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Research article

Growth performance of *Tectona grandis* provenance trial in Tanzania

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Abstract

Importance of the work: 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.

Objectives: To assess the performance of teak provenances at Longuza Forest Plantation, Tanzania.

Materials & Methods: 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.

Results: 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.

Main finding: 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.

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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 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 early in the 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.

Materials and Methods

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. 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).

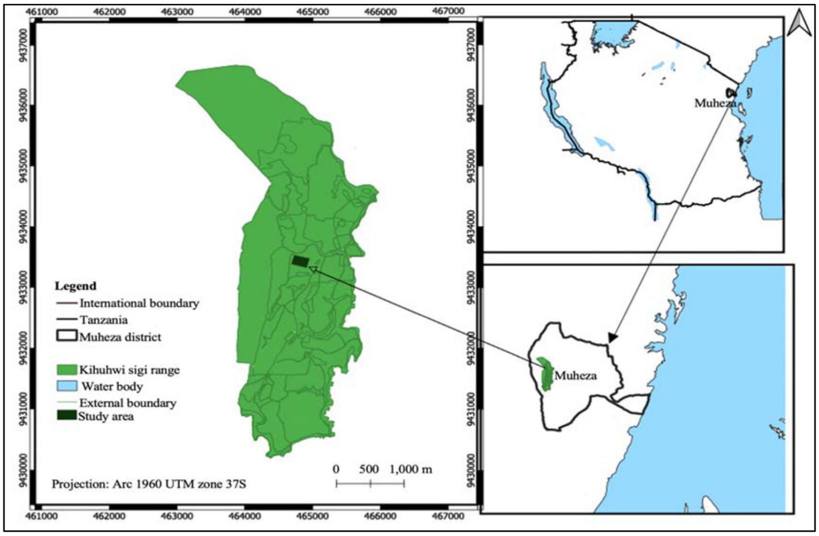


Fig. 1 Maps showing study area in Longuza Forest Plantation

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 Figs. 2 and 3 respectively.

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 Table 1 (Rance and Monteuuis, 2004; Hansen et al., 2017; Kollert and Kleine, 2017).

Data collection

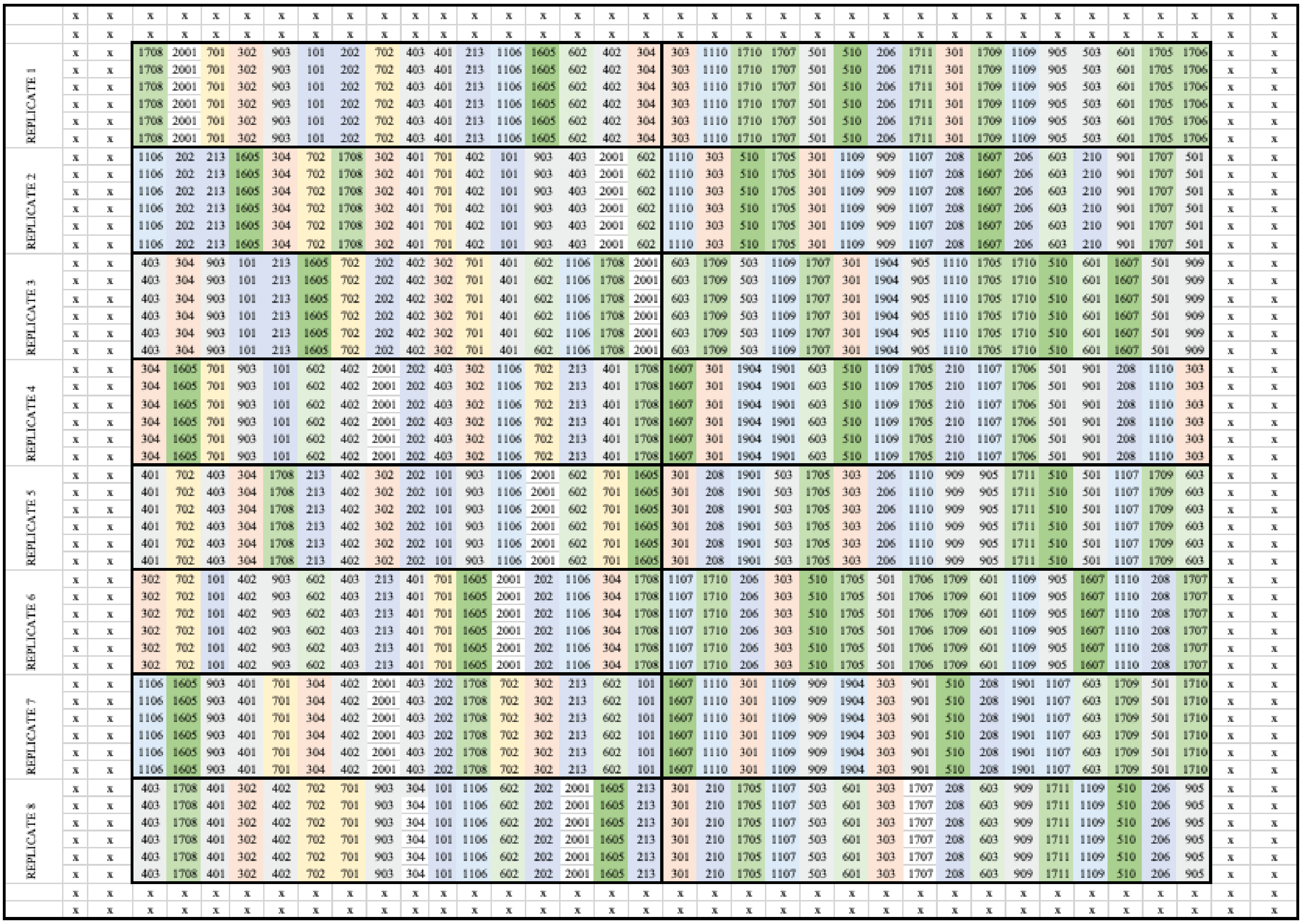
All teak trees were assessed for their height, survival and diameter at breast height (1.3 m above the base) over bark (Dbh). Survival was monitored by recording the initial condition of the planted seedlings, based on measuring the seedling height, root collar diameter and health status. Then, the percentage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

$$\text{Survival rate} = (\text{Number of surviving trees} / \text{Initial number of trees}) \times 100 \quad (1)$$

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

Source: Tanzania Forest Research Institute (2011)

Fig. 2 Study area trial layout



Source: Tanzania Forest Research Institute (2011)

Fig. 3 Experimental map trial layout with family codes for each provenance, where X represents border rows and different colors indicate different families

Table 1 *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

Table 1 Continued

Country	Provenance name	Provenance code	Family code	Latitude	Longitude	Altitude (m)
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 Organisation of the Australian government

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 and height data were used to determine BA based on Equation 2:

$$BA=\left(\frac{\pi}{4}\times Dbh^2\right)\times 0.0001 \quad (2)$$

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:

$$Vol = 0.00014 \times (Ht \text{ x } Dbh^2) \times 0.8793 \quad (3)$$

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:

$$\text{Mean annual increment} = \text{Final volume} / \text{Number of years} \quad (4)$$

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.

Ethics statements

This study was approved by the Board of the College of Forestry, Wildlife and Tourism of Sokoine University of Agriculture (Approval no. SUA/DPRTC/MFO/D/2021/0015/07).

Results

Significant differences at a high level ($p < 0.0001$) were observed among provenances, replications, families and their interactions, as indicated in Table 2. The DMRT results, presented in Table 3, 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 although without statistical support, whereas the East Africa Longuza seed outperformed in terms of Dbh, Ht, Vol, BA and MAI.

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 (Table 2). 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 Table 3.

Diameter at breast height

There were highly significant ($p < 0.0001$, Table 2)

Table 2 Results of analysis of variance conducted for all measured variables

Source of variation	df	Survival (%)	Dbh (cm)	Ht (m)	BA (m^2/ha)	Vol (m^3/ha)	MAI (m^3/ha/yr)
		p-value	*p*-value	*p*-value	*p*-value	*p*-value	*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.

Table 3 Results for Duncan's multiple range test conducted for measured growth and productivity parameters

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 Organisation of the Australian government.
Mean ± SD in the same column superscripted with different lowercase letters are significantly ($p < 0.05$) different.

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 (Table 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 Table 2. 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 Table 3.

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 m^2/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 Table 2. 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 Table 3.

Volume

The variation in mean total tree volume among provenances and families was highly significant ($p < 0.0001$) as indicated in Table 2. 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. Table 3 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).

Mean annual increment

Highly ($p < 0.0001$) significant differences were observed in the MAI values among the teak provenances, indicating variations in growth performance (Table 2). 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 (Table 3).

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 Table 4, 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. Table 5 shows the ordinal ranking of the families based on their performance in the study.

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 (Table 5), indicating their potential for high-yield plantations and quality wood production. These findings were similar to those reported by Kaosa-ard et al. (1992).

Table 4 Ordinal ranking for growth and productivity parameters of studied *Tectona grandis* provenances

Provenance code	Country	Provenance name	Dbh (cm)	Ht (m)	BA (m^2/ha)	Vol (m^3/ha)	MAI (m^3/ha/yr)	Sum rank	Mean rank	Overall rank
5	Tanzania	East Africa Longuza seed stand	1	1	1	1	1	5	1.0	1
4	Tanzania	East Africa Longuza provenance trial	2	2	2	2	2	10	2.0	2
3	Tanzania	East Africa Longuza progeny trial	3	3	3	3	3	15	3.0	3
9	Indonesia	Sumalindo	4	4	4	4	4	20	4.0	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	12.0	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

Table 5 Ordinal ranking for growth and productivity parameters of studied *Tectona grandis* families

S/n	Family code	Country	Family name	Dbh (cm)	Ht (m)	BA (m^2/ha)	Vol (m^3/ha)	MAI (m^3/ha/yr)	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	-2.0	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	-19.0	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	22.0	23
24	213	Colombia	Refocosta seed stand	24	25	23	24	24	120	24.0	24
25	602	Tanzania	East Africa Mtibwa	25	20	25	25	25	120	24.0	25
26	2001	Venezuela	SKCV bulk	29	15	29	26	26	125	25.0	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	30.0	30

Table 5 Continued

S/n	Family code	Country	Family name	Dbh (cm)	Ht (m)	BA (m^2/ha)	Vol (m^3/ha)	MAI (m^3/ha/yr)	Sum rank	Mean rank	Overall rank
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

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

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.

Diameter at breast height

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.

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).

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).

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).

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).

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.

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.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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