stand, East Africa Longuza provenance trial and East Africa Longuza progeny trial to be planted on a large scale in Longuza and in pilot plantations when establishing Teak plantations in areas with similar climatic and soil conditions.

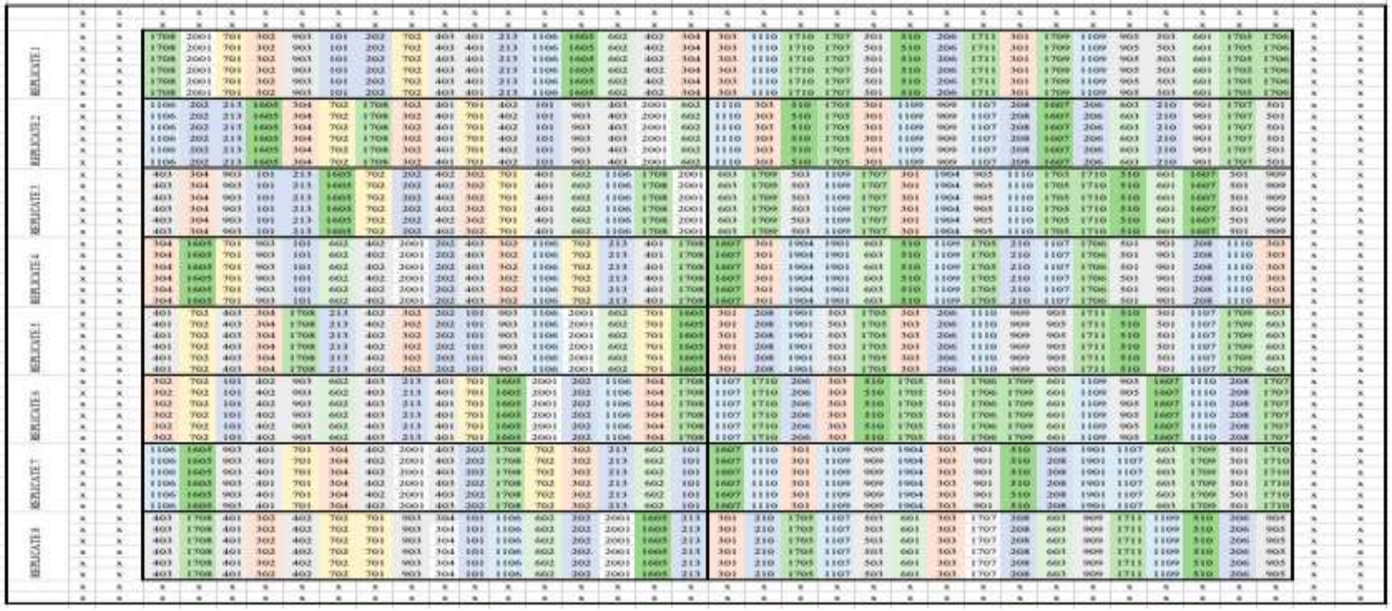
ii. Since there were no significant differences in survival rates among the tested Teak provenances, it suggests that various provenances can be equally viable in terms of tree survival. This allows for flexibility in selecting provenances without compromising survival rates.

iii. The choice of provenance should align with the specific objectives of the plantation projects. Provenances that demonstrate superior stem straightness like East Africa Mtibwa, CSIRO Thailand and East Africa Longuza seed stand, are preferred when the straightness of the stems is critical, especially in applications where it directly impacts timber production, particularly for industries that require high-quality, straight-grained wood. This strategic selection of provenances can lead to more efficient and economically viable plantation management and timber harvesting practices.

iv. The lack of significant variations in BD among Teak provenances at the study site implies that wood quality, in terms of density, remains relatively consistent across different provenances. This finding suggests that stakeholders involved in wood processing and utilization can expect a consistent quality of Teak wood, making it easier to plan and implement various applications.

APPENDICES

Appendix 1: Experimental map trial layout with family codes for each provenance, where X represents border rows and different colors indicate different families



Source: **Tanzania Forest Research Institute (2011)**

Appendix 2: *Tectona grandis* provenances assessed at Longuza Forest Plantation

Country	Provenance name	Provenance code	Family code	Latitude	Longitude	Altitude (m)
Colombia	Refocosta seed stand	2	101	10°01' N	74° 12' W	950
Colombia	Refocosta seed stand	2	202	10°01' N	74° 12' W	950
Colombia	Refocosta seed stand	2	206	10°01' N	74° 12' W	950
Colombia	Refocosta seed stand	2	208	10°01' N	74° 12 W	950
Colombia	Refocosta seed stand	2	210	10°01' N	74° 12' W	950
Colombia	Refocosta seed stand	2	213	10°01' N	74° 12' W	950
Tanzania	East Africa Longuza progeny trial	3	301	5°12' S	38°39' E	200
Tanzania	East Africa Longuza progeny trial	3	302	5°12' S	38°39' E	200
Tanzania	East Africa Longuza progeny trial	3	303	5°12' S	38°39' E	200
Tanzania	East Africa Longuza progeny trial	3	304	5°12' S	38°39' E	200
Tanzania	East Africa Longuza provenance trial	4	401	5°12' S	38°39' E	200
Tanzania	East Africa Longuza provenance trial	4	402	5°12' S	38°39' E	200
Tanzania	East Africa Longuza provenance trial	4	403	5°12' S	38°39' E	200
Tanzania	East Africa Longuza provenance trial	4	501	5°12' S	38°39' E	200
Tanzania	East Africa Longuza provenance trial	4	503	5°12' S	38°39' E	200
Tanzania	East Africa Longuza seed stand	5	510	5°12' S	38°39' E	200
Tanzania	East Africa Mtibwa	6	601	6°08' S	37°38' E	460
Tanzania	East Africa Mtibwa	6	602	6°08' S	37°38' E	460
Tanzania	East Africa Mtibwa	6	603	6°08' S	37°38' E	460
Tanzania	East Africa Kihuhwi seed stand	7	701	5°12' S	38°39' E	200
Tanzania	East Africa Kihuhwi seed stand	7	702	5°12' S	38°39' E	200
Indonesia	Sumalindo	9	901	1°24' S	118°19' E	70-80

Indonesia	Sumalindo	9	903	1°24’ S	118°19’ E	70-80
Indonesia	Sumalindo	9	905	1°24’ S	118°19’ E	70-80
Indonesia	Sumalindo	9	909	1°24’ S	118°19’ E	70-80
Costa Rica	DeGuate- Tailandia	12	1106	14°15’ N	91°29’ W	60
Costa Rica	DeGuate- Tailandia	12	1107	14°15’ N	91°29’ W	61
Costa Rica	DeGuate- Tailandia	12	1109	14°15’ N	91°29’ W	62
Costa Rica	DeGuate- Tailandia	12	1110	14°15’ N	91°29’ W	63
Thailand	CSIRO Thailand	16	1605	16°20°N	97°101°E	2590
Thailand	CSIRO Thailand	16	1607	16°20°N	97°101°E	2590
Thailand	CSIRO Laos	17	1705	13°54’ N	107°59’ E	1500
Thailand	CSIRO Laos	17	1706	13°54’ N	107°59’ E	1500
Thailand	CSIRO Laos	17	1707	13°54’ N	107°59’ E	1500
Thailand	CSIRO Laos	17	1708	13°54’ N	107°59’ E	1500
Thailand	CSIRO Laos	17	1709	13°54’ N	107°59’ E	1500
Thailand	CSIRO Laos	17	1710	13°54’ N	107°59’ E	1500
Thailand	CSIRO Laos	17	1711	13°54’ N	107°59’ E	1500
Mozambique	Chikweti Niasa-Lichinga	19	1901	15°28’ S	15°28’ S	700
Mozambique	Chikweti Niasa-Lichinga	19	1904	15°28’ S	15°28’ S	700
Venezuela	SKCV Bulk	98	2001	7°16' N	70°55' W	330

CSIRO = Commonwealth Scientific and Industrial Research Organization of the Australian government

Appendix 3: Field form for Dbh, Ht and stem scoring data collection

Compartment ID			**Altitude**				**Slope**					
Plot id			**Planted year**									
Measurer			**Date**									
Observation												
Co-ordinates: Easting			**Northing**									
S/n	**Test Id**	**Replication**	**Block**	**Row**	**Column**	**Plot**	**Provenance**	**Family**	**Tree**	**DBH (cm)**	**HT (m)**	**Stem score**
1	635002C2	1	1	1	1	1	17	1708	1			
2	635002C2	1	1	2	1	1	17	1708	2			
3	635002C2	1	1	3	1	1	17	1708	3			
4	635002C2	1	1	4	1	1	17	1708	4			
5	635002C2	1	1	5	1	1	17	1708	5			
6	635002C2	1	1	6	1	1	17	1708	6			
1	635002C2	1	1	1	2	2	98	2001	1			
2	635002C2	1	1	2	2	2	98	2001	2			
3	635002C2	1	1	3	2	2	98	2001	3			
4	635002C2	1	1	4	2	2	98	2001	4			
5	635002C2	1	1	5	2	2	98	2001	5			
6	635002C2	1	1	6	2	2	98	2001	6			

Appendix 4: Results of the analysis of variance (ANOVA) conducted for all variables measured in the site

Source of variation	df	Survival (%) *p*-value	Dbh (cm) *p*-value	Ht (m) *p*-value	BA (m^2/ha) *p*-value	Vol (m^3/ha) *p*-value	MAI (m^3/ha/yr) *p*-value
Replication	7	0.2406	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Provenance	11	0.8719	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Replication*Provenance	73	0.0946	0.5211	0.4736	0.6024	0.5557	0.5557
Family (Provenance)	29	0.7668	0.0047	0.0286	0.0033	0.0007	0.0007
Replication*Family (Provenance)	135		0.0013	0.0958	0.001	0.0008	0.0008

df = degrees of freedom; Dbh = diameter at breast height (1.3 m above the base) over bark; Ht = total tree height; BA = basal area at breast height; Vol = total tree aboveground volume; MAI = mean annual increment.

Appendix 5: Outcomes of the Duncan Multiple Range Test (DMRT) conducted for the growth and productivity parameters measured in the site

S/n	Country	Provenance name	Dbh Mean (cm)	Ht Mean (m)	BA Mean (m^2/ha)	Vol Mean (m^3/ha)	MAI Mean (m^3/ha/yr)	Survival Mean (%)
1	Tanzania	East Africa Longuza seed stand	24.26±4.34^{a}	20.10±2.48^{a}	12.70±4.24^{a}	410.69±164.70^{a}	37.34±14.97^{a}	67.47±6.00^{a}
2	Tanzania	East Africa Longuza provenance trial	24.01±4.20^{a}	19.89±2.18^{ab}	12.43±4.20^{ab}	398.54±165.19^{ab}	36.23±15.01^{ab}	67.94 ±7.18^{a}
3	Tanzania	East Africa Longuza progeny trial	23.62±4.72^{ab}	19.82±2.46^{ab}	12.14±4.47^{ab}	390.62±173.78^{abc}	35.51±15.79^{abc}	68.05 ±6.12^{a}
4	Indonesia	Sumalindo	22.8±3.59^{ab}	19.28±1.93^{abc}	11.15±3.45^{abc}	345.02±135.81^{abcd}	31.37±12.34^{abcd}	67.44 ±7.73^{a}
5	Tanzania	East Africa Kihuhwi seed stand	22.53±4.14^{ab}	19.08±2.96^{abc}	10.99±3.66^{abc}	336.70±143.32^{bcd}	30.61±13.02^{bcd}	69.90 ±3.24^{a}
6	Colombia	Refocosta seed stand	21.85±3.55^{abc}	18.89±2.07^{abc}	10.26±3.41^{bcd}	312.44±135.10^{cde}	28.40±12.28^{cde}	69.34 ±4.03^{a}
7	Costa Rica	DeGuate- Tailandia	20.38±3.41^{bcd}	18.31±2.05^{cd}	9.09±4.09^{cde}	275.78±150.97^{def}	25.07±13.72^{def}	68.78 ±5.63^{a}
8	Venezuela	SKCV bulk	20.35±3.29 ^{cd}	19.15±2.50^{abc}	8.94±2.88^{def}	273.39±104.95^{ef}	24.85±9.54^{ef}	67.47 ±6.00^{a}
9	Tanzania	East Africa Mtibwa	20.31±4.71^{cd}	18.50±2.51^{bcd}	8.89±2.76^{def}	262.73±103.46^{efg}	23.88±9.40^{efg}	69.88 ±5.11^{a}
10	Thailand	CSIRO Thailand	18.85±3.47^{cde}	17.79±1.62^{cde}	7.99±4.19^{def}	230.05±144.86^{efg}	20.91±13.16^{efg}	70.55 ±4.89^{a}
11	Mozambique	Chikweti Niasa-Lichinga	18.83±5.35 ^{de}	17.05±3.35^{de}	7.69±2.80^{ef}	219.20±95.29^{fg}	19.93±8.66^{fg}	68.55 ±5.29^{a}
12	Thailand	CSIRO Laos	18.32±3.76 ^{de}	16.91±2.60^{e}	7.32±3.01^{ef}	202.82±107.01^{fg}	18.44±9.72^{fg}	69.06 ±6.46^{a}

Dbh = diameter at breast height (1.3 m above the base) over bark; Ht = total tree height; BA = basal area at breast height; Vol = total tree aboveground volume; MAI = mean annual increment; CSIRO = Commonwealth Scientific and Industrial Research Organization of the Australian government. Mean ± SD in the same column superscripted with different lowercase letters are significantly ($p < 0.05$) different.

Appendix 6: Ordinal ranking for the growth and productivity parameters of *Tectona grandis* provenances in the study site

Provenance Code	Country	Provenance Name	Dbh (cm)	Ht (m)	BA (m^2ha^{-1})	Vol (m^3ha^{-1})	MAI ($m^3ha^{-1}yr^{-1}$)	Sum rank	Mean rank	Overall rank
5	Tanzania	East Africa Longuza seed stand	1	1	1	1	1	5	1	1
4	Tanzania	East Africa Longuza Provenance Trial	2	2	2	2	2	10	2	2
3	Tanzania	East Africa Longuza Progeny Trial	3	3	3	3	3	15	3	3
9	Indonesia	Sumalindo	4	4	4	4	4	20	4	4
7	Tanzania	East Africa Kihuhwi Seed stand	5	6	5	5	5	26	5.2	5
2	Colombia	Refocosta seed stand	6	7	6	6	6	31	6.2	6
98	Venezuela	SKCV Bulk	8	5	9	8	8	38	7.6	7
6	Tanzania	East Africa Mtibwa	9	8	7	7	7	38	7.6	8
12	Costa Rica	DeGuate- Tailandia	7	9	8	9	9	42	8.4	9
19	Mozambique	Chikweti Niasa-Lichinga	11	11	10	10	10	52	10.4	10
16	Thailand	CSIRO Thailand	10	10	11	11	11	53	10.6	11
17	Thailand	CSIRO Laos	12	12	12	12	12	60	12	12

Dbh = diameter at breast height (1.3 m above the base) over bark; Ht = total tree height; BA = basal area at breast height; Vol = total tree aboveground volume; MAI = mean annual increment; CSIRO = Commonwealth Scientific and Industrial Research Organisation of the Australian government

Appendix 7: Ordinal ranking for the growth and productivity parameters of *Tectona grandis* families in the study site

S/n	Family Code	Country	Family name	Dbh (cm)	Ht (m)	BA (m^2ha^{-1})	Vol (m^3ha^{-1})	MAI ($m^3ha^{-1}yr^{-1}$)	Sum rank	Mean rank	Overall rank
1	501	Tanzania	East Africa Longuza Provenance Trial	2	1	2	1	1	7	1.4	1
2	403	Tanzania	East Africa Longuza Provenance Trial	1	4	1	2	2	10	2	2
3	503	Tanzania	East Africa Longuza Provenance Trial	3	2	3	3	3	14	2.8	3
4	909	Indonesia	Sumalindo	4	6	4	4	4	22	4.4	4
5	304	Tanzania	East Africa Longuza Progeny Trial	7	3	6	5	5	26	5.2	5
6	510	Tanzania	East Africa Longuza seed stand	5	7	5	6	6	29	5.8	6
7	302	Tanzania	East Africa Longuza Progeny Trial	6	5	7	7	7	32	6.4	7
8	303	Tanzania	East Africa Longuza Progeny Trial	9	10	9	8	8	44	8.8	8
9	701	Tanzania	East Africa Kihuhwi Seed stand	8	12	8	9	9	46	9.2	9
10	905	Indonesia	Sumalindo	12	11	12	11	11	57	11.4	10
11	901	Indonesia	Sumalindo	11	16	11	10	10	58	11.6	11
12	101	Colombia	Refocosta seed stand	14	9	14	13	13	63	12.6	12
13	301	Tanzania	East Africa Longuza Progeny Trial	10	22	10	12	12	66	13.2	13
14	401	Tanzania	East Africa Longuza Provenance Trial	13	14	13	14	14	68	13.6	14
15	210	Colombia	Refocosta seed stand	16	8	18	17	17	76	15.2	15
16	206	Colombia	Refocosta seed stand	15	19	15	15	15	79	15.8	16
17	402	Tanzania	East Africa Longuza Provenance Trial	17	17	17	18	18	87	17.4	17
18	601	Tanzania	East Africa Mtibwa	22	18	19	16	16	91	18.2	18
19	208	Colombia	Refocosta seed stand	18	23	16	19	19	95	19	19
20	702	Tanzania	East Africa Kihuhwi Seed stand	20	21	20	20	20	101	20.2	20
21	1107	Costa Rica	DeGuate- Tailandia	23	13	24	23	23	106	21.2	21
22	903	Indonesia	Sumalindo	21	24	22	21	21	109	21.8	22
23	202	Colombia	Refocosta seed stand	19	26	21	22	22	110	22	23
24	213	Colombia	Refocosta seed stand	24	25	23	24	24	120	24	24
25	602	Tanzania	East Africa Mtibwa	25	20	25	25	25	120	24	25
26	2001	Venezuela	SKCV Bulk	29	15	29	26	26	125	25	26
27	1110	Costa Rica	DeGuate- Tailandia	26	29	27	28	28	138	27.6	27
28	1901	Mozambique	Chikweti Niasa-Lichinga	28	34	26	27	27	142	28.4	28
29	1106	Costa Rica	DeGuate- Tailandia	30	27	28	29	29	143	28.6	29

30	1711	Thailand	CSIRO Laos	31	28	31	30	30	150	30	30
31	1709	Thailand	CSIRO Laos	27	35	30	31	31	154	30.8	31
32	1109	Costa Rica	DeGuate- Tailandia	32	32	32	32	32	160	32	32
33	603	Tanzania	East Africa Mtibwa	33	31	33	33	33	163	32.6	33
34	1607	Thailand	CSIRO Thailand	34	30	34	34	34	166	33.2	34
35	1605	Thailand	CSIRO Thailand	35	33	36	35	35	174	34.8	35
36	1708	Thailand	CSIRO Laos	36	36	35	36	36	179	35.8	36
37	1706	Thailand	CSIRO Laos	37	37	37	39	39	189	37.8	37
38	1707	Thailand	CSIRO Laos	41	39	40	37	37	194	38.8	38
39	1904	Mozambique	Chikweti Niasa-Lichinga	40	40	38	38	38	194	38.8	39
40	1705	Thailand	CSIRO Laos	39	38	41	40	40	198	39.6	40
41	1710	Thailand	CSIRO Laos	38	41	39	41	41	200	40	41

Appendix 8: Description of stem straightness scores

S/n	Description of Stem quality class	Class
1	Straight to the top and good stem form	1
2	Straight and good stem form but with straight top forks	
1	Straight and good stem form but with one slight bend less than 1m in length	2
2	Straight and good stem form but with slightly bent or crooked mid/top forks	
3	Straight and good stem form but with buttresses within 1 m height	
1	Slight bends less than 1 m at bottom and at top with straight middle part	3
2	One slight bend more than 1 m in length	
3	Slight crook, slight taper, buttressed within 2 m height	
1	Serious crook, excess taper and buttressed beyond 2 m height	4

Appendix 9: Stem straightness means score of *Tectona grandis* families in the study site

S/n	Family code	Country	Family name	Mean score
1	603	Tanzania	East Africa Mtibwa	1.53±0.69
2	1107	Costa Rica	DeGuate- Tailandia	1.56±0.72
3	403	Tanzania	East Africa Longuza Provenance Trial	1.57±0.67
4	501	Tanzania	East Africa Longuza Provenance Trial	1.60±0.82
5	210	Colombia	Refocosta seed stand	1.63±0.91
6	1607	Thailand	CSIRO Thailand	1.64±0.84
7	208	Colombia	Refocosta seed stand	1.71±0.84
8	101	Colombia	Refocosta seed stand	1.78±0.85
9	1106	Costa Rica	DeGuate- Tailandia	1.79±0.72
11	302	Tanzania	East Africa Longuza Progeny Trial	1.82±0.90
10	510	Tanzania	East Africa Longuza seed stand	1.82±0.79
12	909	Indonesia	Sumalindo	1.86±0.94
13	213	Colombia	Refocosta seed stand	1.88±1.03
14	303	Tanzania	East Africa Longuza Progeny Trial	1.89±0.87
15	1109	Costa Rica	DeGuate- Tailandia	1.90±0.85
16	601	Tanzania	East Africa Mtibwa	1.92±0.90
17	1605	Thailand	CSIRO Thailand	1.92±0.77
18	206	Colombia	Refocosta seed stand	1.93±0.82
19	304	Tanzania	East Africa Longuza Progeny Trial	1.96±0.97
20	301	Tanzania	East Africa Longuza Progeny Trial	2.00±0.90
21	401	Tanzania	East Africa Longuza Provenance Trial	2.00±0.81
23	602	Tanzania	East Africa Mtibwa	2.00±0.69
22	702	Tanzania	East Africa Kihuhwi Seed stand	2.00±0.79
24	701	Tanzania	East Africa Kihuhwi Seed stand	2.04±0.80
25	1110	Costa Rica	DeGuate- Tailandia	2.05±0.88
26	1709	Thailand	CSIRO Laos	2.07±0.88
27	2001	Venezuela	SKCV Bulk	2.09±0.81
28	1901	Mozambique	Chikweti Niasa-Lichinga	2.11±0.60
29	1904	Mozambique	Chikweti Niasa-Lichinga	2.13±0.64
30	402	Tanzania	East Africa Longuza Provenance Trial	2.13±0.96
31	503	Tanzania	East Africa Longuza Provenance Trial	2.17±0.93
32	903	Indonesia	Sumalindo	2.18±0.77
33	905	Indonesia	Sumalindo	2.20±0.97
34	1706	Thailand	CSIRO Laos	2.22±0.87
35	1705	Thailand	CSIRO Laos	2.26±1.03
36	1707	Thailand	CSIRO Laos	2.27±0.70
37	1708	Thailand	CSIRO Laos	2.30±0.65
38	1710	Thailand	CSIRO Laos	2.33±1.29
39	1711	Thailand	CSIRO Laos	2.50±0.92
40	202	Colombia	Refocosta seed stand	2.54±0.58
41	901	Indonesia	Sumalindo	2.57±0.97