Variations in Density and Mechanical Properties of *Acacia melanoxylon* Grown in Chencha, SNNPR, Ethiopia

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Abstract

In Ethiopia, the demand for wood has been increasing due to higher rate of population growth and development of wood industries.This study investigated the density and mechanical properties of *Acacia melanoxylon* along the stem height and radial direction. For this study, representatives of *A. melanoxylon* trees were selected randomnly and harvested from Chencha, SNNPR Ethiopia. The sample logs collected from the three portions of stem height and converted into lumber. Specimens were prepared for determination of density and mechanical properties along the three stem height and two radial directions (heartwood and sapwood) in green and at 12% moisture content (MC) conditions. The overall mean values of density (0.695 and 0.609 g/cm3), modulus of elasticity (9249.7 and 13671.89 N/mm^2), modulus of rupture (69.49 and 147.98 N/mm^2), maximum crushing strength (33.96 and 62.71 N/mm^2), impact bending (9519.60 and 9880.81 Nm/m^2), and hardness in tangential (3720.64 and 5373.10 N) and radial (3825.8 and 5415.40 N) in green and at 12% MC conditions respectively. For both moisture conditions, the stem height had significant ($p<0.05$) effects on density and mechanical properties. However, effects didn't show significant difference ($p<0.05$) between the heartwood and sapwood in both moisture conditions of density and mechanical properties. The interaction effect between tree height and heartwood-sapwood had significant effects on MOE, MCS and impact bending in case of both moisture conditions. In the case of both moisture conditions, the highest values of density and mechanical properties observed at the bottom portion and lowest at the top stem of *A. melaxylon*. The tree has potential as an alternative timber species to supply the wood industry.

Keywords: Blackwood, MOE, MOR, Compression parallel to the grain, Hardness, Stem height, radial direction

Introduction

In Ethiopia, due to higher rate of population growth and development of wood industries coupled with increased demand for wood has caused a dramatic decrease in forest resources. Ministry of Environment, Forest and Climate Change (MEFCC) (2017) report indicated that in 2013, Ethiopia consumed more than 124 million cubic meters of wood each year. With population growth and economic development projections, total wood product demand will increase by about 27% over the next 20 years, reaching an annual consumption of 158 million cubic meters by 2033 (MEFCC, 2017). To satisfy the ever-increasing demands of the consumers, large quantities of lumber, panel and fiber products are being imported from different countries with hard currency (Kelemwork and Gurmu, 2000; Desalegn *et al*., 2012). Besides the high demand for wood coupled with high deforestation rates of natural forest has led to an increase in the adoption of exotic trees and the introduction of plantation forestry into the country.

Though tree species utilized by the different industries for various wood products are limited in number for instance, *Cupressus lustanica* (Desalegn*et al*., 2015). According to Teketay*et al*. (2010), there are numerous plantations and potential species whose industrial and other commercial benefits are not yet fully realized. The selective use of the species paired with an inefficient further processing and inappropriate utilization due to lack of information and/or technologies on different wood properties and utilization methods for the alternative timber species. Consequently, it has resulted in the degradation of the existing forests and the selected tree species. A number of fast-growing exotic tree species including Eucalyptus species, *Cupressus lustanica*, Acacia species and other species were introduced to Ethiopia to be used as an alternative source of raw material to meet the ever-increasing demand for different forest products. *A. melanoxylon* was introduced to Ethiopia from Australia and the species was less utilized in case of Ethiopia. This species has been found or planted in the country in cooler and wetter upland areas, Moist and Wet Kolla, Weyna Dega and Degaagroclimatic zones (Bekele, 2007).

Acacia melanoxylon R.Br belongs to the family Leguminosae and subfamily Mimosoideae. It is a fast-growing species with a tall and straight bole form. It is commonly called Australian Blackwood (Nicholas and Brown, 2002; Lemmens 2006) and locally known as Omedla in Ethiopia (Bekele, 2007). *A. melanoxylon* is unusual among the acacias in that it is adapted to moist rather than dry areas (Nicholas and Brown, 2002). It performs well in altitude ranging from 1500 to 2300 meters above sea level with mean annual temperature 6 to 19 ^{0}C, mean annual rainfall is 750 to 2300 mm (Orwa*et al*., 2009).

Acacia melanoxylon is a valued timber species since the physical appearance of the wood is considered attractive and has an even texture. It has goodstrength and machining properties. These properties make the wood suitable for high-quality furniture, cabinet making, fancy veneer, turnery, paneling, carving, flooring, boat building, gunstocks, plywood, tennis racquets and knobs (Chudnoff, 1980; Boland *et al*., 1984; Nicholas and Brown, 2002; Bradbury *et al*., 2010b). The wood is also used for light construction, tool handles, musical instruments, fence posts, firewood and charcoal (Lemmens, 2006). The heartwood of *A. melanoxylon* trees is a rich brown color and high natural durability (Searle, 2000; Monteoliva*et al*., 2009). Its percentage of heartwood content was about 61%of the total tree volume (Knapic*et al*., 2006).

The use of wood is influenced by the physical and mechanical properties of the timber such as density, moisture, MOE, MOR, compression strength, impact bending, hardness and etc.Density is an important physical property of wood and one of the first to be considered when assessing wood quality, since it correlates with most of the strength properties of wood and conversion processes, including cutting, gluing, finishing, drying and papermaking (Zobel and van Buijtenen 1989; Desch and Dinwoodie 1996; Searle and Owen, 2005). Mechanical properties of wood indicate the ability of wood to resist various types of external forces, static or dynamic, which may act on it (FPL, 2010). Mechanical properties are very much important in the case of constructional and structural purposes of timber.

The wood properties can vary from species to species, at different site qualities, within species and within individual trees (Haygreen and Bowyer, 1996). Within single tree can vary along the tree height and along radial directions. Nicholas and Brown (2002) noted that the density and mechanical properties of the *A. melanoxylon* are extremely variable within a tree. In addition, many scholars (Santos *et al*., 2012; Santos *et al*., 2013) have been reported on the variation of density of the species. However, a few published information on variations of mechanicalproperties of the species. Machado *et al.* (2014) has reported the variation of density and some mechanical properties along the tree height and from pith to bark of *A. melanoxylon* grown in Portugal. Who observed that the density and mechanical properties of the species have irregular variation along with tree height with the value decrease from the base to 5% and then increased from 35% towards 65%. Whereas, he observed an increasing trend from the pith towards the bark of tree. The variability of all properties is among the main disadvantages of wood as a raw material. So, knowing this is the basis for optimal selection and use of timber for structural purposes. Within a stem variation statistics of mechanical properties is important for effective use of plantation timbers. Engineers and designers require explicit data on the uniformity of mechanical properties within a tree to estimate its lowest strength. According to Mohd-Jamil and Khairul (2016), within a stem variation of properties affects log during processing into sawn timber and drying procedures. Information on variation of mechanical properties could also assist in the development of yield rotation scheme.

Acacia melanoxylon density ranges from (0.465 to 0.670 g/cm3) (Santos *et al.*, 2012).The density is directly related to strengthof wood (Nicholas and Brown, 2002).The main reason why density is an index for predicting strength properties is that it is highly affected by cell wall thickness, cell diameter and the ratio of earlywood to latewood (Dinwoodie, 1981). The species has very good bending property (TTPB, 2001) and it is highly appreciated due to high crushing strength and resistance to impact, which are all important properties for structural uses (Nicholas and Brown, 2002). *Acacia melanoxylon* is not yet known by the development sectors, manufactures, and end users in Ethiopia. It is important to undertake research on such economically lesser-known and fast growing timber species in order to maintain sustainable supply of alternative raw materials and increase value addition and select appropriate utilization of technologies for the construction, industry, and furniture manufacturing sectors.

Therefore, the objective of this study was to examine the variations of wood density and mechanical properties along with the three tree height (bottom, middle and top) and along with two radial directions (heartwood and sapwood) of *Acacia melanoxylon* grown in Chencha, SNNPR Ethiopia.

Materials and Methods

Study site description

The species grows on an elevation between 1,300 and 3,250 m above sea level with geographical direction of 6^{o}8’0”-6^{o}26’0’’N and 37^{o}22’30”- 37^{o}43’30”E (Fig. 1). The mean annual precipitation and temperature of this area are usually about 1353 mm and 14^{0}C respectively (Yewubdar and Aseffa, 2017).

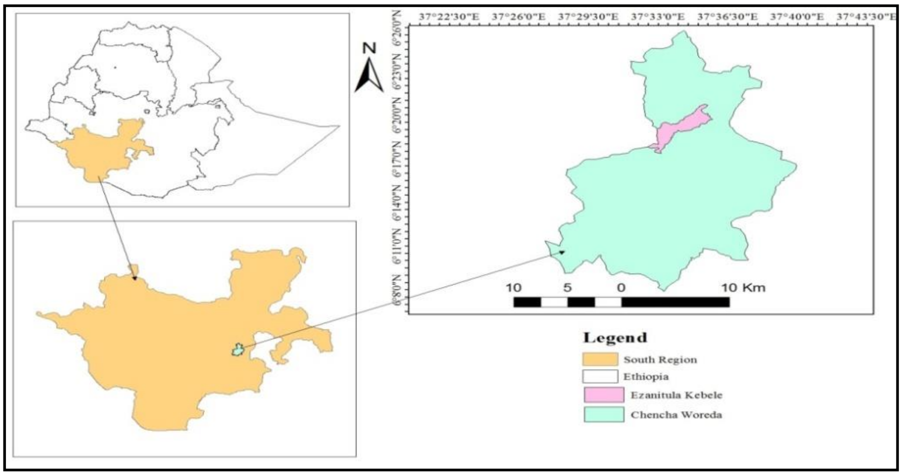

Figure 1: Map of Ethiopia showing the study area

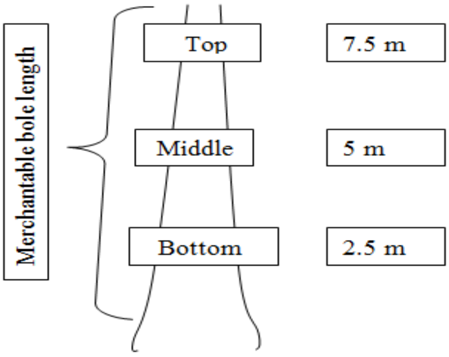

Figure 2: Sample log taken along the three stem height of *Acacia melanoxylon* tree

Tree Sampling

A total of five trees of 30 years old *Acacia melanoxylon* were randomly selected and harvested from the Chencha woreda community forest. The selected sample trees are straight trunks, normal branching and had no disease or pest symptoms (ISO 3129, 1975; Desalegn *et al*., 2012). The height and diameter at breast height (dbh) of the trees were ranging from 17 to 20 m and 21 to 26 cm, respectively. Each sample tree was cross-cut into three 2.5 m logs which represent the bottom, middle and top of the tree height (Desalegn, 2006; Moya *et al*., 2013) and, the end logs were sealed with paint to avoid moisture loss and end check/splitting. Then the sample logs were transported Addis Ababa, Forest Products Innovation Research and Training Center (FPIRTC) laboratory for further processing.

Sawing and Preparation of Wood Specimens

The sample logs were sawn tangentially using circular sawmill produced boards of 3 cm thickness in Forest Products Innovation Research and Training Center, Addis Ababa. According to Burley and Wood (1977), the sawn boards for density and mechanical properties were cross-cut into a series of 1.25m long stringers (Fig. 3). These were grouped and coded into odd and even numbers for the green and air-dry tests respectively. Boards for the dry tests were subjected to air seasoning yard under shade up to 12% MC reached. While the green test sample boards were planned, ripped and cross-cut into a final cross-section of 2x2 cm and 100 cm length and finally, the heartwood and sapwood from each section separately cross-cut into standard length specimens corresponding to each wood properties test. The stringers at air-dry conditions after it reached 12% MC, similar to the green test specimen preparation procedure, the heartwood and sapwood from each section separately cross-cut into standard length specimens corresponding to each wood properties test.

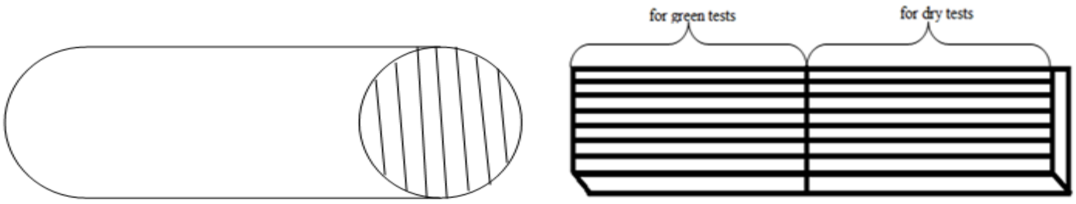

Figure 3: Sawing pattern and specimens preparations from sawn lumber for density and mechanical properties determination in green and air-dry condition tests

Density and Mechanical Properties Test

The specimens were prepared along the three tree heights (bottom, middle and top) and along radial direction (heartwood and sapwood) from green and at 12% MC conditions for testing of density and mechanical properties (Table 1).

Table 1: Dimensions, standards and numbers of test specimen used for Density and mechanical properties test

Property	Specimen dimensions (mm)*	Standards	Number of specimens
Density	20 x 20 x 60	ISO 3131	180
Static bending	20 x 20 x 300	ISO 3133	180
Compression// grain	20 x 20 x 60	ISO 3387	180
Impact bending	20 x 20 x 300	ISO 3348	180
Hardness	20 x 20 x 45	ISO 3348	360

(Radial x tangential x longitudinal)*

Density Tests

The density of wood was determined on a green-mass and air-dry-mass basis. A digital caliper was used to measure the dimensions of the samples at the green and air-dried wood at12% moisture content (MC) in order to determine their volumes. The specimens were then weighed using an electronic balance.Then Densities calculated using the following formulas:

$$\rho g= \frac{\mathbf{Mg}}{\mathbf{Vg}} \text{--} (1)$$

$$\rho 12=\frac{\mathbf{M12}}{\mathbf{V12}} \text{---} (2)$$

Where, ρg is density at green (g/cm^3), ρ12 is density at 12% MC, Mg is mass at the green, M12 is mass at 12% MC(g), Vg is the volume at green (cm^3) V12 is volume at 12% MC.

Mechanical Properties Test

Static Bending

The static bending strength was determined based on ISO 3133, 1975 standard by using the Universal Strength Testing Machine (UTM), type FM2750 with maximum loads of 50 Kilo Newton (KN). The distance between the points of suspension was 280 mm. The load was applied to the centerof the specimen, on the radial face at a constant speed of 0.11mm/s. Load of the force plate and corresponding deflection was recorded from the dial gauge manually for each sample. Graph plotting was done for each specimen using Microsoft Excel to calculate MOE and MOR. From each plotted graph, MOE and MOR were calculated using the following formulae:

$$\text{MOE} = \frac{p^1L^3}{4d^1bh^3} \text{---} (3)$$

$$\text{MOR} = \frac{3PL}{2bh^2} \text{---} (4)$$

Where: MOE=Modulus of elasticity (N/mm^2), MOR=Modulus of rupture (N/mm^2) P^1= Load at the limit of proportionality (N), P= Maximum Load (N) L= Span length (mm), d^1= Deflection at the limit of proportionality (mm), b= Width of specimen (mm) h= Thickness of the specimen (mm)

Compression Parallel to the Grain

Compression parallel to grain test was done based on ISO 3387, 1975 standard. The specimens were tested using Universal Testing Machine with speed of loading 0.01 mm/sec.The load was applied through a spherical bearing block, preferably of the suspended self-aligning type, to ensure uniform distribution of stress. On some of the specimens, the load and the deformation in a 15 cm central gage length was read simultaneously until the proportional limit was passed. The test was discontinued when the maximum load is passed and the failure occurs. The Maximum Crushing Strength (MCS) was determined using the following formula:

$$\text{MCS} = \frac{C}{bh} \text{ --} (5)$$

Where: MCS=Maximum crushing strength (N/mm^2), C=Maximum load (N), b=width of the specimen (mm), h=Thickness of the specimen (mm)

Impact bending

Impact bending or specific impact resistance is the work consumed in causing total failure in impact bending and it is determined based on ISO 3348, 1975. The specimens were tested using a pendulum hammer (Impact Bending Testing Machine, model PW5-S). The specimens were placed on the machine and the load was applied to the center and perpendicular to the radial face of the test specimen. The joule value was read from the force plate of the test machine and the strength was computed using the following formula.

$$\text{Sp.Im.Re.} = \frac{P}{bh} \text{--} (6)$$

Where: Sp.Im.Re=Specific impact resistance in (Nm/m^2), P=Joule value (Nm), b=width of the specimen (mm), h=Thickness of the specimen (mm).

Hardness test

Hardness represents the resistance of wood to indentation and marring. Hardness was comparatively measured by force required to embed 11.3 mm ball one-half its diameter into the wood (FPL, 2010). Hardness values were obtained by using the Janka method (ISO 3348, 1975). The specimens were tested using UTM with the rate of loading was 0.11mm/s for both radial and tangential face.

Statistical analysis

Statistical Package for the Social Sciences (SPSS) version 20 (IBM Corp. released 2011) was used to analyze the data using descriptive statistics and analysis of variance (ANOVA) Procedure. A least significant difference (LSD) method was used for mean comparison at $P<0.05$.

Results and Discussion

Density

The mean values of density along the three stem height in green and at 12% MC conditions are shown in Table 2 and Table 3. In case of both moisture conditions, the stem height had a significant effect on the density (Table 4 and Table 5) at $p<0.05$. However, the heartwood and sapwood didn’t show significant effect on density in green and at 12% MCconditions of *A. melanoxylon* timber.The interaction effect between tree height and radial direction didn’t have significant effectin the case of both moisture conditions (Table 4 and Table 5). From the study, it was found that *A. melanoxylon* at the base had higher density and decreased from the base to top of the tree height in both moisture conditions. Similar variation to this study, a significant decrease with height was found in *Acacia melanoxylon* trees in Argentina (Igartúa and Monteoliva, 2009). The result of the study agrees with the finding on Oriental beech (*Fagusorientalis*) where density decreased from base to top (Topaloglu and Erisir, 2018). Similar patterns were also reported for *Populus euramericana* (Kord*et al*., 2010) and for Athel wood (Kiaei and Sadegh, 2011). On the other hand, a significant decrease in specific gravity with increasing stem height was observed in the hardwood of *Acacia mangium*, *Bomba copsisquinata*, *Sweitenia macrophylla*, *Termenalia amazonia* and *Termenalia oblonga* (Moya and Muñoz, 2010) in Costa Rica.

The variation along the stem height might be due to maturity at the base and juvenility at the tip of the tree. Juvenility increases from bottom to top and as juvenility increases density decreases (Getahun *et al*., 2014). Density in the juvenile wood zone is low because there are relatively few late woods/summer wood cells and a high proportion of cells have thin wall layers (Haygreen and Bowyer, 1996). Ishengoma *et al*. (1998) noted that density was the main criterion for the prediction of wood strength properties. Ishengoma *et al*. (1997) also reported that juvenile wood is significantly lower in density than mature wood and hence the decrease in density as you move away from the bottom of the stem. This implies that the high-density wood from bottom logs should be used for structural purposes where high strength is required.

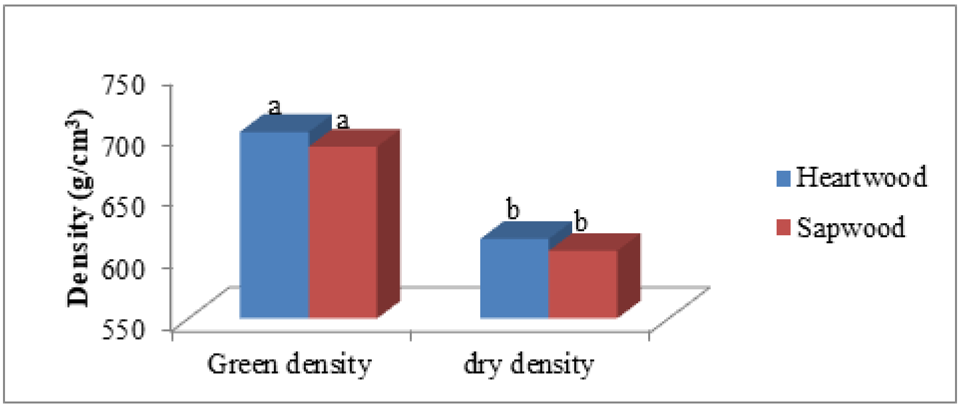

Figure 4: Density variation between heart-sapwood and between green-dry conditions of *Acacia melanoxylon* timber.

Note: Means having different letters were significant difference between green and dry conditions of density at $P<0.05$.

In the case of both moisture conditions, the heartwood density was slightly higher than the corresponding sapwood density (Fig 4). Similar variation to this finding was reported for the same species (Aguilera and Zamora, 2009) in Australia. Higher values of heartwood density compared to the corresponding sapwood density were reported for *Acacia burkea* and *Spirostachays africana* (Mmoloti *et al*., 2013) and for *Albizzia julibrissin* (Kiaei and Farsi, 2016).The differences may be due to extractives deposited in the heartwood. Aguilera and Zamora (2009) reported that the phenol extractive content of heartwood was more than double that of sapwood and affected the wood properties of *Acacia melanoxylon*.

The overall mean values of density in green and at 12% MC conditions were 0.695 g/cm^3 and 0.609 g/cm^3 respectively. Similar value of density at 12% MC was reported for *A. melanoxylon* (Igartu´a *et al*., 2009) in Argentina, who found 0.604 g/cm^3 and similarly, in the range of 0.515–0.71 g/cm^3 reported for the same species (Lemmens, 2006). On the other hand, superior values than this findings were reported by Machado *et al*. (2014) with a value of 0.654 g/cm^3 for this species. These variations may be attributed to genetics and local environmental factors which affect the growth of the trees such as soil characteristics, the density of stand, precipitation, solar radiation and age of the trees (Panshin and de Zeeuw, 1980).

In relation to commercially known and endangered tree species in Ethiopia, the density of *A. melanoxylon* (0.61 g/cm^3) was comparable with density at 12% MC reported for *Hagenia abyssinica* (0.56 g/cm^3) and *Pouteria adolfi-friederici* (0.6 g/cm^3) but higher than that of *Cupressus lustanica* (0.43 g/cm^3), *Pinus patula* (0.45g/cm^3), *Juniperus procera* (0.54 g/cm^3); and lower than those of *E. globulus* (0.78 g/cm^3) and *E. camaldulensis* (0.853 g/cm^3) (Desalegn *et al*., 2012; Desalegn *et al*., 2015). According to Chudnoff (1980), the density tested at 12% moisture content of *A. melanoxylon* was in the interval of medium density species.

Mechanical Properties

The results of the mechanical properties of *Acacia melanoxylon* along with the three stem height in green and at 12% moisture content (MC) conditions are presented in Table 2 and

Table 3 respectively. Table 4 and Table 5 show the statistical analysis of the mechanical properties in green and at 12% MC conditions tested specimens respectively.

Static bending

Modulus of elasticity

Modulus of elasticity is the stress at elastic limit. The mean values of modulus of elasticity (MOE) along the three stem height in green and at 12%MC conditions are shown in Table 2 and Table 3. The Analysis of variance revealed that the tree height and the interaction between tree height and heartwood-sapwood had significant effects on MOE in the case of both MC conditions at $P<0.05$ (Table 4 and Table 5). However, it didn’t show significant difference between the heartwood and sapwood at $P<0.05$ (Table 4 and Table 5). The results showed that in the case of both MC conditions, the highest values of MOE found at the base of the stem and decreased from the base towards the tip along with the stem height (Table 2 and Table 3). A similar pattern to this finding was reported for *Albizzia julibrissin* species (Kiaei and Farsi, 2016) grown in Iran.This result is similar to the trend of variation of wood density of the species. As reported by different scholars (Panshin and de Zeeuw, 1980; Nicholas and Brown, 2002) density was significantly correlated with the mechanical properties of wood. This noted that the density of the species can predict the values of mechanical properties of the species.

Table 2: The means and standard deviation values of density and mechanical properties in green basis at the bottom, middle and top of *A. melanoxylon* tree

Tested properties	n	Bottom	Middle	Top
Density (kg/m^3)	90	727.57±46.05^{a}	682.28±25.78^{b}	675.00±45.12^{b}
MOE (N/mm^2)	90	9655.40±1203.86^{b}	9129.90±1074.59^{ab}	8963.91±1090.29^{a}
MOR (N/mm^2)	90	72.73±8.79^{b}	69.25±8.03^{ab}	66.49±9.57^{a}
MCS (N/mm^2)	90	35.69±7.13^{b}	34.44±5.83^{b}	31.7483±6.56^{a}
Sp.Im.Re. (Nm/m^2)	90	10055.2±1703.51^{b}	9450.00±1855.96^{b}	9054.20±1261.88^{a}
H. tangential (N)	90	3932.33±605.28^{b}	3659.3±466.39^{a}	3570.0±387.51^{a}
Hardness radial (N)	90	3998.0±611.59^{b}	3861.7±483.92^{b}	3617.7±384.59^{a}

Note: Means having the same Superscript letters across the rows were not significantly different at $P<0.05$.Where, MOE: modulus of elasticity, MOR: modulus of rupture, MCS: Maximum compression strength, Sp.Im.Re: Specific impact resistance, T. hardness: Tangential hardness, R. hardness: Radial hardness and n: is the number of specimens.

The result shows that the bottom portion of *A. melanoxylon* had more stiffness than mid and top portions. According to Langum *et al*. (2009), the main factors leading to decreasing stiffness are low density, short fibers, thinner cell walls, and higher microfibril angles in juvenile wood and conversely, it is the reverse in matured wood. Desch (1986) reported that the greater the MOE, the stiffer the timber and conversely, the lower the MOE, the more flexible the timber will be. The mechanical properties are also affected by the presence of knots, spiral grain, relative humidity and temperature (Huang *et al*., 2003). An important element of wood quality is that of stiffness or its modulus of elasticity (Kollman and Côté, 1968). The end-use of wood material, especially for structural timber is strongly related to the modulus of elasticity.

The modulus of elasticity (MOE) for the heartwood (13863.17 and 9400.50 N/mm^2) was slightly higher than the sapwood (13479.62 and 9098.92 N/mm^2) for green and at 12% MC conditions, respectively (Fig. 5). According to Machado *et al*. (2014), the value of MOE decreases from 50% (heartwood) to 90% (sapwood) along with radial positions of *A. melanoxylon*. The finding is also in agreement with hardwood ssuch as Oak species (Merela and Cufar, 2013) andSilkwood (*Albizzia julibrissin*) (Kiaei and Farsi, 2016). For example, the heartwood and sapwood of silkwood had MOE values of 5530 and 4800 N/mm^2, respectively. The difference values of MOE of heartwood and sapwood are related to the chemical properties in heartwood and sapwood. A significant amount of extractives are deposited in the heartwood, up to two or three times more than in sapwood (Panshin and de Zeeuw, 1980).

Table 3: The means and standard deviation values of density and mechanical properties at 12% MC from bottom, middle and top of *A. melanoxylon* tree

Tested properties	n	Bottom	Middle	Top

Density (g/cm^{3})	90	648.64±37.10^{a}	591.00±32.94^{b}	590.00±41.71^{b}
MOE (N/mm^{2})	90	14155.30±1524.14^{b}	13643.20±1395.79^{ab}	13215.50±1507.49^{a}
MOR (N/mm^{2})	90	152.10±13.10^{b}	147.91±8.35^{ab}	143.94±13.05^{a}
MCS (N/mm^{2})	90	65.41±6.61^{b}	62.01±7.05^{a}	60.71±6.50^{a}
Sp.Im.Re (Nm/m^{2})	90	10398.21±1299.11^{b}	9655.80±1726.71^{a}	9589.20±1764.32^{a}
H. tangential (N)	90	5664.70±722.30^{b}	5333.00±611.15^{b}	5121.70±866.55^{a}
H. radial (N)	90	5665.00±536.37^{b}	5321.00±530.49^{a}	5260.30±661.23^{a}

Note: Means having the same Superscript letters across the rows were not significantly different at $P<0.05$. Where, MOE: modulus of elasticity, MOR: modulus of rupture, MCS: Maximum compression strength, Sp.Im.Re: Specific impact resistance, T. hardness: Tangential hardness, R. hardness: Radial hardness and n: is the number of specimens.

Table 4: Summary of ANOVA at green density and mechanical properties of *A. melanoxylon* timber

Source of		Mean-square and statistical significances						
variation	DF	Density (g/cm^{3})	MOE (N/mm^{2})	MOR (N/mm^{2})	MCS (N/mm^{2})	Sp. Im. Re (Nm/m^{2})	T. hardness (N)	R. hardness (N)
Height (H)	2	24343.79*	3909024.63*	292.96*	121.80*	6039583.33*	1068974.44*	1113881.11*
Section (S)	1	3187.06ns	2046989.37ns	118.38ns	132.06ns	3258506.94ns	938401.11ns	693444.44ns
HxS	2	3098.87ns	4345263.35*	616.72*	646.43*	9323000.21*	382987.78ns	32347.33ns

Note: ns-not significant at $p<0.05$,*-significant at $p<0.05$, **-highly significant at $P<0.01$. Where, MOE: modulus of elasticity, MOR: modulus of rupture, MCS: Maximum compression strength, Sp.Im.Re: Specific impact resistance, T. hardness: Tangential hardness, R. hardness: Radial hardness and DF: degree of freedom.

Table 5: Summary of ANOVA at 12% MC of density and mechanical properties of *A. melanoxylon*

Source of		Mean square and statistical significances						
Variation	DF	Density	MOE	MOR	MCS	Sp. Im. Re	T. hardness	R. hardness

		(g/cm^3)	(N/mm^2)	(N/mm^2)	(N/mm^2)	(Nm/m^2)	(N)	(N)
Height (H)	2	34090.42*	6652744.23*	498.53*	176.414*	7614925.21*	2247567.78*	1428857.78*
Section (S)	1	2117.70ns	3324087.49ns	161.36ns	39.64ns	7504179.39ns	932284.44ns	646854.44ns
HxS	2	3091.73ns	6585587.32*	312.23ns	144.28*	52659827*	1219687.78ns	695551.11ns

Note: ns-not significant at $p<0.05$,*-significant at $p<0.05$, **-highly significant at $P<0.01$. Where, MOE: modulus of elasticity, MOR: modulus of rupture, MCS: Maximum compression strength, Sp.Im.Re: Specific impact resistance, T. hardness: Tangential hardness, R. hardness: Radial hardness and DF: degree of freedom.

The overall mean values of MOE in green and at 12% MC conditions were 9249.70 and 13671.89 N/mm^2, respectively. The analysis of variance showed that MOE was significantly different between the green and at 12% MC condition tested specimens (Fig. 5) of *A. melanoxylon* timber. The overall mean value of this finding was greater than the mean values of MOE tested at 12% MC (13,000 N/mm^2) and less than in green condition (13,000 N/mm^2) for this species elsewhere (Bootle, 1983). Igartùa *et al*. (2015) reported less value of MOE in 12% MC condition (10,900 N/mm^2). Less value of MOE in green and air-dry conditions (11781.9 and 14124.5 N/mm^2) respectively also reported for this species (Chudnoff, 1980). However, another study on the same species reported higher MOE values (9095 and 14400 N/mm^2 respectively) in green and air-dry conditions (Haslett, 1986) than the current study.

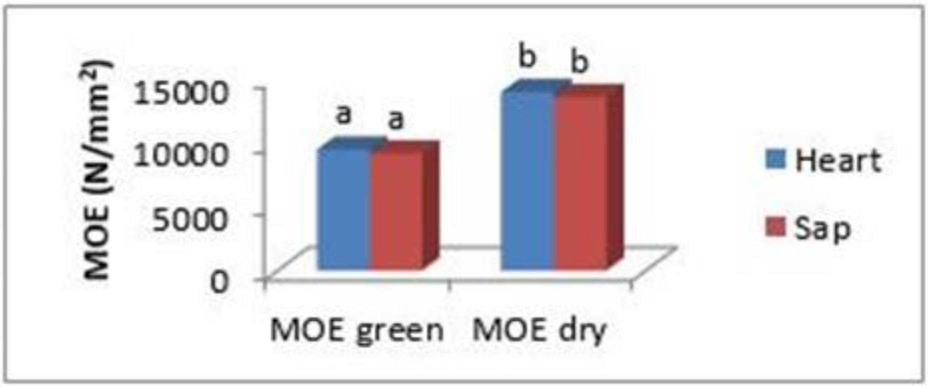

Figure 5: The variation of MOE between heart-sapwood and between green-dry conditions of *A. melanoxylon*timber.

Note: Means having different letters were significant difference between green and dry conditions of MOE at $P<0.05$.

In comparison with other Acacia species, the findings were greater than the values of MOE of *Acacia mangium* and *Acacia auriculiformis* tested at 12% MC (9992 and 8214 N/mm^2), respectively (Jusoh*et al*., 2014). However, values greater than this finding were reported for MOE tested in green and air-dry conditions (14300 and 19700 N/mm^2), respectively for *Acacia schafneri* (Machuca-Valesco *et al*., 2017) and also for *Acacia deccurens* tested at 12 % MC (14310 N/mm^2)(Desalegn *et al*., 2012). In relation to commercially known timber species in the country, the MOE of A. melanoxylon was greater than *Cordia africana* (6996 N/mm^2), *Cupressus lusitanica* (6145 N/mm^2), *E. globulus* (11655 N/mm^2) and *Prunus africana* (12070 N/mm^2) (Desalegn *et al*., 2012, 2015).

Modulus of Rupture

The mean values of Modulus of rupture (MOR) along the three portions in green and at 12% moisture content conditions are shown in Table 2 and Table 3. The analysis of variance showed that the tree height had significant effects on the modulus of rupture (MOR) along with the stem height ($P< 0.05$) for both MC conditions (Table 4 and Table 5). However, there was no stastically significant difference between the heartwood and sapwood for both MC conditions (Table 4 and Table 5). The results revealed that MOR showed a decreasing trend from the base towards the tip of the tree in both MC conditions (Table 2 and 3) and this is similar to the trend of variation of wood density of the species. Similar variation to this finding was reported for Persian wood (*Albizzia julibrissin*) (Kiaei and Farsi, 2016) grown in Iran. The decreasing values of MOR along the tree height from bottom to top might be due to maturity at the base and juvenility at the tip of the tree. A higher value for MOR indicates a greater strength (Desch, 1981).

The mean values of modulus of rupture (MOR) of heartwood (70.64 and 149.63 N/mm^2) was slightly higher than the corresponding sapwood (68.34 and 146.78 N/mm^2)) in both green and at 12% MC conditions of *A. melanoxylon* timber, respectively and this might be influenced by the presence of extractive materials found in the heartwood. According to Machado *et al*. (2014), the MOR decreased from 50% (heartwood) to 90% (sapwood) along the radial direction of *A. melanoxylon* timber. Similar patterns to this finding also reported for *Pseudolachnostylis maprounaefolia* (Uetimane and Ali, 2010) and for Persian Silkwood (Kiaei and Farsi, 2016). According to the report of Haygreen and Bowyer (1996), the heartwood has a higher concentration of extractives and infiltration materials than the sapwood; therefore, the density and strength property of heartwood is often slightly higher than that of sapwood.

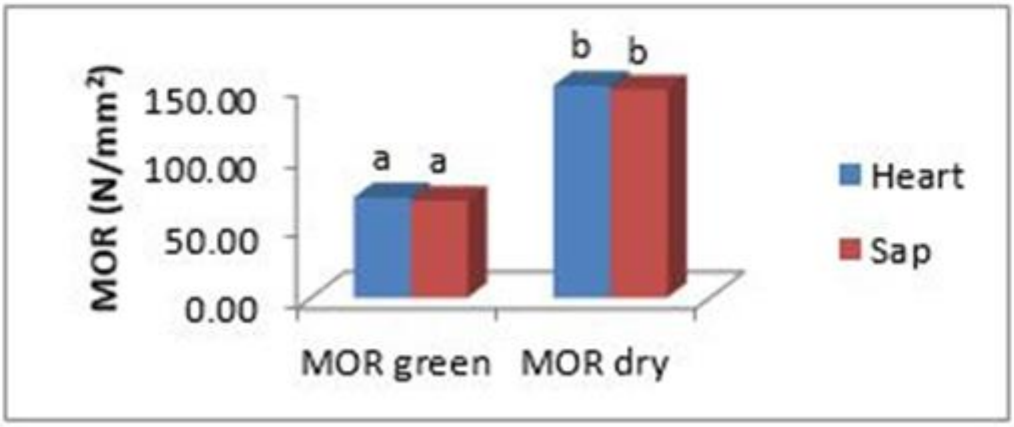

Figure 6: The variation of MOR between heart-sapwood and between green-dry conditions of *A. melanoxylon* timber.

Note: Means having different letters were significant difference between green and dry conditions of MOR at P<0.05.

The overall mean values of Modulus of rupture (MOR) in green and at 12% MC conditions were 147.98 N/mm^2 and 69.49 N/mm^2 with a standard deviation of 12.05 N/mm^2 and 9.09 N/mm^2 respectively. Figure 6 depicted that there was marked difference of MOR between the green and at 12% MC condition tested of *Acacia melanoxylon* tree.

The overall mean values of MOR tested at 12% MC condition was greater than the MOR values reported for the same species: 89.9 N/mm^2 by Igartûa *et al*. (2015), 139 N/mm^2 by Machado *et al*. (2014) and 129.9 N/mm^2 by Haslett (1986). When compared with other Acacia species this finding was greater than reported by Jusoh *et al*. (2014), for *A. mangium* and *A. auriculiformis* (78 and 89 N/mm^2), respectively. In relation to commercially known and endangered tree species in the country, the result was greater than that of *Cordia africana* (64 N/mm^2), *Cupressus lusitanica* (64 N/mm^2) and *Juniperus procera* (87 N/mm^2) tested at 12% MC (Desalegn *et al*., 2015).

Static bending tests, including MOR and MOE, indicated that *A. melanoxylon* can be a useful material for building construction. The MOR and MOE values are used to characterize the strength of beams, joists, rafters, table tops, chair bottoms, trusses, furniture and timbers subjected to transverse bending (Desalegn *et al*., 2012).

Compression Parallel to the grain

Compression parallel to grain (crushing strength) determines load a beam will vertically carry. The mean values of maximum crushing strength (MCS) along with the three stem height tested in green and at 12% MC conditions are shown in Table 2 and Table 3. The analysis of variance revealed that the stem height had significant effects on MCS in both green and at 12% MC conditions of *A. melanoxylon* timber ($P<0.05$) (Table 4 and Table 5). However, no significant difference was observed along radial direction i.e. between heartwood and sapwood ($p<0.05$) (Table 4 and 5). In the case of both moisture conditions, the MCS showed a decreasing trend from the bottom towards the top of the tree height as tabulated in Table 2 and Table 3. This might be due to maturity at the base and juvenility at the tip of the tree height. Similar patterns were reported by Izekor *et al*. (2010) in which a decreasing trend from base to tip in compression parallel to the grain of *Tectona grandis* timber was observed. Similarl results were reported for Oriental beech and Caucasian fir species (Topaloglu and Erisir, 2018).

In contrast to this finding, Machado *et al*. (2014) reported that the compression parallel to the grain of *A. melanoxylon* grown in Portugal increases with tree stem height especially from 35% to 65% of tree height. This indicates that most hardwood species have no common trend variations along with the stem height of the trees.

The maximum crushing strength (MCS) of this finding follows a similar declining trend of the density along with the stem height. Density has usually a significant correlation with compression strength (Gindl and Teischinger, 2002). Desalegn *et al*. (2012) reported that wood with high strength in MCS is suitable for timber used as columns, props, posts, and spokes.

The MCS of heartwood (34.73 and 63.73 N/mm^2) was slightly higher than sapwood (33.26 and 62.23 N/mm^2) in green and at 12% MC conditions respectively. According to Machado *et al*. (2014), the MCS of *A. melanoxylon* timber decreased from 50% (heartwood) to the 90% (sapwood) radial direction. This difference between the heartwood and sapwood can be attributed to the higher ethanol extractive content in the heartwood than the sapwood

(Aguilera and Zamora, 2009). In addition, Haygreen and Bowyer (1996) report indicated that a considerable amount of infiltrated material may somewhat increase the weight of wood and its resistance to crushing.

The overallmean values of MCS in green and at 12% MC conditions were (33.96 and 62.71 N/mm^2) with a standard deviation of (6.67 and 6.94 N/mm^2), respectively. There was a significant difference on maximum crushing strength between green and air-dried to 12% MC (Fig. 7).

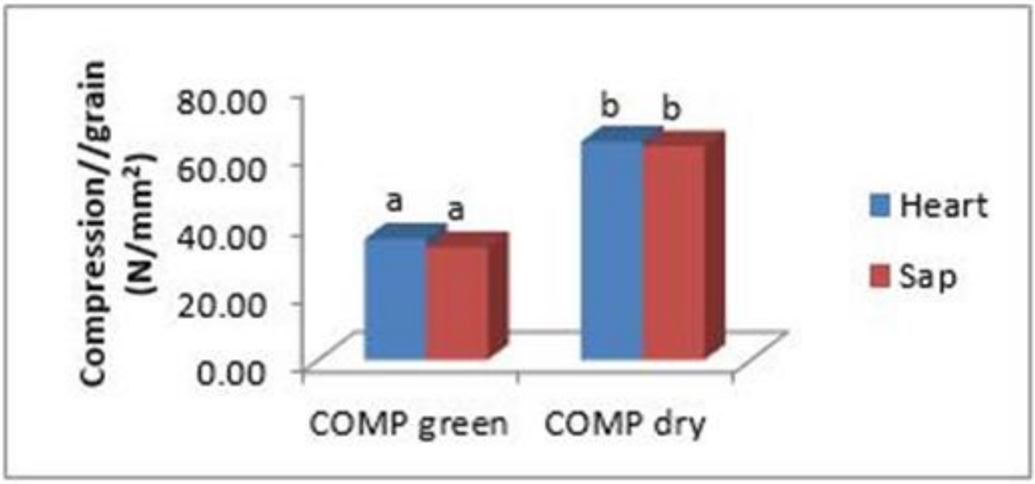

Figure 7: The variation of MCS between heart-sapwood and between green and dry conditions of *A. melanoxylon* timber. Where, COMP is compression//to grain

Note: Means having different letters were significant difference between green and dry conditions of COMP at $P<0.05$.

The overall mean values of MCS obtained in this study were comparable with other study reported by Haslett (1986) for the same species with the values of MCS of 29.4 and 62.5N/mm^2 for green and air-dry conditions, respectively. Similarly, Machado *et al*., (2014) reported that the value for MCS was 61 N/mm^2 for the same species in 12% MC condition. . However, the findings were greater than the values (33 and 48N/mm^2) reported by Bootle, (1983) in green and air-dry conditions, respectively. In comparison with other acacia species, the MCS values of *A. melanoxylon* timber in green and air-dry conditions were less than figures reported (40.8 and 85.8N/mm^2) for *Acacia schaffneri* (Machuca-Velasco *et al*., 2017) and less than that of *A. decurrens* (85 N/mm^2) in air-dry condition (Desalegn*et al*., 2012).

In relation to commercially known and endangered tree species in the country tested in air-dry condition, the MCS (62.71 N/mm^2) was higher than that of *Juniperus procera* (38 N/mm^2), *Cordia africana* (29 N/mm^2), *E. globulus* (52 N/mm^2) and *E. grandis* (45 N/mm^2) (Desalegn *et al*., 2012; Desalegn *et al*., 2015). Based on the classification, compression parallel to the grain was in the interval of high maximum crushing strength and used for short columns, trusts, chair legs, blocks, pillars, roof rafters and pit-props.

Impact bending

Impact bending is the resistance offered by wood specimens to sudden shocks.The mean values of impact bending in green and at 12% MC conditions tested specimens along the three stem heights are shown in Table 2 and Table 3, respectively.The statistical analysis revealed that the tree height had significant effects on specific impact resistance in both green and at 12% MC conditions (Table 4 and Table 5). There was nosignificant difference between heartwood and sapwood in both green and dryconditions (Table 4 and 5). The result showed that the highest value of impact resistance was observed at the base and decreased from the bottom towards top of the tree height. Similar variation to this finding was reported for Black locust (*Robinia pseudoacacia*) (Adamopoulos *et al*., 2007).This is also similar to other mechanical properties affected by the proportion of early wood and late wood along with the stem height of the sample species. This variability may also be influenced by a combination of several other factors, including the inherent variability within trees (Harzman and Koch, 1982), growth and environmental conditions and presence of high extractive contents (Tsoumis, 1991).

The results revealed that the mean values of specific impact resistance of heartwood (10071.11 and 9808.8 Nm/m^2) was to some extent higher than that of the sapwood (9690.6 and 9230.8 Nm/m^2) for green and at 12% MC conditions, respectively. Aguilera and Zamora (2009), reported that *A. melanoxylon* tree density of heartwood (0.583 to 0.987 g/cm^3) is higher than sapwood (0.494 to 0.740 g/cm^3). This denotes that the heartwood is stronger than sapwood because density and strength properties of *A. melanoxylon* are significantly correlated (Nicholas and Brown, 2002). The overall mean values of specific impact resistance in green and at 12% MC conditions tested were 9880.81 and 9519.6 Nm/m^2 with standard deviations of 1654.46 and 1660.71 Nm/m^2, respectively. The analysis of variance revealed that there was no significant difference between green and at 12% MC condition tested of specific impact resistance (Fig. 8). The impact resistance may be influenced by the moisture content of the specimens. . Comparable results were reportedfor *E. globulus, E. grandis* and *E. camaladulensis* (Desalegn and Gezahegn, 2010).

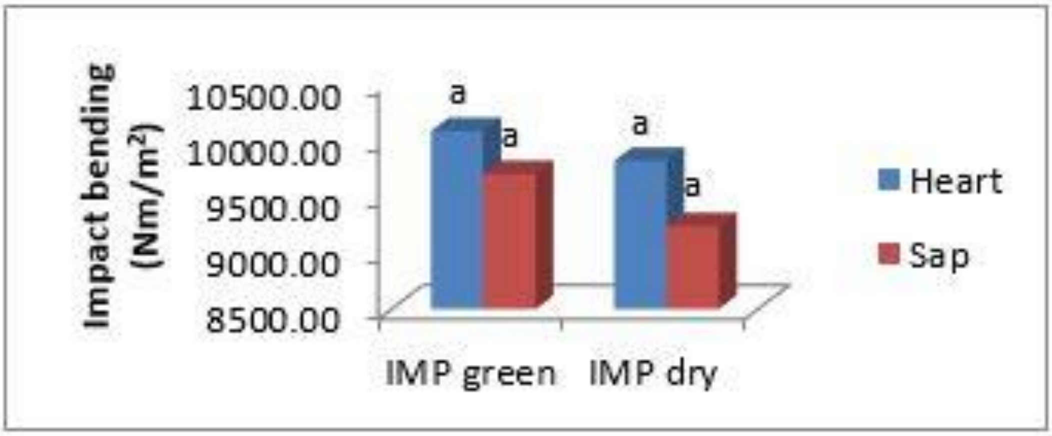

Figure 8: The variation of impact bending between heart-sapwood and between green-dry conditions of A. melanoxylontimber. Where, IMP is impact bending

Means having the same letters were insignificant difference between green and dry conditions of IMP at $P<0.05$.

The average value obtained in dry conditions was greater than that of *A. decurrens* (7313 Nm/m^2) (Desalegn*et al*., 2012), *Cupressus lustanica* (5888 Nm/m^2) and *Pinus patula* (5187 Nm/m^2) but it was less than values reported for *E. saligna* (12873 Nm/m^2) and *Grevillea robusta* (18094 Nm/m^2) by Desalegn *et al*., (2012 and 2015).

Hardness

The mean values of hardness in tangential and radial direction in green and at 12% MC conditions along the tree height of the tree were summarized in Table 2 and Table 3 with other tested mechanical properties of these findings. The ANOVA table (Table 4 and Table 5) revealed that the tree height had significant effects on hardness tangential and radial for both in green and at 12% MC conditions ($P<0.05$). However, no significant difference was observed along the radial direction i.e. between heartwood and sapwood for both MC conditions (Table 4 and Table 5). The mean values of hardness tested in both directions showed that a decreasing trend from the base towards the top of the stem height (Table 2 and 3) in green and at 12% MC conditions respectively. The variation with the tree height might be due to the fact that bottom log of the same tree has more mature-wood than the top log which consists mainly of juvenile wood (Panshin and de Zeeuw, 1980). The overall mean values of hardness were 3720.64N and 5373.10N in tangential) and 3825.80 N and 5415.40N in radial directions in green and at 12% MC conditions, respectively. There was a significant difference observed between green and air-dry conditions for both hardness tested in a tangential and radial directions (Fig. 9).

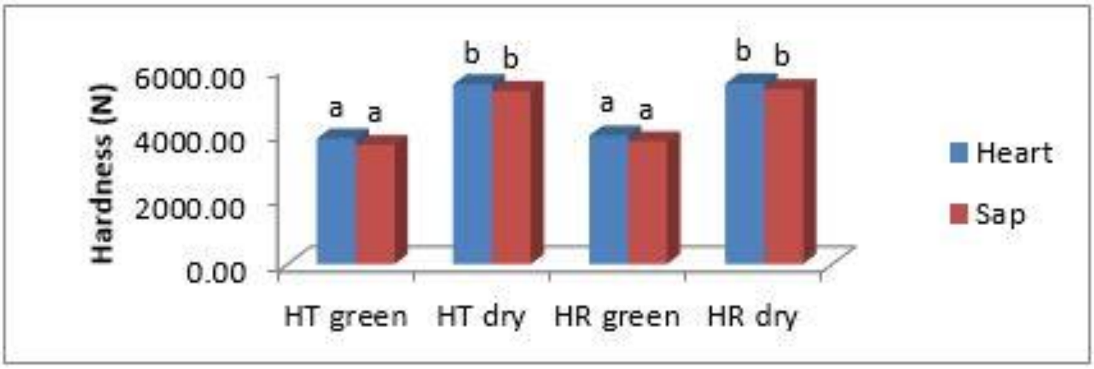

Figure 9: The variation of hardness between heart-sapwood and between green-dry conditions of A. melanoxylontimber. Where, HT: hardness in tangential and HR: hardness in radial direction

Means having defferent letters were significant deifference between green and dry conditions of HT and HR at P<0.05.

The results showed that the mean values of hardness (tangential and radial) in heartwood were slightly higher than sapwood in both green and at 12% MC conditions. Similar patterns reported for hardwoods of White and Red Oak species at 12% MC conditions (Merela and Cufar, 2013). Mmolotsi and Kejekgabo (2013) reported significant differences in wood density between the heartwood and sapwood found in *Acacia burkea* and *Spirostachys africanum* species.

The overall mean value of hardness in air-dry conditions was less than the value (5900 N) reported by Bootle, (1983) and that of the value (6600 N) reported by Nicholas and Brown (2002) at 12% MC condition for the species. The current value was greater than the value (3600 N) reported for *A. deccurens*, *Cuprussus lustanica* (2761 N) and *Pinus patula* (2179 N) (Desalegn*et al*., 2015) in air-dry condition.

Conclusions and Recommendations

- Several wood properties of *Acacia melanoxylon* in green and air-dry conditions was investigated for assessing the potential of the species for various utilizations. The density and all tested mechanical properties were affected by tree height in both green and air-dry conditions. However, in green and air-dry conditions, the heartwood and sapwood didn't affect the density and mechanical properties of the timber. The interaction effect of tree height and heartwood-sapwood had significant effect on MOE, MCS and impact bending in the case of both moisture conditions.
- In both moisture conditions, the highest values of density and mechanical properties were observed at the base and lowest at the top of *Acacia melanoxylon* timber.This denoted that the bottom portion has strongest than the middle and top portions of the tree.
- The heartwood density and mechanical properties were slightly higher than the sapwood.
- Because the overall mechanical properties get greatly enhanced at 12% MC conditions, the wood materials should be properly seasoned before using.
- *Acacia melanoxylon* timber density and mechanical properties showed that the species belonges to medium to high-density timber species. Therefore, it is suitable for multiple uses that require strength and hardness and can substitute over-utilized native tree species.
- Further studies should be conducted on tensile and shears strength, natural durability, and treatability with preservatives, finishing and working properties of this lesser-known and lesser utilized of *Acaciamelanoxyon* timber species in Ethiopia.

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