Sokoine University of Agriculture

MSc Dissertation

Effects of Spacing on Growth, Yield and Wood Properties of *Tectona Grandis* at Longuza Forest Plantation, Tanzania

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EFFECTS OF SPACING ON GROWTH, YIELD AND WOOD PROPERTIES OF *TECTONA GRANDIS* AT LONGUZA FOREST PLANTATION, TANZANIA

This 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

In forest management, understanding the influence of spacing on tree growth is crucial, as it goes hand in hand with stand growth as well as yield at the final harvest. Also, spacing, especially narrow spacing, has been used to control the stem quality of trees, as it influences the stem straightness as well as the branching behaviour. On the other hand, tree growth, particularly radial growth, means an increase in wood materials such as cell wall substances, latewood, and earlywood. Those wood materials influence the physical and mechanical properties of wood. Behind those influences, an understanding of the influence of spacing on the final harvest is required to decide on appropriate spacing to economize the value of the final harvest. However, information on the spacing influence on growth, yield, and wood properties of *Tectona grandis* at an older age in Tanzania is limited. Thus, this study is intended to evaluate the influence of spacing on the growth, yield, and wood properties of 24-year-old *Tectona grandis* at Longuza Forest plantation, Tanzania. Data were collected from a spacing trial with a randomized complete block design with three treatments, namely 2 x 2 m, 3 x 3 m, and 4 x 4 m, replicated three times. For growth and stem quality, all trees' diameter at breast height (dbh), height, and stem quality were evaluated. Then, dbh data were used to obtain basal area (Ba), volume, and the mean annual increment (MAI). Furthermore, three trees from each spacing were sampled for physical and mechanical properties. The basic density (BD) was determined using over-dry weight and green volume, while the heartwood (HW) percentage was calculated using the cross-sectional area of the HW and disk underbark. Moreover, all mechanical properties were tested using a Monsanto tensiometer machine. An analysis of variance (ANOVA) was used to evaluate the influence of spacing. Then, Tukey's Honest Significant Difference test (p = 0.05) was used for multiple comparisons of means. Results revealed that at the older age of 24 years, spacing did not statistically influence all growth and yield parameters studied. A 4 x 4 m spacing produced trees with higher dbh and height, while higher Ba, volume, and MAI values were observed at 3 x 3 m. Stem quality was statistically different in some spacings, where only 2 x 2 m differed statistically from 4 x 4 m. All physical and mechanical properties evaluated were not statistically influenced by spacing except CLST to grain, whereby the spacings of 2 x 2 m and 3 x 3 m had significantly higher values than a spacing of 4 x 4 m. In conclusion, results showed that despite the growth and yield parameters not being statistically influenced by spacing, a spacing of 3 x 3 m could ensure a higher yield compared to other spacings. Also, it produces trees with high stem quality, similar to closer spacing, without affecting both physical and mechanical properties. This is because the values of those properties appear to have slight differences among the spacings.

Keywords: *Tectona grandis*, Spacing, Volume, Stem quality, Basic density, Heartwood percentage

IKISIRI KUU

Katika menejimenti ya misitu, kuelewa athari/faida ya nafasi kati ya mti na mti kwenye ukuaji wa miti ni muhimu sana, kwani inakwenda sambamba na ukuaji wa msitu pamoja na mavuno kabla na wakati wa uvunaji wa mwisho. Pia, nafasi, haswa nafasi ndogo, imetumika kudhibiti ubora wa shina la miti, kwani unaathiri unyooke wa shina pamoja na tabia ya matawi. Kwa upande mwingine, ukuaji wa mti, haswa ukuaji wa mduara, una maana ya ongezeko la vitengeneza mbao kama vitu vya ukuta wa seli, *latewood*, na *earlywood*. Vitengeneza mbao vinaweza kuathiri ubora wa mbao kwa matumizi mbalimbali. Nyuma ya athari hizo, kuelewa athari ya nafasi kati ya mti na mti kwenye mavuno ya mwisho kunahitajika ili kuamua nafasi sahihi ili kuwa na mvuno ya mwisho yenye thamani. Hata hivyo, taarifa juu ya athari/faida ya nafasi kati ya mti na mti kwa ukuaji, mavuno, na ubora wa mbao za Msaji (*Tectona grandis*) kwa umri mkubwa nchini Tanzania ni chache. Kwa hivyo, utafiti huu ulikusudia kutathmini athari/faida ya nafasi kati ya mti na mti kwenye ukuaji, mavuno, na ubora wa mbao za Msaji wenye umri wa miaka 24 katika shamba la Miti Longuza, Tanzania. Data ilikusanywa kutoka kwa majaribio ya umbali na muundo wa block kamili wa *random* na *treatment* tatu, yaani 2 x 2 m, 3 x 3 m, na 4 x 4 m, zikirudiwa mara tatu. Kwa ukuaji na ubora wa shina, kipenyo cha shina kwenye urefu wa mita 1.3 kutoka aridhini (dbh), urefu, na ubora wa shina wa miti yote ulipimwa. Kisha, data ya dbh ilitumika kupata eneo la msingi (Ba), kiasi, na ongezeko la wastani la kila mwaka (MAI). Zaidi ya hayo, miti mitatu kutoka kila nafasi ilipimwa kujua ubora wa mbao. Uzito msingi (BD) ulipimwa kwa kutumia uzito wa juu na kiasi cha kijani, wakati asilimia ya ubao wa moyo (HW) ilihesabiwa kwa kutumia eneo la msingi la HW na diski chini ya gome. Zaidi ya hayo, sifa zote za ubora wa mbao zilipimwa kwa kutumia mashine ya *tensiometer* ya Monsanto. Uchambuzi wa utofauti (ANOVA) ulitumika kutathmini athari/faida ya nafasi kati ya mti na mti. Kisha, jaribio la Tofauti Kubwa ya Maana ya Tukey ($p = 0.05$) lilitumika kwa kulinganisha wastani. Matokeo yalionesha kuwa kwa umri wa miaka

24, nafasi kati ya mti na mti haukuathiri kwa kiwango cha takwimu paramita zote za ukuaji na mavuno zilizosomwa. Nafasi ya 4 x 4 m ulizalisha miti yenye dbh kubwa na urefu, wakati thamani kubwa ya BA, kiasi, na MAI ilionekana kwenye nafasi ya 3 x 3 m. Ubora wa shina ulikuwa tofauti kwa kiwango cha takwimu katika baadhi ya nafasi, ambapo tu 2 x 2 m ilikuwa tofauti kwa kiwango cha takwimu na 4 x 4 m. Sifa zote za ubora wa mbao hazikuathiriwa kwa kiwango cha takwimu na nafasi kati ya mti na mti isipokuwa CLST , ambapo nafasi ya 2 x 2 m na 3 x 3 m ilikuwa na thamani kubwa sana kuliko nafasi ya 4 x 4 m. Kwa muhtasari, matokeo yalionesha kuwa licha ya paramita za ukuaji na mavuno kutokuwa na tofauti kubwa kati nafasi ya mti na mti, nafasi ya 3 x 3 m inaweza kuhakikisha mavuno makubwa ikilinganishwa na nafasi nyingine. Pia, inazalisha miti yenye ubora wa shina wa juu, kama vile nafasi ya karibu, bila kuathiri ubora wa mbao. Hii ni kwa sababu thamani za sifa hizo zinaonekana kuwa na tofauti ndogo kati ya nafasi.

Maneno muhimu: Msaji (*Tectona grandis*), Nafasi kati ya mti na mti, Kiasi, Ubora wa Shina, Ugumu wa Msingi, Asilimia ya Ubao wa Moyo.

DECLARATION

I, **ENOS SAMAMBA**, 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 that it has neither been submitted nor being concurrently submitted in any other institution.

Enos Samamba Date
(MSc. Candidate)

The above is confirmed by;

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

Mr. Japhet N. Mwambusi Date
(Supervisor)

LIST OF MANUSCRIPTS

Manuscript 1: Growth, yield, and stem quality of *Tectona grandis* grown with different spacings at Longuza Forest Plantation, Tanzania

Manuscript 2: Physical and mechanical properties of *Tectona grandis* under different spacings at Longuza Forest Plantation, Tanzania

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DEDICATION

This study is dedicated to my beloved parents, who laid the foundation of my education. It is also dedicated to my family, especially my wife and my sons, together with my brothers and sisters, who were a fountain of inspiration, encouragement, and love that contributed to my success.

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LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

Ba	Basal area
BD	Basic density
CLSP	Cleavage strength perpendicular to grain
CLST	Cleavage strength tangential to grain
cm	centimetre
CSP	Compressive strength parallel to grain
Dbh	Diameter at breast height
HW	Heartwood
kg	Kilogramme
m	meter
MAI	Mean annual increment
mm	millimetre
MOE	Modulus of elasticity
MOR	Modulus of rupture
N	Newton
SS	Shear strength

CHAPTER ONE

GENERAL INTRODUCTION

1.1 Background Information

In forest plantations, silviculture practices are mainly a management tool to ensure tree growth and improvement the value of the final crop. This involves practices such as spacing, thinning, and pruning that influence the growth and value of the final crop directly. In addition, other silvicultural practices, such as weed suppression and fertilizer application, influence the growth and value of the final crop indirectly (Macdonald & Hubert, 2002). Of all silvicultural practices, spacing is the most important, specifically during the establishment and maintenance of planted forest stands. Spacing determines the stocking level of the stand, which is the sole foundation for other practices. For instance, during the establishment, the stocking level required depicts the number of seedlings required as well as the planting cost. Further, during the maintenance of forest stands, other practices such as pruning, thinning, and weeding will be based on the number of seedlings planted initially (Jozsa & Middleton, 1994). For instance, spacing influences the timing of thinning by determining the stocking level at the time of thinning (Pérez & Kanninen, 2005). In Tanzania, when 2.44 x 2.44 m spacing was used, the thinning was done five times at 4, 8, 12, 16, and 20 years, followed by clear-felling at 60 years (Malende & Temu, 1990). On the other hand, the timing of thinning was adjusted after the spacing of 2.5 x 2.5 m was in use, and then the timing of thinning was to be done twice at 5, and 15 years. Similarly, at a spacing of 3 x 3 m in Tanzania, thinning has to be done twice at 8 and 13 years (Gumadi *et al*., 2023). Regarding the timing of thinning with respect to the spacing used, it implies that at narrow spacing, trees will reach the canopy closer sooner compared to wider spacing, whereby competition starts earlier and thinning has to be done earlier than at wider spacing (Kollert & Kleine, 2017).

The spacing regime used depends on the site, species, and intended product at the end of the rotation, as well as their size (Iddi *et al*., 1996). In hardwood species, particularly *Tectona grandis* L.f. (Teak), different spacing regimes have been used. In tropical regions where Teak is extensively planted, the spacing ranges from 1.8 x 1. 8 m to around 3 x 3 m (Pachas *et al*., 2019a). Furthermore, the spacing commonly used in Teak plantations managed for sawlog production ranges from 3 x 3 m to 3.5 x 3.5 m in some areas (Pachas *et al*., 2019a). In addition, when Teak is planted in an agroforestry system, the spacing between tree rows is increased to leave space for agricultural crops (Kollert & Kleine, 2017). In the agroforestry system, the common spacings reported are 6 x 2 m and 8 x 2 m (Ugalde Arias & Monteuuis, 2013).

Regarding recommended spacing in different areas growing *Tectona grandis*, in Lao PDR, the spacing of 3 x 3 m is mostly recommended in planted Teak forests (Pachas *et al*., 2019a). In Costa Rica, the spacing of 2.5 x 2.5 m is no longer practised; instead, the spacing of 3 x 3 m is currently practised (Pérez & Kanninen, 2005). Also in Ghana, the spacing of 3 x 3 m is currently in use and was adopted from Côte d'Ivoire (Wanders and Tollenaar, 2017, as cited by Gumadi, 2019). In Tanzania, the spacing of 2.5 x 2.5 m is commonly used in state-owned *Tectona grandis* plantations, namely Longuza and Mtibwa Forest plantations (Malimbwi, 2016; Gumadi, 2019). However, the most recommended spacing of 3 x 3 for sawlog production is also described in Technical Order No. 1 of 2021 (URT, 2021). On the other hand, Kilombero Valley Teak Company has also started using 3 x 3 m spacing since 2000 instead of the 2 x 2 m spacing practised from 1993 to 1999 (Gumadi, 2019).

In light of the different spacings being used in areas growing *Tectona grandis*, adjusting the spacing is a silvicultural technique to optimize tree growth and then eventually yield at the final harvest age (Sopacua *et al*., 2021). It has been reported that spacing has effects on growth, yield, and the wood properties of the final harvest by influencing tree growth and eventually wood formation (Macdonald & Hubert, 2002). Several studies have been conducted to assess the spacing effects on growth, yield, and wood properties. In Indonesia, the study by Rahmawati *et al*. (2022) on 8-year-old *Tectona grandis* used four different spacings of 3 x 3 m, 6 x 2 m, 8 x 2 m, and 10 x 2 m. Similar study by Kamara *et al*. (2020) on a 9-year-old *Tectona grandis* planted at spacings of 1.8 x 1.8 m, 2 x 2 m, 3 x 3 m, and 4 x 4 m in Sierra Leone. Also, the study by Kainyande *et al*. (2023) evaluated the growth of five-year-old *Tectona grandis* grown at four different spacings in Sierra Leone. Furthermore, Ola-Adams (1990) did a study to evaluate how four different planting spacings affect the growth and yield of 18-year-old Teak in Nigeria. Moreover, in Tanzania, Sibomana *et al*. (1997), conducted the study to evaluate the effect of four different spacings on 14-year-old Teak. Also, in Tanzania, Zahabu *et al*. (2015) conducted a study to investigate how spacing influences the growth, yield, and wood properties of *Tectona grandis* at the age of 14.

Behind these several studies conducted regarding the effect of spacing on growth, yield, and wood properties, most of them were conducted at a young age. But the effect of spacing does not remain the same until the older age i.e. the final harvest. Macdonald & Hubert (2002) reported that competition among trees at narrow spacings at an early stage is higher compared to wider spacing but is being reduced with time. Hence, the effect of spacing at an older age could probably be different. Thus, this study is intended to evaluate how different spacings affect the growth, yield, and wood properties of *Tectona grandis* at the age of 24.

1.2 Problem Statement and Justification

Spacing is among the factors that influence the growth rate, as it would be expected that trees grown at wider spacing would have a higher DBH compared to those grown at close spacing as a result of less competition for moisture and nutrients (Palik & Pregitzer, 1995). The effects of spacing on the growth, yield, and wood properties of

Tectona grandis have been widely studied elsewhere. Currently, it is not known how spacing affects growth and yield parameters as well as wood properties on *T. grandis* in Tanzania at an older age (24 years).

However, a study by Zahabu *et al*. (2015) at age 14 years showed that DBH, height, and MAI were significantly influenced by spacing, while Ba and total volume were insignificantly influenced by spacing. On the contrary, most of the wood properties studied were not statistically influenced by spacing at a young age (14 years), as reported by Zahabu *et al*. (2015). Further, Pérez & Kanninen (2005) found that important wood properties such as HW proportion and BD are related to age. For example, HW proportion at DBH has been reported to be relatively proportional with age, as it accounts for 80 to 90% of trunk at age greater than 30 years of plantation-grown *T. grandis* in different regions of the world (Bhat, 1995; Kokutse *et al.,* 2004). On the other hand, the HW proportion determines the yield; as expected, trees with a high proportion of HW will account for a high percentage of the final total and merchantable volume (Pérez & Kanninen, 2005).

The study by Zahabu *et al*. (2015) is about 10 years old by 2022. Since that time, no study has been done to evaluate the effects of spacing on growth, yield, stem quality and wood properties at an older age. Thus, this study intended to assess the effects of spacing on growth, yield, and some wood properties at the age of 24 years. The result from this study will provide knowledge on spacing effects on growth, yield, and wood properties at older ages to Tanzania Forest Services Agency (TFS), which manages public Teak plantations, and other stakeholders such as Kilombero Valley Teak Company, as well as small-scale farmers dealing with *Tectona grandis*. And the optimal initial spacing, which will yield more as well as produce timber with good wood properties for structural and construction usage.

1.3 Objectives

1.3.1 Main objective

The main objective of this study was to assess the effects of spacing on the growth, yield, and wood properties of 24-year-old *Tectona grandis* at Longuza Forest Plantation.

1.3.2 Specific objectives

The specific objectives of this study were;

i. To determine the growth increment, yield and stem quality for each spacing regime.
ii. To determine the physical properties of each spacing regime.
iii. To determine the mechanical properties of each spacing regime

1.4 Dissertation Structure

This dissertation is made up of five chapters and follows the layout of a publishable paper format. Chapter 1 describes the background information, problem statement, justification, and objectives of the research subject. Chapter 2 presents manuscript one titled Growth, Yield, and Stem Quality of *Tectona grandis* grown with different spacings at Longuza Forest Plantation, Tanzania, while chapter 3 presents manuscript two titled the physical and mechanical properties of *Tectona grandis* under different spacings at Longuza Forest Plantation, Tanzania. Chapter 4 details a general discussion of the research findings. Lastly, Chapter 5 gives key contributions, conclusions, and recommendations for the study.

CHAPTER TWO

MANUSCRIPT ONE

Growth, yield, and stem quality of *Tectona grandis* grown with different spacings at Longuza Forest Plantation, Tanzania

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Abstract
Spacing is among the silvicultural practices that affect the growth of individual trees in forest plantations. However, the yield depends on growth, which is determined by spacing. In addition, spacing influences the quantity of final crop available for harvesting specifically in forest plantations for sawlog production. Spacing is also being used as a management practice to control the quality of trees, as dense stands are expected to have trees with good stem quality. However, little has been done to address the effect of spacing on growth, yield, and stem quality of *Tectona grandis* until its final harvesting age. Teak plantations in Tanzania are now grown at a rotation age of 20 years. Thus, this study aimed to assess the effect of spacing on the growth, yield, and stem quality of 24-year-old *Tectona grandis* at Longuza Forest plantation, Muheza, Tanzania. Data were collected from a spacing trial with a randomized complete block design with three treatments: 2 x 2 m, 3 x 3 m, and 4 x 4 m with three replications. The growth and yield parameters assessed were diameter at breast height (dbh) total tree height and stem quality. Data were analyzed to obtain basal area, volume, and mean annual increment. Statistical analysis was performed using Analysis of Variance (ANOVA), and multiple comparisons among treatment means were done using Tukey's Honest Significant Difference test (*p-value* = 0.05). The results showed that spacing did not significantly affect growth and yield parameters. The stem quality was significantly different in some treatments. The highest dbh and height growth were observed at 4 x 4 m spacing. The highest values of basal area, volume, and mean annual increment were observed at 3 x 3 m spacing. Stem quality differed significantly between the 2 m x 2 m and 4 x 4 m spacings. Because Teak plantations in Tanzania are aimed at sawlog production, it is recommended to continue practising a spacing of 3 x 3 m, which will ensure a higher mean annual increment with a higher volume at stand level. In addition, a spacing of 3 x 3 m will ensure a higher percentage of trees with good stem quality.

Keywords: *Tectona grandis*, spacing, volume, mean annual increment, stem quality

2.1 Introduction

Tectona grandis L.f. (Teak) is the most valuable tropical cultivated hardwood in the world as attributed to its excellent wood properties. Those properties include strength, straightness, workability, resistance to many pests, good dimensional stability, aesthetic qualities, and pathogens (Bermejo *et al*., 2004; Zanin, 2005), and durability and stability (Palanisamy *et al*., 2009). It occurs naturally in India, Myanmar, Laos, and Thailand (Nocetti *et al*., 2011).

Globally, the source of *T.grandis* wood is >29 million ha of natural forests and 6.89 million ha of plantations (Kollert & Cherubini, 2012). However, the global demand for *T. grandis* continue to increase, whereas the source of *T. grandis* from its natural range is decreasing due to illegal logging and competition with other natural resources (Rahmawati *et al*., 2021). This has drawn attention to its artificial cultivation in plantations (Robertson & Reilly, 2004). The area covered by Teak plantations ranges from 4.35 to 6.89 million ha worldwide of which tropical Asia (India, Indonesia, Thailand, Myanmar, Bangladesh, and Sri Lanka) accounts for more than 80%, while tropical Africa accounts for only 10%, and tropical America (Costa Rica, Trinidad, and Tobago) accounts for 6% of the total planted area (Kollert & Kleine, 2017).

In Tanzania, *T. grandis* was first introduced during the colonial era by Germans in 1898 using seeds originating from the Calcutta region of India. Good performance from established experimental trials in 1905 and 1936 using seeds from Java, Burma, India, and Thailand led to the establishment of *T. grandis* plantations in 1952 (Longuza and Rondo) and 1961 (Mtibwa) (Madoffe & Maghembe, 1988; Ngaga, 2011).

In forest plantations aimed at sawlog, spacing is among the factors that influence the growth rate, as it is expected that trees grown at wider spacing would have larger diameters than those of the same age at close spacing, resulting from reduced competition for moisture and nutrients. Additionally, understanding optimal spacing for *T. grandis* plantations ensures growth, quality wood products (Iddi *et al*., 1996), and larger diameters (Zahabu *et al*., 2015)**.** Moreover, the value of the final crop in forest plantations is mainly determined by log size and stem quality (Glencross *et al*., 2012). Some spacings commonly used in *T. grandis* plantations have been reported by several studies, including 1.37 x 1.37 m, 1.98 x 1.98 m, and 2.9 x 2.9 m (Ola-Adams, 1990);1.5 x 1.5 m, 2 x 2 m, 2.5 x 2.5 m and 3 x 3 m (Sibomana *et al*., 1997; 1 x 1 m (Haninec *et al.*, 2016); and 2 x 2 m, 3 x 3 m, and 4 x 4 m (Zahabu *et al*., 2015)

The effects of spacing on the growth, yield, and stem quality of young *T. grandis have* been widely studied. Rahmawati *et al.* (2022) evaluated an eight-year-old clonal teak plantation in Java Monsoon Forest, Indonesia. Rahmawati *et al*. (2021) studied a seven-year-old clonal Teak plantation in the East Java Monsoon Forest Area. In addition, Kamara *et al*. (2020) studied a nine-year-old Forest plantation in the transition rainforest of Sierra Leone. Likewise, a study, (Kainyande *et al*., 2023) on five-year-old spacing trial plots at Njala University, Southern Province, Sierra Leone.

Since planted tree species, especially *Tectona grandis* need to remain in the field until the final harvesting age (rotation age), effects of spacing on growth, yield, and stem quality at older age needs to be known. In contrast, little has been done to address this in Tanzania where a study by Sibomana *et al*. (1997) reported that at 9 years diameter at breast height, total height and basal area were statistically affected by spacing. Also, the study by Zahabu *et al*. (2015) at the age of 14 years showed that diameter growth, height growth, and volume increment were statistically influenced by spacing. Both studies did not report on the effects of spacing on stem quality but spacing has been used to control the quality of trees by maintaining a high-quality stem shape and restricting branch growth (Glencross *et al*., 2012).

Although in Tanzania teak plantation are now grown at 20-year rotation, they were previously grown at 25years rotation age. It is thus, not known if spacing will have the same effect at full rotation compared to half rotation reported by Zahabu *et al*. (2015) on studied growth and yield parameters. Thus, this study was intended to assess the effects of spacing on growth, yield, and stem quality 10 years after last assessment but 4 years after the current rotation age.at an older age. The results of this study have a potential in widening knowledge on spacing effects at older ages of the studied parameters. The results also provide guidance to decision makers during development of various tree planting guidelines.

2.2 Materials and Methods

2.2.1 Study area description

The study was conducted on a 24-year-old *T. grandis* spacing trial located at Longuza Forest Plantation (LFP), Muheza district, Tanga region, at latitudes S4° 48' and S5° 13’ and longitudes E38° 32' and E38° 48'. The area has an average altitude of 180 m above sea level and a mean annual rainfall of 1,548 mm of rainfall, with long rains from March to May, followed by a dry season between June and September. This area experiences short periods of rainfall, from October and December. The maximum temperature of the area varies 26 and 32 °C, and the minimum temperature ranges from 15 to 20 °C. The topography ranges from undulating lower slopes between 5.71° and 11.31° degrees to a steeper upper slope from 14.04° to 19.29°. The soil texture is sandy clay loam, dark reddish-brown to dark red or red, and becomes redder down the profile, with a pH ranging from strongly acid (4.5–5.0) to neutral (6.6–7.3). The soil is characterized by shallow depth (less than 20 cm deep) to very deep (greater than 120 cm), although most are moderately deep (40 to 80 cm) (Zahabu *et al*., 2015).

2.2.2 Experimental design

The spacing trial assessed in this study was established in April 1998 at the Longuza Forest Plantation by the Sokoine University of

Agriculture in collaboration with the Forest and Beekeeping Division under the Ministry of Natural Resources and Tourism. The trial followed a complete randomized block design consisting of three planting spacing levels of 2 × 2 m, 3 × 3 m, and 4 × 4 m, each replicated three times (Figure. 2.1). Each plot was planted with 25 seedlings in a 5 × 5 tree layout (variable area plots), except for the centre plot with 4 × 4 m spacing, which had 23 trees. The trial had two guard rows to avoid edge effects.

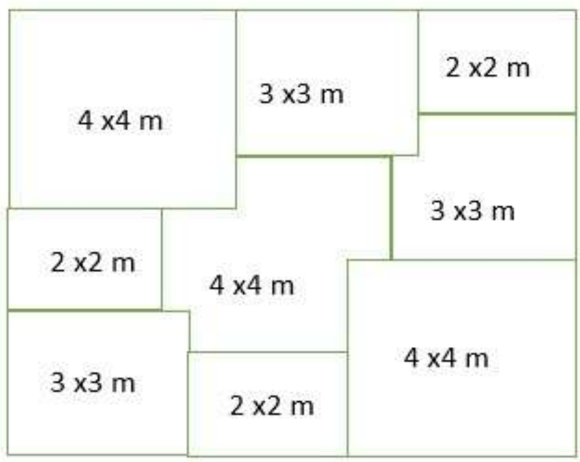

Figure 2.1: Spacing trial layout

2.2.3 Data collection

In this study, data on dbh, tree height and stem quality were collected at each spacing. The total tree height and dbh were measured using Vertex IV and Caliper, respectively. The stem quality of all trees was assessed by scoring, with four scores of 1 to 4 based on the merchantable height and tree form (Table 2.1).

Table 2.1: A detailed description of stem quality scores

S/No	Description	Score
a	Straight to the top and good stem form	
b	Straight and good stem form but with straight top forks	1
a	Straight and good stem but with one slight bend less than 1 m length	
b	Straight and good stem form but with slightly bent or crooked mid/top forks	2
c	Straight and good stem form but with buttresses within 1 m height	
a	Slight bends less than 1 m at bottom and top with a straight middle part	
b	One slight bend more than 1 m in length	3
c	Slightly crook, slight taper, buttressed within 2 m height	
a	Serious crook, excess taper, and buttressed beyond 2 m height.	4

Source: Gumadi *et al*. (2023)

2.2.4 Data analysis

The basal area (m^2) of the individual tree was calculated as the cross-sectional area of the tree at dbh, using Equation *[1]*

$Ba = 0.0000785 * dbh^2$ ………………………………………………*[1]*

note: *Ba* = basal area (m^2), *dbh* = diameter at breast height (cm).

The total volume (m^3) of individual trees was calculated using the single-volume model (Malimbwi *et al*., 1998), as shown in Equation *[2]*.

$V = 0.00024 * dbh^{2.35}$ ……………………………………………………*[2]*

note: *V* = volume (m^3), *dbh* = diameter at breast height (cm)

The mean annual increment (MAI) was calculated as the total tree volume divided by the tree age using Equation *[3].*

$MAI = V_t / A$ ……………………………………………………*[3]*

note: *MAI* = Mean Annual Increment ($m^3ha^{-1}year^{-1}$), V_t= total volume per ha (m^3ha^{-1}), *A* = Tree Age in Years

2.2.5 Statistical analysis

A one-way ANOVA was used to determine the effect of spacing on all studied variables, including dbh, height, basal area, volume, MAI, and stem quality. The score data for stem quality were square root transformed before being subjected to statistical analysis (Chamshama *et al.,* 1999). Tukey's honest significant difference test at *p-value* = 0.05 was used for multiple comparisons among variable means. All the analyses were performed with R Software version 4.2.3.

2.3 Results

2.3.1 Effects of spacing on growth

Spacing had no significant effect on dbh (F = 2.34; p-value > 0.05), and height (F = 0.87; p-value > 0.05) (Table 2.2) at the age of 24-year-old. The results showed a difference in the mean values of dbh, and height, but the difference was not significant. The spacing of 4 x 4 m had the highest mean dbh of 32.17 cm, followed by 2 x 2 m with a mean of 28.37 cm, and then 3 x 3 m with a mean of 28.00 cm. Furthermore, the highest mean height (29.40 m) was observed at 4 x 4 m, followed by 2 x 2 m, with a mean of 27.18 m and 3 x 3 m had the lowest mean height of 27.07 m.

Table 2.2: Effects of spacing on dbh and height

Variable	Spacing(m)			F value
	2 x 2	3 x 3	4 x 4	
Dbh (cm)	28.37 ± 4.26[a]	28.00 0.85[a]	32.17 ±1.27[a]	2.34[ns]
Height (m)	27.18 ± 3.83[a]	27.07 ± 1.66[a]	29.40 ± 0.73[a]	0.87[ns]

Note: within the same row, mean ± standard deviation followed by the same letter are not significantly different, p-value > 0.05; ns = non-significant, p-value > 0.05

2.3.2 Effects of spacing on yield

The results showed that spacing had no significant effect on basal area per ha ($F = 0.97$; *p*-value > 0.05), volume per ha ($F = 1.04$; *p*-value > 0.05) and MAI ($F = 1.04$; *p*-value > 0.05) at the age of 24-year-old (Table 2.3). A spacing of 3 x 3 m produced the highest mean basal of 33.33 m^2ha^{-1} followed by 4 x 4 m with a mean of 29.44 m^2ha^{-1} and the spacing of 2 x 2 m had the lowest mean of 22.05 m^2ha^{-1}. Moreover, the highest mean volume at a spacing of 3 x 3 m (336.76 m^3ha^{-1}) did not differ much from a spacing of 4 x 4 m with a mean volume of 312.53 m^3ha^{-1}, while the lowest mean volume was observed at a spacing of 2 x 2 m with a mean volume of 220.68 m^3ha^{-1}. Similarly, the highest MAI was observed at a spacing of 3 x 3 m (14.03 $m^3ha^{-1}year^{-1}$), followed by a spacing of 4 x 4 m with an MAI of 13.02 $m^3ha^{-1}year^{-1}$, and then the lowest MAI of 9.02 $m^3ha^{-1}year^{-1}$ was observed at a spacing of 2 x 2 m.

Table 2.3: Effects of spacing on basal area, volume and mean annual increment

Variable	Spacing (m)			F value
	2 x 2	3 x 3	4 x 4	
Basal area (m^2/ha)	22.05 ± 12.28^a	33.33 ± 7.27^a	29.44 ± 10.06^a	0.97^{ns}
Volume (m^3/ha)	220.68 ± 121.57^a	336.76 ± 75.98^a	312.53 ± 108.81^a	1.04^{ns}
MAI (m^3/ha/year)	9.20 ± 5.07^a	14.03 ± 2.17^a	13.02 ± 4.53^a	1.04^{ns}

Note: within the same row, means ± standard deviation followed by same letter are not significantly different, *p*-value > 0.05; ns = non-significant, *p*-value > 0.05

2.3.3 Effects of spacing stem quality

Spacing had a significant effect on stem quality ($F = 7.93$; *p*-value < 0.05) of *T. grandis* at 24 years of age (Table 2.4). The spacing of 2 x

2 m differed significantly from the spacing of 4 x 4 m. There were no significant differences in the other spacings. Based on the scoring point scale used (i.e., 1–4), the lower the score, the higher the stem quality. The spacing of 2 x 2 m had the lowest mean score of 1.41, followed by 3 x 3 m spacing with a mean of 1.51, and the highest mean score was observed at the spacing of 4 x 4 m. This implies that most of the trees with higher stem quality were at a spacing of 2 x 2 m, which did not differ significantly from the spacing of 3 x 3 m. In the contrast, most trees with lower stem quality were observed at a spacing of 4 x 4 m which also did not differ significantly from the spacing of 3 x 3 m.

Table 2.4: Effects of spacing on stem quality

Variable	Spacing (m)			F value
	2 x 2	3 x 3	4 x 4	
Stem quality	1.41 ± 0.01^{b}	1.51 ± 0.05^{ab}	1.59 ± 0.08^{a}	7.93^{ns}

Note: within the same row, mean ± standard deviation followed by the same letter are not significantly different, *p*-value > 0.05; different letters indicate significant differences, *p*-value < 0.05); * = significant, *p*-value < 0.05

2.4 Discussion

2.4.1 Growth

The results revealed that dbh increased with increasing spacing, although the increase was not statistically significant at the older age of 24 years. This is in contrast to other findings, that reported a significant increase in dbh with an increase in spacing. For instance, at the age of 14 years, Zahabu *et al.* (2015) reported a significant increase in dbh with an increase in spacing, where a spacing of 4 x 4 m had the highest mean dbh. Similarly, Rahmawati *et al.* (2021) revealed that the wider spacing of 10 m x 2 m produced a significantly higher dbh at eight years old. Moreover, after seven years, Rahmawati *et al.* (2022) showed that the wider spacing of 10 x 2 m still produced a significantly higher dbh. In the present study, the differences in mean dbh were not significant, which may be due to competition being higher at closer spacing (Vigulu *et al*., 2019). Thus, mortality was higher with closer spacing and the remaining trees had more space for growth. Regarding height growth, results showed an insignificant difference in mean height among the spacings, with the highest mean height being at 4 x 4 m. This is in agreement with several findings that revealed that height growth is not affected by spacing but is sensitive to differences in site quality (Cardoso *et al.,* 2013, 2013; Medeiros *et al*., 2018). In addition, Rahmawati *et al.* (2021) found similar findings where the difference in mean height was not statistically significant among the spacings of 3 x 3 m, 6 x 2 m, 8 x 2 m, and 10 x 2 m.

2.4.2 Yield

Although spacing had no significant effect on either volume or MAI, both volume and MAI at a spacing of 3 x 3 m had a higher mean value, which was, however, relatively higher compared to 2 x 2 m than at a 4 x 4 m spacing. The lower volume and MAI at 2 x 2 m may be attributed to low stocking because of higher mortality due to competition from individual trees. Similar results were reported by Zahabu *et al*. (2015), where 3 x 3 m spacing produced a relatively higher volume and MAI than 2 x 2 m and 4 x 4 m spacing. In contrast, other findings reported a significantly higher value of volume with closer spacing during the early age of planting. For example, at 8 years old of age, Rahmawati *et al.* (2022) reported a higher volume in a 3 x 3 m spacing compared to other spacings of 6 x 2 m, 8 x 2 m, and 10 x 2 m. This indicates a decrease in volume with an increase in spacing. Rahmawati *et al.* (2021) reported the same trend of a decrease in volume with an increase in spacing at 7 years old. Furthermore, the spacing of 3 x 3 m recorded a higher non-significant mean basal area than the other two spacings. Similar results were reported in the study conducted at the age of 14 (Zahabu *et al*., 2015).

2.4.2 Stem quality

The results revealed a significant decrease in the mean stem quality score with an increase in spacing. Similar results were reported by Adegbehin (1982), as cited in Pérez & Kanninen (2005), who reported decrease in stem quality with an increase in spacing in a spacing trial for Teak in Nigeria.

2.5 Conclusion and Recommendation

The results of a *T. grandis* spacing trial at the age of 24 years, four years after end of rotation showed that dbh and height growth increased nonsignificantly with an increase in spacing even though the spacing of 2 x 2 m had a slightly higher value than 3 x 3 m for both dbh and height. Moreover, the basal area, volume, and MAI also increased non-significantly with an increase in spacing. In addition, the results revealed a higher value of basal area, volume, and MAI at a spacing of 3 x 3 m compared to the other two spacings studied. This means that based on growth and yield, the spacing of 3 x 3 m although had relatively lower growth in dbh and height, produced a higher volume per ha than the closer spacing (2 x 2 m) and wider spacing (4 x 4 m). In addition, a spacing of 3 x 3 m had the highest MAI. In contrast, spacing significantly affected stem quality at 2 x 2 m and 4 x 4 m, and stem quality tended to decrease with an increase in spacing. This implies that a higher percentage of trees with good stem quality is more likely to be found in stands with closer spacing. Generally, since Teak plantations in Tanzania are aimed at sawlog production, it is recommended to continue practising a spacing of 3 x 3 m, which will ensure a higher MAI with a higher volume at stand level. Also, the spacing of 3 x 3 m will ensure a higher percentage of trees with good stem quality.

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CHAPTER THREE

MANUSCRIPT TWO

Physical and mechanical properties of *Tectona grandis* under different spacings at Longuza Forest Plantation, Tanzania

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Abstract

Understanding the effect of silvicultural practices, specifically spacing, on final harvest quality is important to meet end-user requirements. The quality of the final harvest depends mainly on its physical and mechanical properties. However, information on the effects of spacing on -the physical and mechanical properties of *Tectona grandis* at an older age is limited, specifically in Tanzania. Thus, this study aimed to assess the effect of spacing on the physical and mechanical properties of 24-year-old *Tectona grandis* at Longuza Forest plantation, Muheza, Tanzania. Data were collected from a spacing trial with a randomized complete block design with three treatments, namely 2 x 2 m, 3 x 3 m, and 4 x 4 m, replicated three times. Basic density was calculated as the ratio of oven-dry weight to green weight using the oven-dry and displacement methods. HW percentage was calculated as the ratio of the cross-sectional area of HW to the disk under bark using four radii measured by a vernier calliper. Mechanical properties were determined using a Monsanto tensiometer machine. Data analysis was performed using Analysis of Variance (ANOVA), and multiple comparisons among treatment means were done using Tukey's Honest Significant Difference test (p = 0.05). Results showed the mean values of all physical and mechanical properties studied were not significantly different except for tangential cleavage strength among the spacings. The tangential cleavage strength at the spacing of 3 x 3 m was significantly different from other spacings. Also, all studied properties except shear strength showed a decrease in mean value with an increase in spacing, where the highest mean was observed at 2 x 2 m. Shear strength was higher at 3 x 3 m spacing, while the lowest was observed at 4 x 4 m spacing. it is recommended that when considering the quality of *Tectona grandis*, a spacing of 2 x 2 m is most appropriate since it produces wood of high quality in terms of physical and mechanical properties.

Keywords: *Tectona grandis*, Basic density, Heartwood percentage, Modulus of elasticity, Modulus of rupture

3.1 Introduction

Forest plantations play an important role in supplying wood for different purposes around the world, especially those growing hardwood species, specifically *Tectona grandis* L.f. (Teak). Teak wood has been variously used, including heavy construction, furniture and cabinets, railway sleepers, decorative veneers, joinery, and shipbuilding (Thulasidas & Bhat, 2012). This is contributed by its good physical and mechanical properties, such as basic density, HW percentage, modulus of elasticity, modulus of rupture, and compressive strength.

Concerning wood quality, basic density and HW percentage are known to be two wood properties that influence the quality of Teak wood. Basic density is used as an index of wood substances such as latewood content, wall thickness, cell size, the amount of ray cells, and the size and amount of vessel elements (Sinha *et al*., 2017). Subsequently, those wood substances affect the wood's strength, especially its mechanical properties. In addition, the high natural durability of Teak is due to the chemical composition of HW (Kokutse *et al*., 2006).

In forest plantations, spacing is a silvicultural tool that may be used to ensure the quality of end products by interfering with the growth rate and morphology of individual trees, which in turn affects the wood properties (Hébert *et al*., 2016). For example, spacing affects the HW percentage through its influence on radial growth. HW percentage is associated with tree size. Thus, spacing that ensures higher radial growth may produce valuable wood in terms of HW percentage. Zahabu *et al*. (2015) observed the highest HW percentage at a wider spacing of 3 x 3 m, which also produced trees with higher diameters at breast height. Based on the influence of spacing on growth rate, it is expected that a slow growth rate in narrow spacing, specifically radial growth, is associated with a higher basic density. This is in agreement with Zahabu *et al*. (2015), who observed a higher basic density at two spacings of 2 x 2 m and

3 x 3 m compared to a wider spacing of 4 x 4 m. This has been reported due to the latewood and earlywood proportions difference between slow and fast-growing planted trees.

Few studies on spacing effects on wood properties of *Tectona grandis* at young ages have been conducted in different tropical countries. In Indonesia, the study by Rahmawati *et al*. (2022) reported no significant effect of spacing on the physical and mechanical properties of eight-year-old *Tectona grandis*. Furthermore, they showed a decreasing trend in mechanical properties with an increase in spacing. In Tanzania, at the age of 14 years, Zahabu *et al*. (2015) also reported no significant difference in the physical and mechanical properties of *Tectona grandis* at three different spacings. Moreover, at the same age, Sibomana *et al*. (1997) showed a significant difference in mean values of the physical and mechanical properties of 14-year-old *Tectona grandis* at four different spacings in Tanzania.

Regarding wood properties, studies reported a substantial increase in wood properties such as basic density, modulus of elasticity, and modulus of rupture at an older age. Those properties tend to increase due to increasing cellular wall thickness while decreasing vessel frequency (Víquez & Pérez, 2005; Moya & Perez, 2008). Thus, information on the spacing effect on physical and mechanical properties at an older age for species like Teak is limited.
This study assessed the effects of spacing on the physical and mechanical properties of *Tectona grandis* at an older age of 24 years. The results will help to increase knowledge on spacing effects at older ages, specifically on wood quality in terms of physical and mechanical properties.

3.2 Materials and Methods

3.2.1 Study area description

The spacing trial is located at Longuza Forest Plantation, Muheza district, Tanga region. It lies at an altitude of 180 m above sea level between 4° 48' and 5° 13' S latitudes and 38° 32' and 38° 48' E longitudes. The rainfall occurs biannually, with an average of 1,548 mm per year, whereby the long rain is from March to May, followed by short rains between October and December. The dry season occurs from June to September. The area has a maximum temperature ranging from 26 to 32°C, while the minimum temperature varies from 15 to 20°C. The topography is characterized by undulating lower slopes of 5.71 to 11.31 degrees and a steeper upper slope from 14.04 to 19.29 degrees. The soil texture is sandy clay loam with a dark reddish-brown to dark red that becomes redder down the profile with a pH of strongly acid (4.5–5.0) to neutral (6.6–7.3). The soil in the area varies from being relatively shallow (less than 20 cm deep) to exceptionally deep (exceeding 120 cm), with the large part falling within the category of moderately deep (ranging from 40 to 80 cm in depth) (Zahabu *et al*., 2015).

3.2.2 Experimental design

The spacing trial of 24-year-old *Tectona grandis* with a complete randomized block design was used in this study. The trial was composed of three treatments, namely 2 x 2 m, 3 x 3 m, and 4 x 4 m, replicated three times. Each plot is planted with 25 seedlings in a 5 x 5 tree layout with two guard rows of trees to avoid edge effects.

3.2.3 Data collection

Three trees (one per replicate) with straight stems, normal branching, free from disease or pest attack, and without any physical defects were selected randomly on each spacing, felled, and marked accordingly, totalling nine randomly sampled trees. Disk sizes of 5 cm thick were cut at breast height (1.3 m), 30%, 60%, and 90% of the total tree height (Barros-Junior *et al*., 2022; Moya & Perez, 2008; Zahabu *et al*., 2015) for physical properties. then, a billet of 1 m length was cut just above breast height and marked for mechanical properties (Hamza *et al.*, 2004). The billets were sawn to a cant measuring 65 mm thick and 1 m long with pith in the centre (Lavers, 1969; Gillah *et al*., 2008). The cants were resawned into planks from the pith left and right towards the bark. The planks were numbered and labelled accordingly, to show the extraction position and then air-dried in the laboratory to about 12% moisture content. Each disk's radius from the pith to the HW-sapwood boundary and under bark was measured using a vernier calliper in four axes, along the longest axis and perpendicular to the longest axis. The HW percentage was determined using the cross-sectional area of the HW and the underbark of the disk (Kokutse *et al*., 2010; Yang *et al*., 2020). Two opposite wedges extending from pith to bark were cut from each disk. From each wedge, four samples were cut at 1%, 33%, 66%, and 100% of the total wedge length (Barros-Junior *et al*., 2022; Hamza *et al*., 2004). Basic density was determined by using oven-dry weight and green volume. The green volume was determined by using the water displacement method. For oven-dry weight, samples were dried at a temperature of 103 ± 2°C until constant weight was reached and then cooled in desiccators (Zahabu *et al.*, 2015). Also, in each dried plank, test specimens for mechanical properties were prepared in accordance with Lavers (1969). Then, mechanical properties were tested according to BS 373 (1957); Lavers (1969); and Ishengoma & Nagoda (1991) using a Monsanto tensiometer machine, and deflection curves were plotted manually. Hereafter, the test specimens with a moisture content below or above 12% were corrected to 12% using the formula by Desch & Dinwoodie (1981).

3.2.4 Data analysis

In this study, the mechanical properties determined were the modulus of elasticity (MOE), modulus of rupture (MOR), compressive strength parallel to the grain (CSP), shear strength (SS), and cleavage strength (CLS). The physical properties included basic density (BD) and heartwood (HW) proportion. The following formulas were used to determine MOE (Equation I), MOR (Equation II), CSP to the grain (Equation III), SS parallel to the grain (Equation IV), and CLS (Equation V):

MOR (Nmm^{-2}) = $3PL/2bd^2$ ……………………………………(Equation I)
MOE ($N\ mm^{-2}$) = $P^1\ L^3\ /4Ybd^3$ …………………………..(Equation II)
Note: P = Maximum load in Newton's (N); L = Span length (mm); B = Width of the test sample (mm); P^1 = Load in Newton's to limit of proportionality; D = Depth of the test sample (mm); Y = Deflection in mm at midlength at limit of proportionality.

CSP ($N\ mm^{-2}$) = P (max) / A ……………………………(Equation III)
Note: P (max) = Maximum crushing load in Newton's (N); A = Cross-sectional area (mm^2)

SS ($N\ mm^{-2}$) = P/A ………………………………………(Equation IV)
Note: P = Maximum load (N); A = Area in shear (mm^2)

CLS ($N\ mm^{-2}$) = P (max)/B ………………………………(Equation V)
Note: P = Maximum load (N); B = Specimen width (mm)

The HW percentage was calculated as the ratio of the cross-sectional area of heartwood and disk under bark using the quadratic mean of the four radii:

$$H_W = H_{CA}/D_{CA} * 100$$

Note: HW = heartwood percentage; H_{CA} = cross-sectional area of heartwood; D_{CA} = disk under bark cross-sectional area.

BD was calculated as the ratio of oven-dry weight to the green volume of the sample, expressed in kg/m^3, using an equation:

$$BD = [\text{oven dry weight (g)} / \text{green volume } (cm^3)] *1000$$

Note: BD = basic density (kg/m^3).

3.2.5 Statistical analysis

The effect of spacing on all studied physical and mechanical properties was evaluated by using one-way analysis of variance (ANOVA), where the Tukey honest significant difference test was used for multiple comparisons among the spacings. The statistical analysis was done by using the R system for statistical computing (R Core Team, 2016).

3.3 Results

3.3.1 Effect of spacing on physical properties

Spacing had no significant effect on both BD ($F = 5.91$; $p > 0.05$) and HW percentage ($F = 0.06$; $p > 0.05$) at the age of 24 years (Table 3.1). However, the BD at a spacing of 2 x 2 m (568.13 kg/m^3) was higher compared to other spacings of 3 x 3 m and 4 x 4 m. On the other hand, the highest value of HW percentage was observed at a spacing of 4 x 4 m with a mean of 52.33%, followed by a spacing of 2 x 2 m and a spacing of 3 x 3m.

Table 3.1: Effects of Spacing on Basic Density and Heartwood Percentage of Teak

Variable	Spacing			F value
	2 x 2	3 x 3	4 x 4	
Basic density (kg/m^3)	568.13[a]	531.48[a]	533.85[a]	1.15
Heartwood percentage	50.62[a]	49.48[a]	52.33[a]	0.06

Across the row, the same letter implies means are not statistically different among the spacings ($p > 0.05$).

3.3.2 Effects of spacing on mechanical properties

Spacing had a significant effect only on CLST ($F = 11.91$; $p < 0.05$). Meanwhile, spacing did not affect the MOE ($F = 2.28$; $p > 0.05$), the MOR ($F = 1.23$; $p > 0.05$), CSP ($F = 2.39$; $p > 0.05$), SS ($F = 1.56$; $p > 0.05$), and CLS ($F = 2.29$; $p > 0.05$) (Table 3.2). The spacing of 2 x 2 m had the highest value in all studied mechanical properties except SS, which was higher at 3 x 3 m. The spacing of 4 x 4 m had the lowest value in all mechanical properties.

Table 3.2: Effects of Spacing on MOE, MOR, CSP, SS, CLSP, and CLST of Teak

Variable	Spacing (m)			F value
	2 X 2	3 X 3	4 X 4	
MOE(N/mm^2)	8 536.83[a]	7 568.30[a]	6 835.61[a]	2.80
MOR(N/mm^2)	91.16[a]	82.83[a]	81.69[a]	1.23
CSP(N/mm^2)	48.98[a]	42.98[a]	41.50[a]	2.39
SS(N/mm^2)	9.47[a]	9.85[a]	8.92[a]	1.56
CLSP(N/mm)	14.93[a]	13.12[a]	13.10[a]	2.29
CLST(N/mm)	16.98[a]	16.60[a]	15.30[b]	11.91

Note: MOE: modulus of elasticity; MOR: modulus of rupture; CSP: compressive strength parallel to grain; SS: shear strength; CLSP: Cleavage strength perpendicular to grain: CLST: cleavage strength tangential to grain, Across the row, the same letter implies that means are not statistically different ($p > 0.05$), while different letters imply that means are statistically different ($p < 0.05$).

3.4 Discussion

3.4.1 Physical properties

Results revealed a non-significant decreasing trend in BD with an increase in spacing, even though the spacing of 3 x 3 m had a relatively low BD compared to 4 x 4 m. This may be explained by the fact that an increase in spacing leads to an increase in radial growth. This in turn causes an increase in earlywood proportion, which is associated with large cell lumens and relatively thin cell walls (Feduccia, 1979), as cited by Hébert *et al*. (2016). A similar trend was reported by Zahabu *et al*. (2015), who observed higher BD at 2 x 2 m spacing in 14-year-old *Tectona grandis*. On the other hand, the HW percentage showed an increasing trend with an increase in spacing, even though the spacing of 3 x 3 m still had a slightly low HW percentage compared to 2 x 2 m spacing at 24 years old. Similarly, at 14 years old, Zahabu *et al*. (2015) reported an increase in HW percentage with an increase in spacing, where the spacing of 4 x 4 m had the highest HW percentage. Furthermore, Rahmawati *et* *al*. (2022) observed an increasing trend in HW percentage with spacing in 8-year-old *Tectona grandis*.

3.4.2 Mechanical properties

The results showed a similar tend of non-significant decrease with an increase in spacing in all studied mechanical properties except SS, where there was a slight increase from 2 x 2 m to 3 x 3 m, then a decrease to 4 x 4 m. The same trend was reported by Rahmawati *et al*. (2022) in 8-year-old *Tectona grandis.* They reported a non-significant decrease in the MOE, MOR, and CSP with an increase in spacing at four different spacings. Also, at 14 years, Zahabu *et al*. (2015) reported that mechanical properties decreased nonsignificantly with an increase in spacing. These included only the MOE, CSP to the grain, SS, and CLSR, while the MOR increased non significantly with spacing. Furthermore, Zahabu *et al*. (2015) showed that CLST increased significantly with an increase in spacing. On the contrary, Sibomana *et al*. (1997) reported that the MOE, CSP, and SS increased significantly at 14 years. Additionally, they reported the MOR increased non-significantly with an increase in spacing at spacings of 2 x 2 m, 2.5 x 2.5 m, and 3 x 3 m.

3.5 Conclusion and Recommendation

Results from the *Tectona grandis* spacing trial showed spacing had no significant effect on all studied physical and mechanical properties except CLST at the age of 24 years. However, spacing did not affect all studied physical and mechanical properties; results showed a decreasing trend in all physical and mechanical properties with an increase in spacing. The highest mean values of BD, HW, MOE, MOR, CSP, and CLS were observed at a closer spacing of 2 x 2 m. Furthermore, the lowest mean values of those properties were observed at a wider spacing of 4 x 4 m. On the other hand, the highest SS was observed at a spacing of 3 x 3 m, while the lowest was still at a 4 x 4 m spacing. Even though there was no significant difference in physical and mechanical properties among spacings, the wood at a spacing of 2 x 2 m showed good quality in most of its physical and mechanical properties; the properties did not differ much with a spacing of 3 x 3 m, and the wood at a spacing of 4 x 4 m showed a greater decrease in properties compared to 2 x 2 m. Generally, it is recommended that when considering the quality of *Tectona grandis*, a spacing of 2 x 2 m is most appropriate since it produces wood of high quality in terms of physical and mechanical properties.

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CHAPTER FOUR

GENERAL DISCUSSION

4.1 Growth, Yield and Stem Quality

This study indicated that growth and yield parameters, namely, dbh, height, Ba, volume, and MAI, did not differ significantly among the spacings at an older age of 24 years. On average, dbh and height showed a similar trend of increasing with an increase in spacing. The spacing of 4 x 4 m produced the trees with the highest dbh, while the spacing of 2 x 2 m and 3 x 3 m had slightly similar dbh. On the basis of height, the spacing of 4 x 4 m still produced trees with the highest height compared to 2 x 2 m and 3 x 3 m, whereby their mean values difference is small. The difference in mean values for both dbh and height did not show a significant difference at an older age of 24 may be due to the fact that at an older age, the effect of spacing is reduced or negligible due to high mortality at closer spacing (Macdonald & Hubert, 2002). The mean height in all spacings appeared to be similar since the height growth was reported to be highly influenced by site quality rather than spacing (Zahabu *et al*., 2015; Medeiros *et al*., 2018; Rahmawati *et al*., 2021). Furthermore, the highest dbh observed at 4 x 4 m is because of tree growth, particularly the diameter reported to increase with an increase in spacing (Pachas *et al*., 2019b; Rahmawati *et al*., 2021). Also, there was a relatively higher increasing trend in Ba, volume, and MAI from 2 x 2 m to 3 x 3 m, then a slight decrease from 3 x 3 m to 4 x 4 m. This is in agreement with Ola-Adams (1990), who reported that at high stocking, i.e., narrow spacing, tree growth is restricted as a result of overstocking, while stand growth does not reach its potential at low stocking, i.e., wider spacing, due to understocking. This means the spacing of 3 x 3 m provides the optimal space to facilitate tree growth as well as stand growth as evidenced by the higher value of stand parameters. On the other hand, the spacing of 2 x 2 m produced trees with significantly higher stem quality than 4 x 4 m but similar to 3 x 3 m.

Also, the stem quality at 3 x 3 m did not differ significantly with 4 x 4 m spacing. This implies that trees grown at narrow spacing had higher stem quality, as it has been reported that narrow spacing is commonly used to control the stem quality of trees, specifically for trees grown for sawlog production (Glencross *et al*., 2012).

4.2 Physical properties

Regarding the physical properties, both BD and HW percentage did not differ significantly among the spacings. Despite the fact that there was a nonsignificant effect of spacing on those physical properties, they showed a decreasing trend with an increase in spacing. The spacing of 2 x 2 m produced the wood with the highest BD, while the wood at a spacing of 3 x 3 m had slightly less BD compared to 4 x 4 m. This trend could be explained by the difference in earlywood and latewood proportions as part of wood formation affected by tree growth. The higher dbh previously observed at a spacing of 4 x 4 m means there was more wood formation as a result of the wider spacing. But it has been reported that higher wood formation is associated with a high proportion of early wood due to rapid growth at a wider spacing as the result of less inter-tree competition (Hébert *et al*., 2016). The higher proportion of early wood account for lower BD at wider spacing. In light of HW percentage, it was also reported that HW development in trees mainly depends on the tree size, particularly the diameter (Miranda *et al*., 2009). Also, in this study, trees grown at a wider spacing of 4 x 4 m had a higher dbh associated with a higher HW percentage.

4.3 Mechanical Properties

The study showed that all the mechanical properties studied did not differ significantly except CLST, whereby the spacing of 4 x 4 m differed significantly from the spacings of 2 x 2 m and 3 x 3 m. There was a decreasing trend in MOE, MOR, CSP, CLSP, and CLST to grain with an increase in spacing. In contrast, the SS tends to increase from 2 x 2 m to 3 x 3 m spacing, then slightly decrease to 4 x 4 m spacing. The mechanical properties determine the wood's strength, which is primarily determined by the wood substance present in the wood. This implies that mechanical properties relate to BD, as it is known to be an index of the wood substance present in wood (Sinha *et al*., 2017). In the present study also the wood at spacing of 2 x 2 m had higher value of all mechanical properties except SS which was higher at 3 x 3 m. Thus, the higher values of those mechanical properties at a spacing of 2 x 2 m are attributed to the higher BD reported previously.

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CHAPTER FIVE

KEY CONTRIBUTIONS, CONCLUSIONS AND RECOMMENDATIONS

5.1 Key Contributions of the Study

The study showed that at an old age (24 years), the choice of spacing used had no significant effect on all growth and yield parameters, namely dbh, height, Ba, volume, and MAI. Furthermore, the study showed that as the spacing increases, the stem quality of trees decreases, particularly stem straightness; thus, narrow spacing is more appropriate for stem quality. The study also showed that spacing had no effect on all the physical and mechanical properties studied except CLST.

5.3 Conclusions

The study provided information on the effect of spacing on the growth, yield, and wood properties of 24-year-old *Tectona grandis* from a spacing trial. The study highlighted the following: dbh and height increased nonsignificantly with the increase in spacing, even though the spacing of 3 x 3 m produced trees with slightly lower dbh compared to 2 x 2 m spacing. Ba volume, and MAI were not significantly different among the spacings, but the spacing of 3 x 3 m produced trees with relatively higher values compared to both 2 x 2 m and 4 x 4 m spacings. Regarding the stem quality of trees produced in each spacing, the stem quality of trees at a spacing of 2 x 2 m differed significantly from trees at a spacing of 4 x 4 m but produced trees with similar stem quality compared to trees at a spacing of 3 x 3 m. BD and HW percentage did not differ significantly among the spacings, but BD showed a decreasing trend with an increase in spacing, even though the BD at the spacing of 3 x 3 m was slightly less compared to 4 x 4 m spacing. In contrast, HW percentage showed an increasing trend with an increase in spacing, and the spacing of 3 x 3 m also produced trees with slightly less HW percentage compared to 2 x 2 m spacing. All of the mechanical properties were not significantly affected by spacing except CLST. Also, they showed a decreasing trend with an increase in spacing, whereby a spacing of 2 x 2 m produced wood with high values in all mechanical properties except SS, which was high at a spacing of 3 x 3 m.

5.4 Recommendations

Based on the results, *Tectona grandis* plantations in Tanzania are mainly managed for sawlog production. Thus, the spacing of 3 x 3 m is most appropriate to ensure maximum yield with trees of high stem quality without affecting the mechanical properties, which are directly linked to quality requirements for end users.