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Inter- and Intraspecific Differences in Physical and Mechanical Properties of Wood from *Sclerocarya birrea* and *Anogeissus leiocarpus*

Fath Alrhman Awad Ahmed YOUNIS[a,d*] – Abdelazim Yassin ABDELGADIR[b] – Zeinab A. Abd Elhameed AHMED[b] – James Kudjo GOVINA[c,d] – Róbert NÉMETH[d]

[a] Department of Wood Science and Technology, Faculty of Forest Sciences and Technology, University of Gezira, Wad Madani - AL Gezira State, Sudan
[b] Department of Forest Products and Industries, Faculty of Forestry, University of Khartoum- Khartoum North - Shambat area, Sudan
[c] CSIR–Forestry Research Institute of Ghana, Kumasi, Ghana
[d] Institute of Wood Technology and Technical Sciences, Faculty of Wood Engineering and Creative Industries, University of Sopron, Sopron, Hungary

Abstract – This paper studied the basic density and mechanical properties differences of wood among and within *Sclerocarya birrea* and *Anogeissus leiocarpus*. Three trees from each species were selected from the Lagawa Natural Forest Reserve in Western Kordofan State, Sudan. Test specimens were selected from three vertical positions (10, 50, and 90% along the bole length) of the trees. Specimens were also collected from three horizontal positions (innerwood, middlewood, and outerwood) within each of the three vertical positions. Tests for basic density of wood (BD), modulus of rupture (MOR), modulus of elasticity (MOE), compressive (CS), and shear strength (SS) parallel to the grain were performed. An analysis of variance shows that only the horizontal positions were a significant source of variation for both species studied. The correlation coefficient of BD was significant, weak, and positive for the mechanical properties of *A. leiocarpus.* A similar observation was found for BD correlated with CS and SS for *S. birrea*.

***Sclerocarya birrea* / *Anogeissus leiocarpus* / basic density / strength / modulus of elasticity**

Kivonat – A *Sclerocarya birrea* és az *Anogeissus leiocarpus* fafajok közötti és fafajon belül kimutatható eltérések a faanyag fizikai és mechanikai tulajdonságaiban vonatkozásában. A kutatásban vizsgáltuk a *Sclerocarya birrea* és az *Anogeissus leiocarpus* faanyagok bázis sűrűségének és mechanikai tulajdonságainak változásait a két fafaj között és a fafajokon belül. Minden fajhoz három faegyedet választottunk ki a szudáni Nyugat-Kordofan állambeli Lagawa Természeti Erdőrezervátumból. A próbatesteket három függőleges helyzetből (10, 50 és 90%-ban a törzshossz mentén) választottuk ki a fákon belül. Ezenkívül a mintákat három vízszintes helyzetből (belső farész, középső farész és külső faszövet) gyűjtöttük a három függőleges pozíció mindegyikén belül. Meghatároztuk a faanyag bázis sűrűségét (BD), vizsgáltuk továbbá a rostiránnyal párhuzamos hajlító szilárdságot (MOR), rugalmassági modulust (MOE), nyomószilárdságot (CS) és nyírószilárdságot. A varianciaanalízis azt mutatja, hogy mindkét vizsgált faj esetében csak a vízszintes helyzet mutatott jelentős eltérést. Az *A. leiocarpus* mechanikai tulajdonságai statisztikailag szignifikáns, de gyenge

* Corresponding author: BT8QC4@uni-sopron.hu; H-9400 SOPRON, Bajcsy-Zs. u. 4., Hungary

korrelációt mutattak a bázis sűrűséggel. A sűrűség növekedésével a szilárdságok is nőttek. A *S. birrea* fafajnál hasonló megfigyelést mutattunk ki, a sűrűség növekedésével nőtt a nyomó- és a nyírószilárdság.

***Sclerocarya birrea* / *Anogeissus leiocarpus* / bázis sűrűség / szilárdságok / rugalmassági modulusz**

1 INTRODUCTION

Wood is a natural material with many utilization purposes (Desch – Dinwoodie 1996). The distinctive features of wood (anisotropic, hygroscopic, orthotropic, and renewable) make it an easily recognizable material (Koch 1985). Generally, cellulose, hemicelluloses, and lignin ratios differ in wood components (Panshin – de Zeeuw 1980) between species. Moreover, these components vary between hardwood and softwood trees (Shmulsky – Jones 2011).

Several factors – including genetics, environment, site, age, and defects – contribute to wood variability (Desch – Dinwoodie 1996). These factors lead to the variation in the anatomical, physical, and mechanical properties of wood (Shmlusky – Jones 2011), which frequently weakens the acceptance of wood as a structural material (Desch – Dinwoodie 1996).

Variations in the physical and mechanical properties of wood among and within tree species have been extensively studied (Karki 2001, Steffenrem et al. 2007, Knapic et al. 2008, Chowdhury et al. 2009, Al-Sagheer – Prasad 2010, Chowdhury et al. 2013, Majumdar et al. 2014, Kiaei et al. 2015, Kiaei – Farsi 2016, Wessels et al. 2016, Xie et al. 2017 and Bektaş 2020). A previous study in Sudan revealed no significant source of variations in basic density within the wood of *Balanites agyptiaca* (Awad 2015). However, significant sources of variations in wood density were found within *Tectona grandis* wood (Izekor et al. 2010). Wood variability attributed to variations between sites has been studied among *Pinus sylvestris* and *Acacia melanoxylon* in Portugal (Fernandes et al. 2017, Machado et al. 2014).

Sclerocarya birrea belongs to the Anacardiaceae family and can grow up to 12 m high (Vogt 1995). The wood is traditionally used for carving, furniture, saddles, and locally for manufacturing. Presently, the species is still important for sustaining rural livelihoods (Sahni 1968). In Sudan, *Sclerocarya birrea* can be found in places such as Kassala, Imatong Mountains, Erkwit, Blue Nile, Kordofan, and Darfur. The wood of *Sclerocarya birrea* is soft, diffuse-porous, and low to medium in density. The color of freshly cut wood is grayish with reddish bands and streaks, brown patches, and delivered to darkening reddish brown. The sapwood has been described as very wide, and it is not sharply differentiated from the heartwood (Goldsmith – Carter 1981).

Anogeissus leiocarpus (African birch) belongs to the Combretaceae family and can grow to a height of up to 20 m. Its wood has been locally used for transmission and building poles, fence posts, and forked poles. It is also used for beams in rural building construction. With its high energy characteristics, it is also used as firewood and for charcoal production. In Sudan, *Anogeissus leiocarpus* is found along streams and rivers and in valleys in South Kassala, Kordofan, South Darfur, and the Blue Nile states (El Amin 1990). The wood of *A. leiocarpus* is grayish outside, dark brown at the heart and very hard. The wood is ring porous and contains surface crystals and traumatic ducts (Ayeola et al. 2009).

Adequate scientific information on the technical properties of these two Sudanese species could lead to effective promotion and efficient utilization of their wood. The objective of this research was to investigate the variability of wood along the height of a tree and horizontal positions (innerwood, middlewood, and outerwood). The specific traits considered are basic density (BD), modulus of rupture (MOR), modulus of elasticity (MOE), compressive strength parallel to the grain (CS), and shear strength parallel to the grain (SS) within and among *S. birrea* and *A. leiocarpus* trees.

2 MATERIALS AND METHODS

2.1 Materials

Three trees each for species of *Sclerocarya birrea* and *Anogeissus leiocarpus* were randomly selected for the study. The trees were growing naturally in Lagawa Natural Forest Reserve located in the Western Kordofan State, Sudan, between 11°24′20″N - 29°8′18″E (Fig. 1). The trees were straight and free from natural defects. *Table 1* provides the basic morphological description of the sampled trees.

Table 1. Diameter at breast height (dbh), tree height and bole length for Sclerocarya birrea and Anogeissus leiocarpus

Species	Tree No.	Dbh (cm)	Tree height (m)	Bole length (m)
S. birrea	1	40	13	2.0
	2	42	16	2.5
	3	47	17	3.5
A. Leiocarpus	1	35	16	2.0
	2	38	15	2.6
	3	36	15.5	2.4

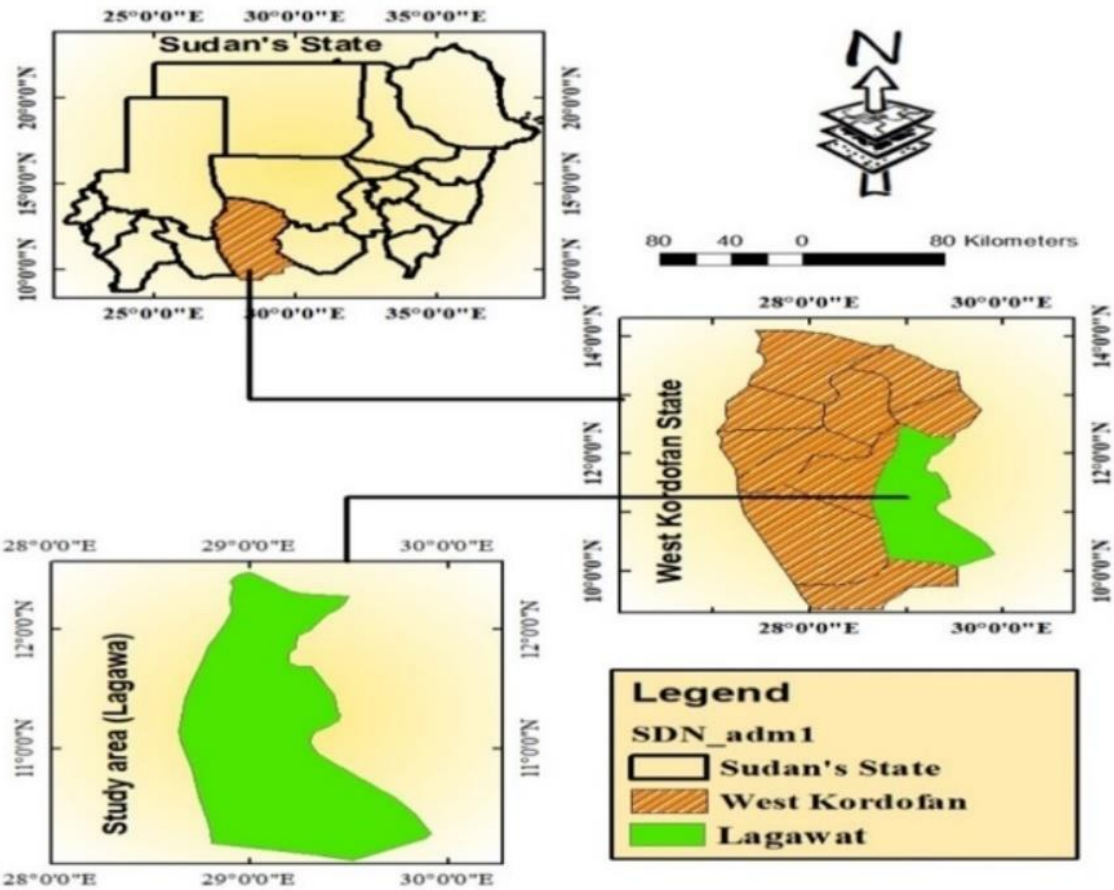

Figure 1. The study area

2.2 Methods

2.2.1 Sample collection and preparation

The trees were felled with a chainsaw and three 50-cm long sample logs were removed at 10, 50, and 90% along the bole length. The logs were sawn to 4 cm thick boards through the pith to the bark. Test specimens for the physical and mechanical properties were selected from wood around the pith, heartwood, and sapwood to represent innerwood, middlewood, and outerwood for each sampled log. Three replicates of test specimens were selected from each group (innerwood, middlewood, and outerwood). Other 20x20x30 mm specimens were taken from either end of all specimens prepared and used for mechanical testing to determine wood basic density based on oven-dry weight (Wo) per unit green volume (V_g) (ISO 3131 1975). The basic density of wood (BD g/cm^3) was calculated using the formula:

$$\mathrm{BD} = Wo/\mathrm{Vg} \tag{1}$$

The mechanical properties specimens were air-dried indoors to constant weight. The size of test specimens was 20x20x300 mm for MOR and MOE (ISO 3349 1975), 20x20x60 mm for CS (ISO 3787 1975), and 20x20x20 mm for SS (ISO 3347 1975). A universal testing machine was used to determine the mechanical properties. The following formulas were used to calculate the MOR, MOE, CS and SS (N/mm^2):

$$\mathrm{MOR} = \frac{3}{2}\frac{\mathrm{pl}}{\mathrm{bd}^2} \tag{2}$$

Where:

p:	load
l:	Length of span
b:	width
d:	depth.

$$\mathrm{MOE} = \frac{\mathrm{pl}^3}{4\Delta \mathrm{bd}^3} \tag{3}$$

Where:

p:	load, at the limit of proportionality
l:	length of span
Δ':	deflection, at the limit of proportionality
b:	width
d:	depth.

$$\mathrm{CS} = \mathrm{P/A} \tag{4}$$

$$\mathrm{SS} = \mathrm{P/A} \tag{5}$$

Where:

P:	Maximum load
A:	Cross-sectional area.

2.3 Statistical Analysis

The data was organized in Microsoft Excel sheets and analyzed using SAS statistical package (SAS 1990). Nested analysis of variance was conducted using PROC Nested to investigate the significance of the variation among sources and their variance components (not to estimate the means of the sources and the differences among them). Using PRPC CORR, the coefficients of correlation and regression were conducted to determine the relationship between mechanical properties and basic density. The significant correlation coefficients were classified as strong (r ≥ 70), moderate (r ≥ 50 < 69), and weak (r ≤ 49). The tests were performed at the significant level of P≤0.05.

3 RESULTS AND DISCUSSION

3.1 Wood Basic Density (BD)

Table 2 presents the mean values of the basic density (BD) for the *S. birrea and A. leiocarpus* wood. The BD for all specimens (n=1620) of *S. birrea* varied from 0.35 to 0.79 g/cm^3, and the mean value was 0.52 g/cm^3. Basic density for *A. leiocarpus* (n=1620) varied from 0.68 to 1.28 g/cm^3 and the mean was 0.92 g/cm^3. This study's mean BD for *S. birrea* is higher when compared to some reported values (0.49 g/cm^3) in Sudan (Mahgoub 2001). On the contrary, the study value was lower than the value (0.64 g/cm^3) reported in Saudi Arabia (Nasroun 2005). Similarly, *A. leiocarpus* wood has the greater BD in comparison to the values 0.82 g/cm^3 found by Mahgoub (2001), 0.88 g/cm^3 found by Mohammed (1999), and 0.731 g/cm^3 found by Ogunwusi et al. (2013). However, the study value was lower than the values of 1.150 g/cm^3 found by Bello-Jimoh (2018). The basic density of wood is the oven dry weight of wood material per green unit volume. Hence, it directly reflects the dry weight of wood as contained in freshly felled wood (Barnett – Jeronimidis 2003). At the same MC, one cubic meter of *A. leiocarpus* green wood is heavier than an equal volume of *S. birrea*. Based on the average BD, the oven-dry weight of one cubic meter of *S. birrea* green wood is estimated to be 520 kg and 940 kg for one cubic meter of *A. leiocarpus* wood. In some cases, it is of interest to estimate the weight of wood at a given MC if its dry weight is known. Then in both cases, the weight of one cubic meter will be multiplied by the actual wood volume to be transported. *Figure 2 and Figure 3* show the mean basic density at the examined vertical (10, 50, and 90%) and horizontal positions (innerwood, middlewood and outerwood).

Table 2. Mean value and descriptive statistic for basic density of wood (g/cm^3) of S. birrea and A. leiocarpus trees. (Min): Minimum; (Max): Maximum; (Std dev): Standard deviation; (CV): Coefficient of variation

Species	Min	Mean	Max	Std dev	CV%
S. birrea	0.35	0.52	0.79	0.06	11.53
A. leiocarpus	0.68	0.92	1.28	0.08	8.69

Results of the variance analysis of the nested random effects (*Table 3*) show that trees and vertical positions within trees were not significant sources of variation in basic density for *S. birrea* (p= 0.96 and p= 0.62, respectively). Nevertheless, horizontal positions within vertical positions were a significant (p= 0.0001) source of variation, although they contributed only 7.22% of the total variation. The percentage of the error variance component (92.77%) reveals that most of the variation in basic density was unexplained by the studied factors. Similar results were found for the basic density of *A. leiocarpus* in this study (*Table 3*). Trees and vertical position did not significantly influence basic density (p= 0.2 and p= 0.07, respectively). Rather, horizontal position was a significant source of variation (p= 0.0001), contributing 25.74% of the total variation. The unexplained variation amounted to 54.93%. The observed variation in wood density among the horizontal positions (from innerwood to outerwood) for both species may be due to the increasing age of cambium (Chowdhury et al. 2009, Izekor et al. 2010).

These results agree with previous research findings that a horizontal position was a significant source of variation in the basic density for hardwood species such as *A. leiocarpus, Eucalyptus grandis* and *Eucalyptus camaldulensis* (Sadiku 2018, Wessels et al. 2016). Similarly, results agree with reports for softwood species such as *Juniperus polycarpos* (Kiaei et al. 2015) and *Pinus kesiya* (Missanjo – Matsumura 2016). However, the results are not in line with previous research findings that vertical positions within trees were a significant source of variation in hardwoods; for instance, within *Acacia nilotica* (Ahmed 1998); *Tectona grandis* (Izkor et al. 2010); *Corylus colurna* (Zeidler 2012); *Acacia saligna*, (Mmolotsi et al. 2013); *Balanites aegytica* (Awad 2015), and *Albizzia julibrissin* (Kiaei - Farsi 2016).

Table 3. Nested random effects analysis of variance for basic density of S. birrea and A. leiocarpus wood. (***): P < 0.0001; (**): P < 0.001; (*): P < 0.05; (ns): not significant; (TR): tree; (VP): vertical position; (HP): horizontal position; (V comp): variable component

Variation sources	BD of *S. birrea*	BD of *A. leiocarpus*
TR	ns	ns
V comp%	0.00	0.00
VP(TR)	ns	ns
V comp%	0.00	0.00
HP(VP)	***	***
V comp%	7.22	25.74

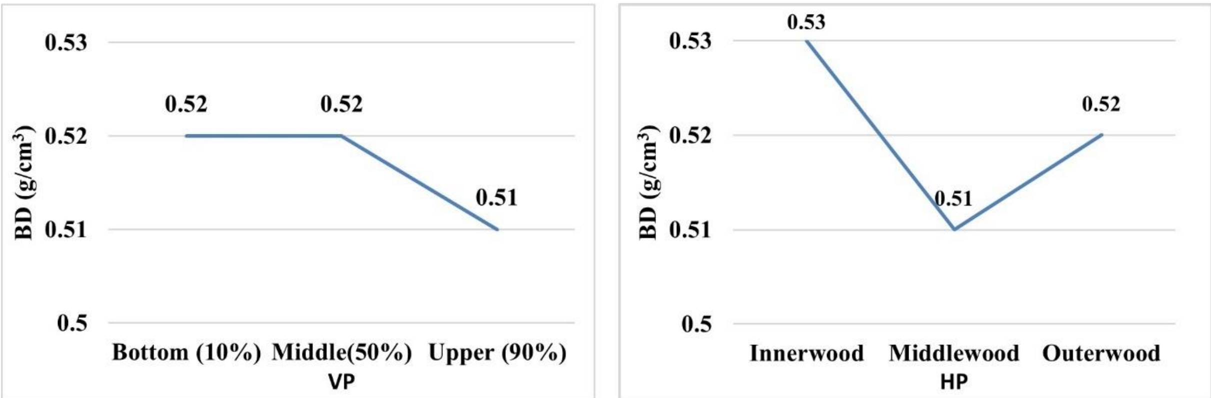

Figure 2. Showing the basic density within vertical and horizontal positions for S. birrea. (BD): basic density; (VP): vertical positions; (HP): horizontal positions

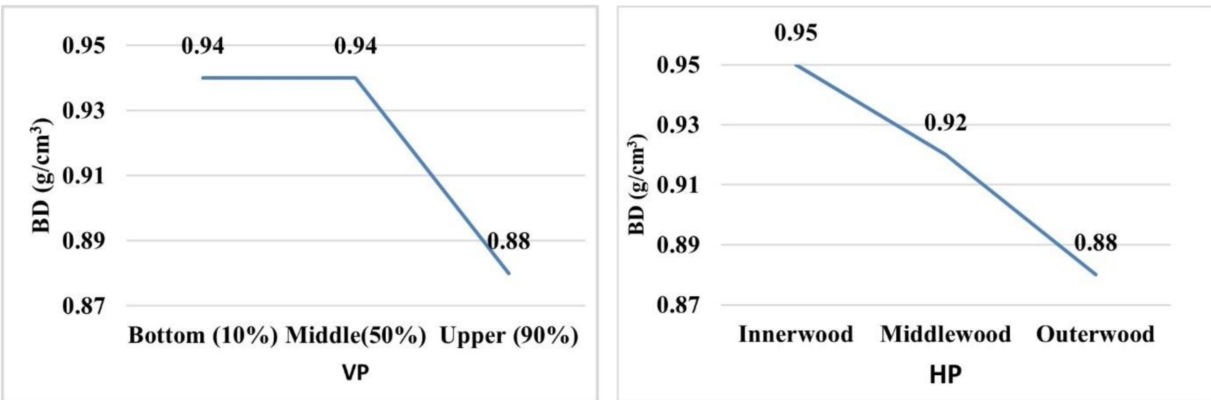

Figure 3. Showing the basic density within vertical and horizontal positions for A. leiocarpus. (BD): basic density; (VP): vertical positions; (HP): horizontal positions

3.2 Mechanical properties

Tables 4 and 5 present the mean values with standard deviation for the mechanical properties of *S. birrea* and *A. leiocarpus* wood. An analysis of variance of the nested random effects for mechanical properties shows that vertical positions (VP) were not a significant source of variation in the traits, except for MOR and MOE of *S. birrea (Table 6)*. The same can be said for MOE and CS of *A. leiocarpus (Table 7)*. However, the horizontal positions (HP) were a significant source of variation for both species in all traits. There are similar trends in mechanical properties among VP within trees of *Blanites aegyptiaca* (Awad 2015) and *Acacia melanoxylon* (Machado et al. 2014). The variations in mechanical properties among HP are probably due to several factors such as the density variability of the timber, cell arrangement and grain angle, and the microfibril angle within the cell wall (Panshin – de Zeeuw 1980). *Figures 4 and 5* show the mean mechanical properties at the examined VP (10, 50, and 90%) and HP (innerwood, middlewood, and outerwood).

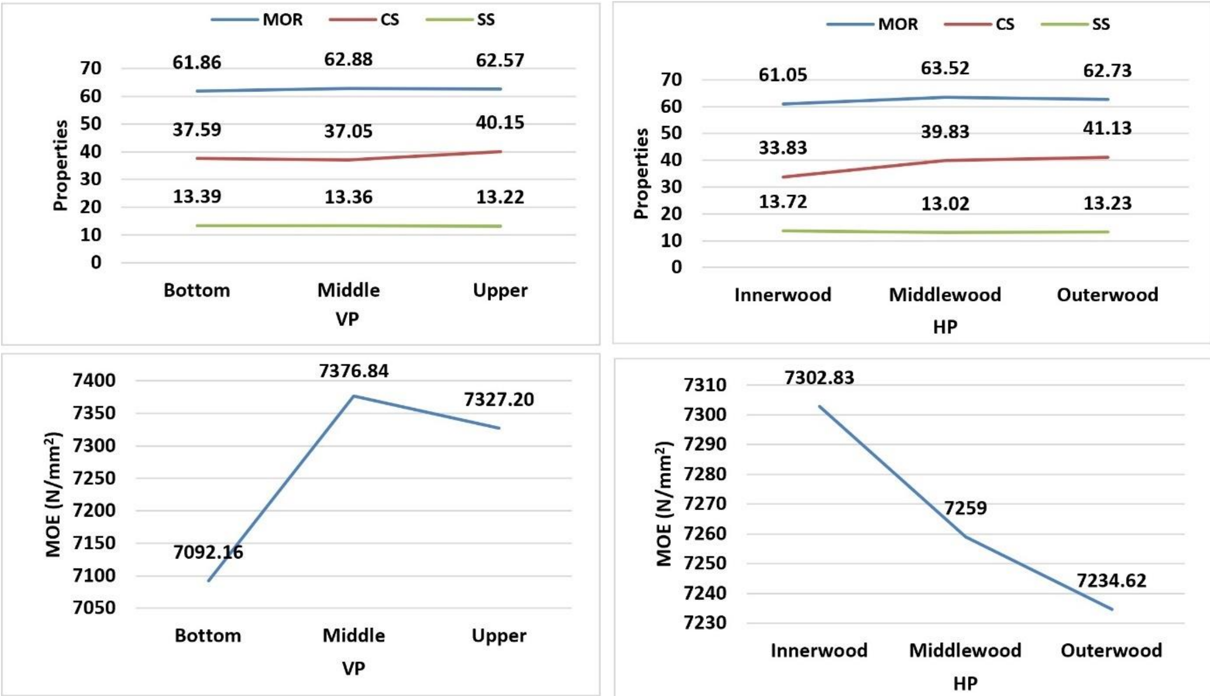

Figure 4. Showing the mechanical properties (N/mm^2) within VP and HP for S. birrea. (VP): vertical positions; (HP): horizontal positions; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain

Figure 5. Showing the mechanical properties(N/mm^2) within VP and HP for A. leiocarpus. (VP): vertical positions; (HP): horizontal positions; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain

Table 4. Mean values and simple statistics of mechanical properties in (Nmm^2) of S. birrea. (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain

Variable	Min	Mean	Max	Std. dev	CV%
MOR	37.13	62.43	96.03	10	16.02
MOE	2884.41	7265.4	10935.7	1381.87	19.02
CS	12.37	38.26	51.39	6.87	17.96
SS	4.86	13.32	19.26	3.09	23.20

Table 5. Mean values and simple statistic of mechanical properties in (Nmm^2) of A. leiocarpus. (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain.

Variable	Min	Mean	Max	Std. dev	CV %
MOR	41.12	96.97	146.01	18.45	19.03
MOE	4958	12577	23553	3434	27.30
CS	30.55	45.77	68.45	6.85	14.96
SS	5.60	16.64	27.94	4.10	24.09

Table 6. Nested Random Effects Analysis of Variance for basic density and mechanical properties of S. birrea wood. (***): P < 0.0001; (**): P < 0.001; (*): P < 0.05; (ns): not significant; (TR): tree; (VP): vertical position; (HP): horizontal position; (V comp): variable component.

Variation sources	MOR	MOE	CS	SS
TR	***	***	ns	ns
V comp%	11.08	16.15	0.00	0.00
VP(TR)	ns	ns	ns	ns
V comp%	0.00	0.00	0.00	0.00
HP(VP)	***	**	***	***
V comp%	12.79	13.09	48.30	21.76

Table 7. Nested Random Effects Analysis of Variance for basic density and mechanical properties of A. leiocarpus wood. (***): P < 0.0001; (**): P < 0.001; (*): P < 0.05; (ns): not significant; (TR): tree; (VP): vertical position; (HP): horizontal position; (V comp): variable component.

Variation sources	MOR	MOE	CS	SS
TR	***	Ns	ns	*
V comp%	20.07	0.00	0.00	15.01
VP(TR)	ns	***	ns	ns
V comp%	0.00	17.44	0.00	0.00
HP(VP)	*	***	***	***
V comp	6.03	8.79	18.57	13.53

3.3 Relationships between mechanical properties and basic density

The results of Pearson correlation analysis of *S. birrea* reveal no significant correlation (p= 0.11; r= 0.09 and p= 0.37; r= 0.05) for MOR and MOE with BD. There was a significant but weak positive correlation for CS (p= 0.0004; r= 0.21) and SS (p= 0.0001; r= 0.26). There are contrary results for the correlation of MOR and MOE with BD among other wood species; for example, the wood of *Acacia nilotica* (DafaAlla 1998) and *Balanites agyptiaca* (Awad 2015) in Sudan. Meanwhile, there were significant, weak positive correlations between all mechanical properties and BD of *A. leiocarpus (Table 8).*

The results of the correlation of mechanical properties with BD for both species studied were low, which suggests that relying on only the densities of the species for utilization can be a disadvantage. This suggestion agrees with Machado et al. 2014. The trends found by this study were not in agreement with the general perception that wood density had been considered a good indicator of wood strength (Shmulsky – Jones 2011). Previous research found significant, positive correlation of mechanical properties with wood density in *Tectona grandis* (Izekor et al. 2010) and *Borassus aethiopum* (Asafu et al. 2013). However, their coefficients of correlation ranged between 0.85 to 0.90 %.

Regression coefficients for the significant and insignificant correlation were considered. The regression coefficients of determination (R^2) values ranged from 0.02 to 0. 25, indicating that a small proportion of the variations in mechanical properties were explained by basic density. Consequently, coefficients of determination were low and did not indicate a good fit for both species *Fig 6 and 7*. Based on the results, the basic density of wood *S. birrea* and *A. leiocarpus* is not optimal to estimate the mechanical properties of the wood.

Table 8. Correlation coefficients (and probabilities) for mechanical properties with BD and of S. birrea and A. leiocarpus. (BD): basic density; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain

Mechanical properties	BD of wood *S. birrea*	BD of wood *A. leiocarpus*
MOR	0.09 (0.11)	0.33 (0.0001)
MOE	0.05 (0.37)	0.28 (0.0001)
CS	0.21 (0.0004)	0.30 (0.0001)
SS	0.26 (0.0001)	0.24 (0.0001)

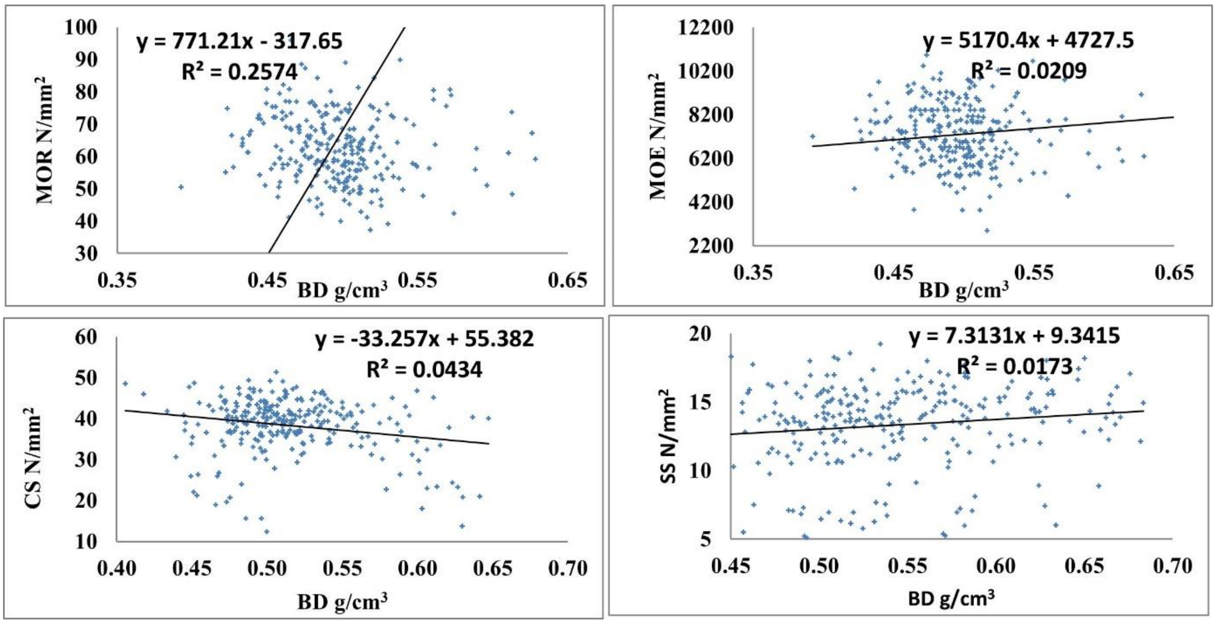

Figure 6. Relationships between mechanical properties and basic density of wood S. birrea tree. (BD): basic density; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain.

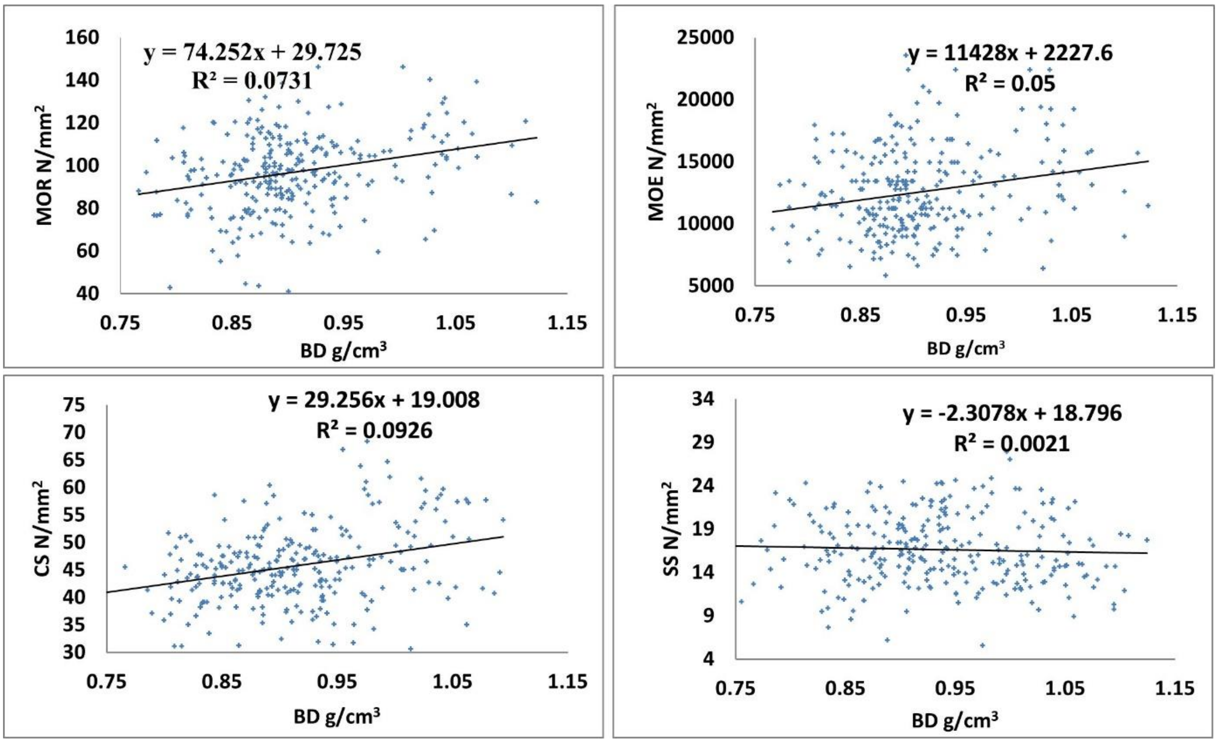

Figure 7. Relationships between mechanical properties and basic density of wood A. leiocarpus tree. (BD): basic density; (MOR): modulus of rupture; (MOE): modulus of elasticity; (CS): compressive strength parallel to the grain; (SS): shear strength parallel to the grain.

5 CONCLUSIONS

The present study draws the following conclusions:

- Horizontal position within vertical position was a significant source of variation in basic density and selected mechanical properties for *S. birrea* and *A. leiocarpus*.
- Vertical position within trees was not a significant source of variation in basic density for *S. birrea* and *A. leiocarpus.*
- Vertical positions within trees were a significant source of variation in MOR and MOE for *S. birrea,* and in MOE and CS for *A. leiocarpus*.
- The correlations of BD with the selected mechanical properties are significant, weak for *A. leiocarpus* and only with CS and SS for *S. birrea*.

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