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Original Article

Physical and Mechanical Properties of *Liquidambar styraciflua* as a Potential Timber Tree for Kenya

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ABSTRACT

The wood of 38-year-old *Liquidambar styraciflua* grown in a provenance trial plot in Kenya was studied to determine its physical and mechanical properties as well as the relationship between the modulus of rupture (MOR) and static modulus of elasticity (MOE) of the timber. Mechanical properties determined were MOE, MOR, compression strength parallel to grain, shear strength parallel to grain and Janka hardness. Physical properties determined were moisture content and specific gravity. Physical and mechanical properties of small clear specimens from the *L. styraciflua* were determined according to British Standards (BS 373:1957) using the Universal Strength Testing Machine. The results were analysed using R statistical software (Version 4.4.2). Three trees were sampled, one from each of the three best-performing *L. styraciflua* provenances, from trials established in 1986 in Lugari Forest Station, Kakamega County, in western Kenya. The sampled trees were from Honduras, Nicaragua and Guatemala provenances. Tree 1 (Honduras provenance) had the highest average strength for all the properties tested. Tree 6 (Guatemala provenance) had the lowest average strength for MOE, compression strength parallel to grain and hardness. Tree 3 (Nicaragua provenance) had the lowest average strength for MOR. Trees 3 and 6 had similar average strength for shear parallel to the grain. Variations in the strength of the three trees may have been due to their different specific gravities. Average strength values for MOE, MOR, compression strength parallel to the grain, shear strength parallel to the grain, and Janka hardness were 12,399 MPa, 106.3 MPa, 52.3 MPa, 16.6 MPa and 5.8 kN, respectively. There was a significant correlation at 5% significance level ($P<2.2e-16$) between the MOR and MOE of *L. styraciflua*; the correlation coefficient was 0.7. Machine strength grading may be suitable for the Liquidambar timber due to its relatively high correlation coefficient. *Liquidambar styraciflua* from this study had superior properties compared to those of the current plantation species in Kenya; cypress, pines and eucalyptus. This study therefore recommends *L. styraciflua* as a suitable tree species for plantation growing for sawn timber in Kenya. In Kenya, *L. styraciflua* provenance trials were conducted at an altitude of 1,600 m above sea level. Provenance trials in lower altitudes could also be established to determine the growing range of *L. styraciflua* within Kenya. Further research to determine the physical and mechanical properties of graded structural timber from the species is necessary for design purposes. Additional studies are also required to assess the wood's susceptibility and resistance to biological agents.

APA CITATION

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INTRODUCTION

Kenya recorded a forest cover of 8.83% in 2021, which is equivalent to an area of 5,226,191.79 hectares. Natural and planted forests make up 84% and 6% of the forest cover, respectively (Kenya Forest Service, 2021). While natural forests are protected for environmental goods and services, plantation forests and trees on farms provide wood for timber, charcoal and fuelwood among other products (Maurice *et al.*, 2017). Exotic species comprising *Cupressus lusitanica,* Pinus, and Eucalyptus species occupy areas of 74,938.9 ha (49%), 28,996.3 ha (19%) and 16,947.76 ha (11.1%) respectively in state forest plantations, but more are grown on private plantations and smallholder farms (Kenya Forest Service, 2024). In the 1960s, *Cupressus macrocarpa* and *Pinus radiata* were attacked by cypress canker and *Dothistroma pinii* (pine needle blight), which necessitated their discontinuation from large-scale planting and were replaced with *C. lusitanica* and *P. patula*, which were more disease resistant (Njuguna *et al.*, 2021). These species have continued to be grown but are also threatened by pests and diseases.

Liquidambar styraciflua (sweetgum) was introduced in Kenya on a trial basis in 1986 to diversify plantation tree species. The species is a hardwood native to the USA., Mexico and Central American countries such as Nicaragua and Honduras, growing from sea level to an altitude of 2,134 metres above sea level (Briscoe, 1973). In the countries of origin, *L. styraciflua* is mainly used for timber, fuelwood, veneer, plywood and pulpwood, among other uses (Johnson, 1985).

The provenance trial in Kenya was established in Lugari in Kakamega County in a Randomized Block Design with ten provenances (plots) replicated in four blocks; trees in the plots were numbered from 1 to 36 (Mbinga, & Chagala-Odera, 2015). Assessment of the provenances in terms of growth at 28 years of age showed the best-performing provenance was Finca Las Victoria – Guatemala, with a mean tree height of

35.8 m and DBH of 37.1 cm. Mbinga, & Chagala-Odera (2015) observed that *L. styraciflua* had better growth performance than *C. lusitanica* in comparable sites in Kenya.

Physical and mechanical properties are highly influenced by growth conditions, which vary by region (Rocha *et al.*, 2019). There is a need, therefore, to determine the physical and mechanical properties of these new tree species in the country to enhance their utilization. This is essential for performance, particularly in load-bearing applications and efficient utilization through species and timber dimension selection.

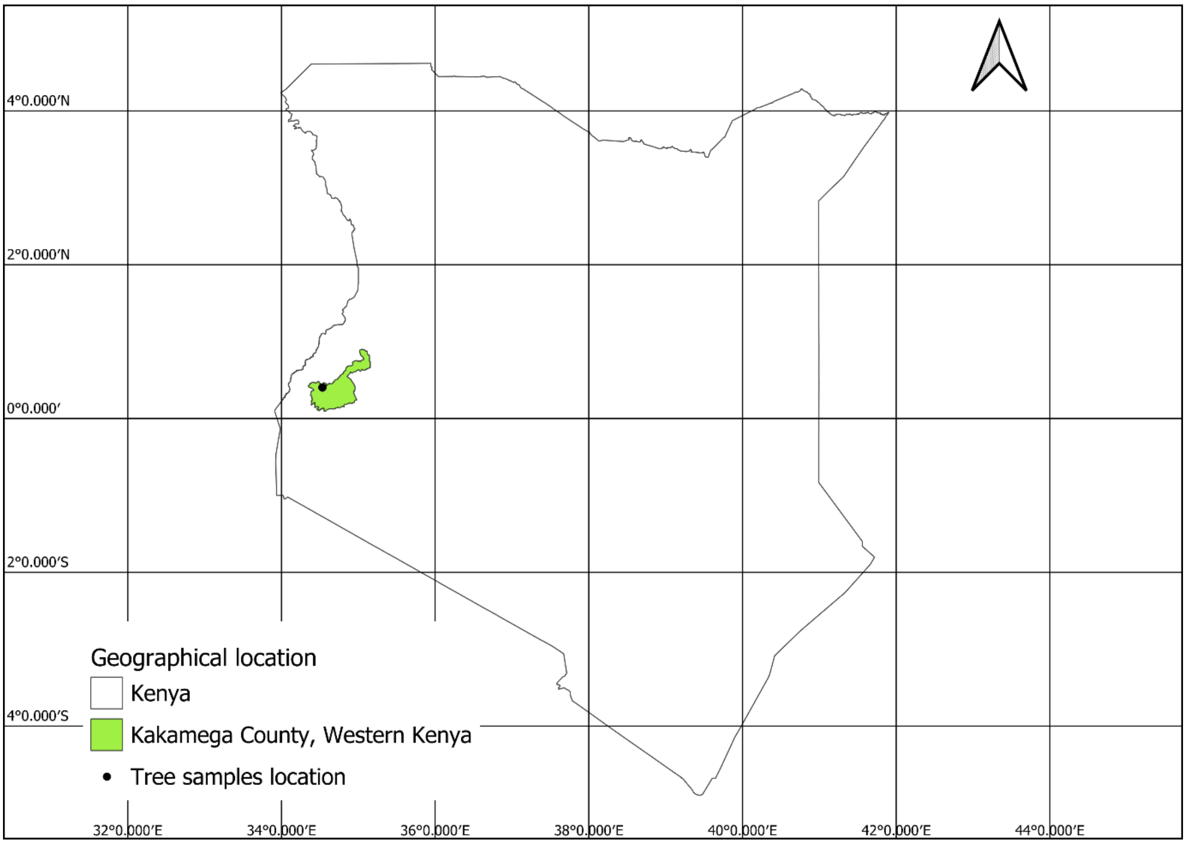
This paper reports on the physical and mechanical properties of *Liquidambar styraciflua* trees from three provenances. Mechanical properties determined were modulus of elasticity, modulus of rupture, compression strength parallel to grain, shear strength parallel to grain and Janka hardness. Physical properties determined were moisture content and specific gravity. Variation of these properties between and within the trees was evaluated.

MATERIALS AND METHODS

Materials

Liquidambar styraciflua tree samples were obtained from the Lugari provenance trial in Kakamega County in Kenya (Figure 1); the map was made with QGIS. The site lies at an altitude of 1,600 m above sea level. Three straight, disease-free, pest-free and damage-free trees were selected. The three trees were selected, each from the Guatemala (Finca Las Victoria), Nicaragua (Yucul Matagalpa) and Honduras (Los Alpes) provenances, which were the best-performing provenances in Kenya (Mbinga, & Chagala-Odera, 2015).

Figure 1*:* **A Map of Kenya Showing the Geographical Location of the Sampled Liquidambar Trees**



Methods

Tree height and diameter at breast height were measured using a clinometer and diameter tape, respectively, before felling the trees. Trees were felled and debarked using a chainsaw and loaded onto a truck. Two of the trees (Tree 6 and Tree 3) were cross-cut into three log sections measuring 3.4 m in length, while Tree 1 was cut into one 3.4 m long log section and two 2.7 m long log sections. Details of the selected trees were recorded in Table 1. The logs were transported to Kenya Forestry Research Institute (KEFRI)’s National Forest Products Research Programme workshop in Karura, Nairobi. Wood specimens were obtained from similar positions from the three trees in terms of total tree height percentages; these are shown in Tables 3 and 4.

Table 1: Details of the *Liquidambar styraciflua* Tree Samples

Provenance	Tree Number	DBH (cm)	Total Tree Height (m)	Latitude (N)	Longitude (E)
Finca Las Victoria –	6	54.0	22.3	0º40'34.146"	34º53'24.761"
Los Alpes – Honduras	1	43.0	36.2	0º40'33.707"	34º53'24.516"
Yucul Matagalpa – Nicaragua	3	42.1	28.0	0º40'35.147"	34º53'24.270"

The logs were converted into sawn timber with a cross-sectional area of 100*50 mm. The timber was then stacked for air-drying away from direct sunlight. Moisture content was periodically monitored and measured using a moisture meter (Kecheng KC-318) until the timber attained a moisture content of about 12%, which is the equilibrium moisture content EMC for Nairobi (Simpson, 1998).

Small clear specimens were prepared from the dried timber for the determination of physical and mechanical properties. Strength tests were performed on the Denison Mayes Group universal strength-testing machine (500 kN). Determination of the mechanical properties was based on the British standards (BS 373:1957). The specimen dimensions and mechanical properties determined are shown in Table 2.

Table 2: Strength Tests, Dimensions of Timber Specimens and Mechanical Properties Determined

Strength Test	Dimensions (mm)	Mechanical Property
Static bending, centre point loading	20 x 20 x 300	Modulus of elasticity (MOE) Modulus of rupture (MOR)
Shear parallel to the grain	20 x 20 x 20	Shear strength parallel to the grain
Compression parallel to the grain	20 x 20 x 60	Compression strength parallel to grain
Janka hardness	20 x 20 x 100	Hardness

The moisture content of the timber specimens was determined as shown in (1), where MC% is the percentage moisture content of the wood specimen at the test. M_{test} is the weight (g) of the specimen at the test, M_{od} is the oven-dry weight (g) of the specimen.

$$MC\% = \frac{M_{test} - M_{od}}{M_{od}} \times 100 \tag{1}$$

The basic density of the timber specimens was determined as shown in (2), where ρ is the basic density of the test specimen (g/cm^3), W is the oven-dry weight of the test specimen (g), l is the length of the test specimen (cm), b is the breadth of the test specimen in (cm), and h is the height of the test specimen (cm).

$$\rho = \frac{W}{l \times b \times h} \tag{2}$$

The basic specific gravity of the timber specimens was determined as shown in (3), where G_b is basic specific gravity, ρ is the density of the test specimen (g/cm^3), ρ_w is density of water at 4ºC, this is 1g/cm^3.

$$G_b = \rho \times \rho_w \tag{3}$$

MOE was determined as shown in (4), where MOE is the modulus of elasticity in bending (N/mm^2 or MPa), P′is the load at the limit of proportionality (N), L is the span (mm) of the specimen, Δ' is deflection at mid-length at the limit of proportionality (mm), b is breadth (mm) of the specimen, h is depth (mm) of the specimen.

$$MOE = \frac{P'L^3}{4\Delta' bh^3} \qquad (4)$$

MOR was determined as shown in (5), where MOR is the modulus of rupture (N/mm^2 or MPa), P is the maximum load (N), L is the span of the specimen, b is the breadth (mm) of the specimen, h is depth (mm) of the specimen.

$$MOR = \frac{3PL}{2bh^2} \qquad (5)$$

Compression strength parallel to grain was determined as shown in (6), where C is compression strength parallel to grain (N/mm^2 or MPa), P is the maximum load (N), and A is the area of cross-section normal to the direction of load (in mm^2).

$$C = \frac{P}{A} \qquad (6)$$

Shear strength parallel to grain was determined as shown in (7), where S is shear strength parallel to grain (N/mm^2 or MPa), P is the maximum load (N), and A is the area in shear (mm^2).

$$S = \frac{P}{A} \qquad (7)$$

Timber hardness was measured by determining the load required to embed a steel ball, 11.28 mm in diameter, to a depth of 5.64 mm into the timber specimen. A descriptive statistical analysis was performed for the physical and mechanical properties of the *Liquidambar styraciflua*; the correlation coefficient between the modulus of elasticity (MOE) and modulus of rupture (MOR) was also computed to determine the reliability of the MOE as a predictor of the timber strength.

RESULTS AND DISCUSSION

Physical and Mechanical Properties of *Liquidambar styraciflua*

During timber air drying, most of the timber pieces at the top of the stack warped by springing, while other pieces developed end splits. Twisting in the timbers was very minimal. The majority of the remaining timber pieces exhibited minimal or no warping, but springing remained the most common defect. In terms of workability, it was relatively hard to drive and withdraw nails from the timber using a hammer, compared to species such as *Cupressus lusitanica*. The timber was, however, easy to machine and stained well.

The values for the physical properties of *Liquidambar styraciflua* wood are shown in Table 3. The mean specific gravity ranged from 0.59 to 0.65, while the moisture content ranged from 10.1 to 12.4% for the three trees. These results corroborate those of Ogunruku *et al*. (2024), where the mean specific gravity of *L. styraciflua* from the USA. was 0.61. In contrast, the specific gravity of Liquidambar timber from this study was higher than that of Liquidambar from Brazil (0.48), as reported by de Lima *et al*. (2016). The mean specific gravity was also higher compared to that of the Kenyan *C. lusitanica*, which was 0.40 (Mutayi *et al.*, 2024) and 0.39 (Ng'ang'a, 1992) and that of Kenyan Eucalyptus between 0.41 and 0.52 (Githiomi, & Kariuki, 2010). The variation could be attributed to the difference in site conditions and tree age as observed by Mugasha *et al*. (2021).

Table 3*: Descriptive Statistics for the Physical Properties of the Liquidambar styraciflua*

Specimen Height	MOE, MOR Specimens		C//g Specimens			S//g Specimens			Hardness Specimens		
	n	MC%	n	MC%	G_b	n	MC%	G_b	n	MC%	G_b
Tree 1											
Bottom	10	12.4	10	11.9	0.64	12	10.6	0.64	10	12.5	0.63
10% (2.8 m)	10	12.3	10	12.7	0.64	13	11.4	0.66	10	12.6	0.63
20% (5.6 m)	10	11.3	10	12.2	0.64	10	11.2	0.65	10	11.4	0.61
30% (8.4 m)	8	11.5	10	11.8	0.63	10	10.8	0.64	10	11.5	0.64

Specimen Height	**MOE, MOR Specimens**		**C//g Specimens**			**S//g Specimens**			**Hardness Specimens**		
	n	**MC%**	**n**	**MC%**	**G_b**	**n**	**MC%**	**G_b**	**n**	**MC%**	**G_b**
	38	**11.9**	**40**	**12.2**	**0.64**	**45**	**11.0**	**0.65**	**40**	**12.0**	**0.63**
Tree 3											
Bottom	10	12.1	10	12.3	0.61	10	10.8	0.61	10	12.3	0.61
10% (3.62 m)	10	11.7	10	12.0	0.59	10	9.9	0.59	10	11.2	0.59
20% (7.24 m)	10	11.2	10	11.4	0.59	10	9.5	0.59	10	10.6	0.58
	30	**11.7**	**30**	**11.9**	**0.60**	**30**	**10.1**	**0.60**	**30**	**11.4**	**0.59**
Tree 6											
Bottom	10	12.2	10	12.2	0.63	10	9.5	0.59	10	12.3	0.65
10% (2.23 m)	10	12.1	10	12.3	0.63	10	11.0	0.62	10	12.2	0.61
20% (4.46 m)	10	11.8	10	11.6	0.63	10	10.2	0.62	10	12.2	0.59
30% (6.69 m)	10	12.4	10	11.9	0.62	10	10.6	0.63	10	12.7	0.59
40% (8.92 m)	10	12.4	10	12.1	0.74	10	10.9	0.62	10	12.8	0.62
	50	**12.2**	**50**	**12.0**	**0.65**	**50**	**10.5**	**0.62**	**50**	**12.4**	**0.61**
Overall	**118**	**11.9**	**120**	**12.0**	**0.63**	**125**	**10.6**	**0.62**	**120**	**12.0**	**0.61**

n - Number of specimens. MOE - Modulus of elasticity. MOR - Modulus of rupture. C//g - Compression strength parallel to grain. S//g - Shear strength parallel to the grain. MC - Moisture content. G_b - Basic specific gravity

Woods with higher MOE values are stiffer than those with lower values, while woods with lower MOR values break under less stress. Compression strength measures the maximum load a wood can sustain before being crushed, whereas shear strength indicates the amount of stress required to cause fibres to slide past each other along the grain. A higher hardness value means greater resistance to wear and scratches.

Tree 1 (Honduras provenance) had the highest mean strength for all the properties, while Tree 6 (Guatemala provenance) had the lowest mean strength for modulus of elasticity, compression strength parallel to grain and hardness. Tree 3 (Nicaragua provenance) had the lowest mean strength for modulus of rupture. Trees 3 and 6 had similar mean strength in shear parallel to the grain. The variation in the strength properties among the three trees may have been due to their different specific gravities and other factors, such as the microfibril angle of the S_2 layer of the secondary cell wall (Forest Products Laboratory, 2021). Tree 1 had the highest specific gravity among the three trees. Tree 6 had lower average strength for compression parallel to grain and hardness compared to Tree 3, even though it had a slightly higher specific gravity; this may be because it had a higher moisture content (Forest Products Laboratory, 2021). The mechanical properties did not exhibit any variation along the height of the trees.

Table 4*:* **Descriptive Statistics for *Liquidambar styraciflua* Mechanical Properties**

Specimen Height		**MOE (MPa)**		**MOR (MPa)**			**C//g (MPa)**			**S//G (MPa)**			**Hardness (kN)**	
	n	**M**	**SD**	**M**	**SD**	**n**	**M**	**SD**	**n**	**M**	**SD**	**n**	**M**	**SD**
Tree 1														
Bottom	10	9724	2574	106.8	14.0	10	49.9	2.5	12	15.9	1.1	10	6.3	0.3
10% (2.8 m)	10	13505	1343	120.5	5.9	10	53.0	3.9	13	16.6	0.6	10	6.2	0.4
20% (5.6 m)	10	14821	1902	125.0	20.3	10	58.2	3.5	10	18.0	1.1	10	5.9	0.2
30% (8.4 m)	8	15144	698	120.7	5.0	10	57.7	2.4	10	18.3	1.2	10	6.4	0.4
	38	**13202**	**2800**	**118.1**	**14.6**	**40**	**54.7**	**4.6**	**45**	**17.1**	**1.4**	**40**	**6.2**	**0.4**
Tree 3														
Bottom	10	11770	1877	97.5	10.5	10	50.1	1.8	10	16.7	0.7	10	6.6	0.4
10% (3.62 m)	10	13859	1328	104.1	8.3	10	53.5	2.9	10	15.9	0.7	10	5.5	0.2
20% (7.24 m)	10	12953	1219	97.8	10.6	10	53.7	2.6	10	16.2	1.0	10	5.3	0.2
	30	**12861**	**1691**	**99.8**	**10.0**	**30**	**52.4**	**2.9**	**30**	**16.3**	**0.8**	**30**	**5.8**	**0.7**
Tree 6														
Bottom	10	9670	2244	98.5	14.0	10	49.4	5.2	10	16.2	1.0	10	5.3	0.3
10% (2.23 m)	10	11185	1909	95.2	14.2	10	48.9	4.3	10	16.4	0.8	10	5.2	0.6
20% (4.46 m)	10	13431	1562	112.8	10.5	10	56.7	4.4	10	17.8	0.8	10	5.6	0.4
30% (6.69 m)	10	12038	1507	103.1	11.9	10	50.2	4.4	10	15.4	0.9	10	5.4	0.4
40% (8.92 m)	10	11234	726	96.7	11.3	10	45.9	3.3	10	15.8	0.9	10	5.9	0.5
	50	**11511**	**2024**	**101.2**	**13.6**	**50**	**50.2**	**5.5**	**50**	**16.3**	**1.2**	**50**	**5.5**	**0.5**
Overall	**118**	**12399**	**2346**	**106.3**	**15.4**	**120**	**52.3**	**5.0**	**125**	**16.6**	**1.2**	**120**	**5.8**	**0.6**

n - Number of specimens. M - Mean values. SD - Standard deviations. MOE - Modulus of elasticity, MOR - Modulus of rupture. C//g - Compression strength parallel to grain. S//g - Shear strength parallel to the grain.

The mean MOE and MOR values in this study were higher than those reported for Liquidambar timber from the USA. (Ogunruku *et al*., 2024). These differences could be attributed to the specimens in that study being of structural size, which could have contained some strength-reducing defects, unlike the current study, where small, clear specimens were used. The mean values for MOE, MOR, compression strength parallel to grain, shear strength parallel to grain and Janka hardness in this study (Table 4) were all higher than those reported by Mutayi *et al*. (2024), de Lima *et al*. (2016) and Ng'ang'a (1992) as shown in Table 5. The difference could be due to genetic and environmental factors as well as the silvicultural treatment applied in the management of the trees (Rocha *et al*., 2019). The varying ages of the trees from which specimens were extracted could also have contributed to the variation of the properties as was observed by Mugasha *et al*. (2021) and, Bijak, & Lachowicz (2021).

Table 5: **Average Physical and Mechanical Properties of Selected Tree Species**

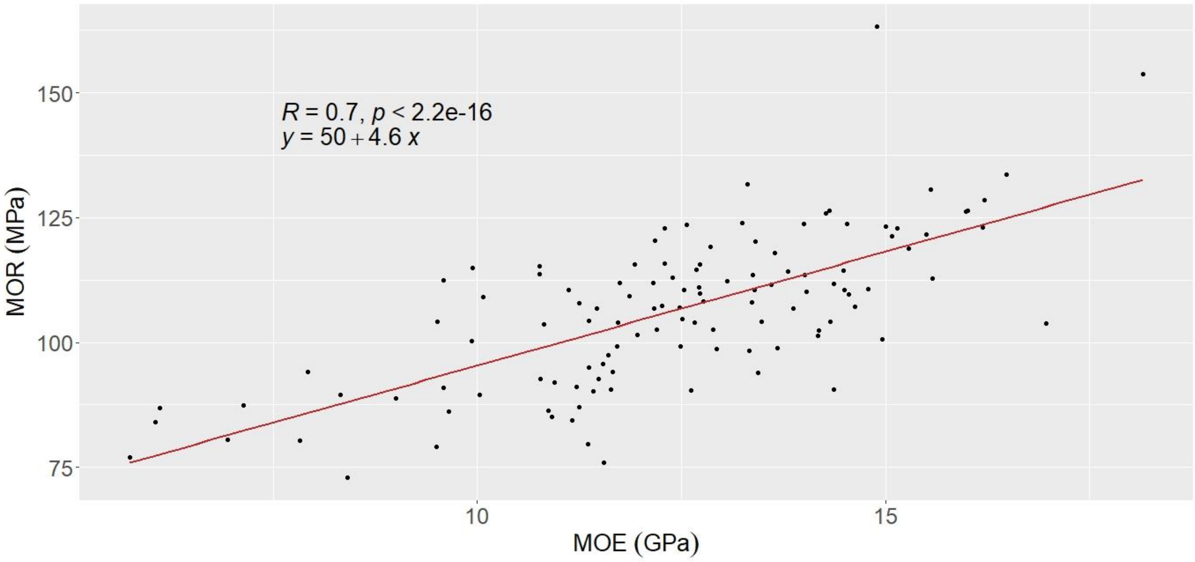
	G_b	MOE (MPa)	MOR (MPa)	C//g (MPa)	S//G (MPa)	Janka Hardness (kN)	Source
L. styraciflua	0.48	8138	70.4	37.6	6.9		(de Lima *et al*., 2016)
C. lusitanica	0.39	6300	44.6	21.9	7.03	2.4	(Ng'ang'a, 1992)
Cypress	0.40		23.7	25.0			(Mutayi *et al*., 2024)
Eucalyptus	0.49		31.6	34.4			

G_b - Basic specific gravity. MOE - Modulus of elasticity. MOR - Modulus of rupture. C//g - Compression strength parallel to grain. S//g - Shear strength parallel to the grain.

Relationship between Modulus of Elasticity and Modulus of Rupture

Figure 2 shows the relationship between the modulus of rupture (MOR) and modulus of elasticity (MOE) for *Liquidambar styraciflua*; the two properties had a significant correlation of 0.7 at a 5% significance level. The correlation between MOR and MOE is highest when compared to a correlation of MOR with other strength predictors, such as density and defects like knots, even when combined. This is because the MOE obtained is a result of the combined effect of the predictors as well as other factors (Thelandersson, & Larsen, 2003). The coefficient of determination of the Kenyan Liquidambar timber was comparable to that of the USA at 0.47, as reported by Ogunruku *et al*. (2024). A high correlation between MOR and MOE indicates a strong relationship between the two properties; non-destructive testing methods such as machine strength grading require a strong relationship between the two properties for reliable prediction of strength (Ross, 2015).

Figure 2: Relationship between MOR and MOE for *Liquidambar styraciflua*



CONCLUSIONS AND RECOMMENDATIONS

This study examined the physical and mechanical properties of *Liquidambar styraciflua* growing in Western Kenya. The specific gravity, modulus of elasticity, modulus of rupture, compression strength parallel to grain, shear strength parallel to grain and Janka hardness were all superior compared to those of the current plantation species in Kenya; cypress, pines and eucalyptus.

There was a relatively strong relationship between the MOR and MOE for the Liquidambar. This indicates the suitability of non-destructive testing on its timber. Non-destructive testing methods, such as machine strength grading, may be preferred because of their advantages over destructive testing. Machine strength grading is cheaper than destructive testing. Economical and relatively accurate grading of timber is necessary due to the increased competition from alternative building materials such as steel. Machine strength grading uses MOE, a factor determined non-destructively by the machine, and a correlation coefficient determined from previous tests, to predict the MOR of timber and classify it into strength classes.

Based on the results of this study, Liquidambar timber can be used in similar or higher load-bearing applications as the three species. This study therefore recommends *L. styraciflua* as a suitable tree species for plantation growing for sawn timber in Kenya. With the availability of breeding and silvicultural regime data, the necessary Technical Orders should be prepared to guide the growth of this species.

In the countries of origin, *L. styraciflua* grows from sea level to an altitude of 2,134 m. In Kenya, *L. styraciflua* provenance trials were conducted at an altitude of 1,600 m above sea level. Provenance trials in lower altitudes could also be established to determine the growing range of *L. styraciflua* within Kenya. Further research to determine the physical and mechanical properties of graded structural timber from the species is necessary for design purposes. The strength of structural timber is lower than that of clear wood because it contains strength-reducing features such as knots. Additional studies on *L. styraciflua* are also required to assess the wood’s susceptibility and resistance to biological agents.

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Declaration of Conflicting Interests

All the authors declared no conflicting interests in the work reported in this paper.

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