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CORRELATION BETWEEN DRY DENSITY AND SHRINKAGE IN EIGHT TROPICAL HARDWOOD SPECIES

ZVEZA MED GOSTOTO IN KRČENJEM LESA OSMIH TROPSKIH VRST

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Abstract / Izvleček

Abstract: Eight tropical hardwood species were assessed for their density and radial, tangential and volumetric shrinkage, after which the relation between the density and different shrinkages was checked through correlation and regression. The results showed that the highest mean density was observed in *Milicia excelsa* with 900.63±50.13 kg/m³, followed by *Afzelia africana*, *Nesogordonia kabingaensis* and *Nauclea diderichii* with 831.25±41.67 kg/m³, 808.75±20.88 kg/m³ and 801.88±46.40 kg/m³, respectively. The mean density for *Cassia simea* was 781.88±27.71 kg/m³, *Mansonia altissima* 593.13±65.98 kg/m³, and *Sterculia tragacantha* 481.25±111.73 kg/m³, while the least density was observed in *Treculia africana* with 463.75±67.88 kg/m³. The highest volumetric shrinkage was observed in *Nesogordonia kabingaensis* with 14.71±2.28%, and the least in *Cassia simea* with 5.11±2.65%. It is concluded that there exists positive but weak correlation between density and the shrinkages in the eight tropical hardwood species.

Keywords: wood, topical hardwoods, density, shrinkage

Izvleček: V raziskavi ocenjujemo zvezo med gostoto in krčenjem za osem tropskih lesnih vrst. Raziskali smo gostoto ter radialno, tangencialno in prostorninsko krčenje osmih tropskih lesnih vrst. Rezultati so pokazali, da je imela največjo povprečno gostoto vrsta *Milicia excelsa* z 900,63±50,13 kg/m³, sledijo *Afzelia africana*, *Nesogordonia kabingaensis* in *Nauclea diderichii* z 831,25±41,67 kg/m³, 808,75±20,88 kg/m³ in 801,88±46,40 kg /m³. Povprečna gostota za vrste *Cassia simea* je bila 781,88±27,71 kg/m³, *Mansonia altissima* 593,13±65,98 kg/m³, *Sterculia tragacantha* 481,25±111,73 kg/m³, medtem ko je bila najmanjša gostota opažena pri vrsti *Treculia africana* s 463,75±67,88 kg/m³. Največje prostorninsko krčenje je bilo zaznano pri vrsti *Nesogordonia kabingaensis* (14,71 ± 2,28 %), najmanjše pa pri vrsti *Cassia simea* (5,11 ± 2,65 %). Ugotavljamo, da obstaja šibka pozitivna korelacija med gostoto in krčenjem pri osmih tropskih vrstah listavcev.

Ključne besede: les, tropski listavci, gostota, krčenje

1 INTRODUCTION
1 UVOD

Water is a natural constituent of a living tree, and it commonly makes up over half the total weight; that is, the weight of water in green wood is commonly equal to or greater than the weight of the dry wood substance (Haygreen & Bower, 1996).

It is well known that wood is an anisotropic material which presents differential dimensional changes in the different structural directions. The magnitude of shrinkage and swelling is affected by the amount of moisture gained or lost by wood when the moisture content fluctuates between zero and the fibre saturation point (Usta & Guray, 2000).

Shrinking and swelling occur as the wood changes moisture content in response to daily as well as seasonal changes in the relative humidity of the atmosphere. That is, when the air is humid wood adsorbs moisture and swells, while when the

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air is dry, wood loses moisture and shrinks. Various finishes and treatments may be used to slow this process, but, in general, they do not stop it (Eckelman, 2012). Likewise, air and kiln drying do not prevent the wood from subsequently gaining or losing moisture. Thus, wood that is kiln dried to 6% moisture content and stored in a dry shed outdoors in a temperate climate, such as that found in Indiana, USA, will regain moisture until it eventually reaches about 12% moisture content. Under the same conditions in a tropical climate, the wood will come to a moisture content of about 16%. The resulting dimensional changes in the wood are a major source of defects in furniture and other wood structures (Ojo et al., 2016).

The changes in wood dimensions as a result of its shrinkage as it dries and swelling during moisture absorption are of great importance to anyone who uses wood, because wood readily takes on or gives off moisture, even from the atmosphere. When wood loses moisture below fibre saturation point (FSP), it shrinks and swells when water is absorbed. The percentage change in wood dimensions as a result of moisture loss is termed shrinkage (Dinwoodie, 1989). The observed changes in wood dimensions as a result of shrinkage are unequal along the three structural directions. This behaviour of wood has been documented widely by various authors (Panshin & de Zeeuw, 1980; Lausberg et al., 1995; Ogunsanwo, 2000; Ojo et al., 2016).

However, Panshin and de Zeeuw (1980), noted that the geometric disposition of cells along the principal directions is mainly responsible for this observation.

The moisture content is the water contained in wood and it is a natural constituent of all parts of a living tree and makes up about half of the total weight (Hossain et al., 1991). Desch and Dinwoodie (1983), reported that timber of living trees and freshly felled logs contains a large amount of water which has a profound influence on the properties of wood, such as weight and strength. Wood is also liable to attack by some insects and fungi when the moisture content is high.

Density is the amount of wood substance per unit volume. Panshin and de Zeeuw (1980), Dinwoodie (1981), and Desch (1988), explained that the density of wood is a function of the cell wall thickness and also depends on the level of cell wall development.

In research activities, densities are frequently reported on an oven-dry weight and volume basis. At any other condition the moisture content has a marked effect on density (Kellog, 1981). As the moisture content increases from the oven-dry condition up to fibre saturation point, the weight increases and as a result of swelling so does the volume (Kellog, 1981). Meanwhile, high density is associated with thick fibre walls and a higher proportion of fibres. These are the qualities which contribute to water absorption and resultant dimensional changes (Shrivastava, 1997). It is therefore necessary to ascertain that in the absence of any other data about the dimensional stability of a particular species, wood density is used as a guide to its utilization by establishing the relationship between the density and dimensional stability of some tropical hard wood species so as to serve as guide for their general technical application.

The eight tropical timbers assessed in this study are as follows: *Nauclea diderrichii* (African peach; opepe) is an evergreen tree that reaches a height of about 30-40 m and a diameter of 0.9-1.5 m; bole cylindrical, slender, straight and branchless, rising to 20-30 m and a broad spherical crown with thick foliage (Orwa, 2009).

It is a commercial timber of West Africa. The wood is yellow and darkens slightly when exposed to light. It is semi-heavy and of medium hardness. Because of its good mechanical properties and natural durability, which can be enhanced by preservative treatment, it is sought after as a timber for outdoor uses (harbour works, railway sleepers), buildings (carpentry, floors, facings, indoor and outdoor woodwork) and for cabinet making. The wood is also suitable for fence posts and bridges as it is moderately termite-resistant and resistant to fungi and marine borers (Orwa, 2009).

The wood is strong and moderately hard to hard. At 12% moisture content the modulus of rupture is 85–166 N/mm², modulus of elasticity 10,490–14,660 N/mm², compression parallel to grain 52–78 N/mm², shear 8.5–17 N/mm², cleavage (7–)12–24 N/mm, Janka side hardness 5790–7260 N, Janka end hardness 7140–9160 N and Chalais-Meudon side hardness 3.0–8.6. (Protabase, 2010).

Milicia excelsa (African teak; iroko) is large deciduous tree, growing up to 50 m high and 350 cm in trunk diameter. The trunk is often buttressed and can be branchless for up to 20 m (Barwick, 2004). The heartwood is pale yellow to yellow, darkening on exposure to yellowish or greenish brown or sometimes to chocolate brown. The wood is somewhat greasy and is odourless (Protabase, 2022).

The wood is of medium weight, moderately hard, of good durability, being resistant to fungi, dry wood borers and termites. The wood is a highly valued commercial timber in Africa, for which demand is also high. It is used for construction work, shipbuilding and marine carpentry, sleepers, sluice gates, framework, trucks, draining boards, outdoor and indoor joinery, stairs, doors, frames, garden furniture, cabinet work, panelling, flooring and profile boards for decorative and structural uses. It is also used for carving, domestic utensils, musical instruments and toys. As it is resistant to acids and bases, it is used for tanks and barrels for food and chemical products and for laboratory benches. It is used as sliced veneer but only rarely as rotary veneer. The wood is also used as firewood and for making charcoal (Protabase, 2022). At 12% moisture content, the modulus of rupture is 75–156 N/mm², modulus of elasticity 8300–13,300 N/mm², compression parallel to grain 42–65 N/mm², shear 5.4–14.1 N/mm², cleavage 10.3–20.9 N/mm, Janka side hardness 4400–5610 N, and Janka end hardness 5360–6640 N (Protabase, 2010).

Afzelia africana (afzelia) is an evergreen, small to fairly large tree up to 40 m tall; bole branchless for up to 20 m, usually straight and cylindrical, up to 150(–200) cm in diameter. Like other *Afzelia* spp., the wood of *Afzelia africana* is characterized by excellent stability with little susceptibility to variations in humidity and a good natural durability. The wood is durable and treatment with preservatives is unnecessary, even for usage in permanently humid conditions or in localities where wood-attacking insects are abundant. This makes it an excellent wood for use in pleasure-crafts, especially for keels, stems and panels, for bridges, as well as interior fittings. The wood is also valued for joinery and panelling, both interior and exterior, parquet floors, doors, frames, stairs, furniture and sporting goods. The wood is also used as firewood and for charcoal production (Gerard & Louppe, 2011).

The heartwood is orange-brown to golden brown, becoming red-brown upon prolonged exposure, sometimes with darker streaks. It is distinctly demarcated from the whitish to pale yellow, up to 8 cm wide sapwood. At 12% moisture content, the modulus of rupture is 105–145(–200) N/mm², modulus of elasticity (9100–)14,000–17,000 N/mm², compression parallel to grain 57–85 N/mm² (Gerard & Louppe, 2011).

Cassia siamea (*Senna siamea*; yellow casia; kassod tree) is large-sized tree species, with a height up to 20-25 m, diameter 50-60 cm. Its stem is cylindrical, twisted. The bark is grey, with regular small and narrow cracks, sometimes segments are formed due to the stem twisting at some points. (SSR-VINA, 2022). Sapwood and heartwood have different colours; sapwood is pale yellow, heartwood got yellowish-brown to blackish brown. *Senna siamea* wood can be used for structures requiring high durability in construction, and transport (SSR-VINA, 2022).

The pressure strength along the grain is 615kg/cm², the static bending strength is 1520kg/cm², splitting strength is 20kg/cm, collision bending is 0.64, Janka hardness 1,490 lbf (6,640 N), modulus of rupture 12,440 lbf/in2 (85.8 MPa), elastic modulus 1,581,000 lbf/in2 (10.90 GPa), crushing strength 10,150 lbf/in2 (70.0 MPa) (Wood database, 2018).

Mansonia altissima (African black walnut; African walnut) is an evergreen medium-sized to fairly large tree up to 45 m tall; bole branchless for up to 30 m, up to 100(–150) cm in diameter, generally straight, cylindrical. The wood is used for general and high-quality joinery, cabinet work, furniture, turnery, decorative veneer and handicrafts. It is also used in construction for doors and windows, in railway coaches and shop fittings, and for boxes and crates (Ohene-Coffie, 2008).

The heartwood is yellowish brown to dark grey-brown or even dark brown, often with purple, reddish or greyish green streaks, often in alternating light and dark bands. It fades on exposure to a somewhat dull brown. It is distinctly demarcated from the 2–4(–6) cm wide, white to pinkish sapwood. The grain is usually straight and the texture fine. The wood is moderately lustrous (Ohene-Coffie, 2008). At 12% moisture content the modulus of rupture is (61–)114–177(–183) N/mm², modulus of elasticity 9320–12,800 N/mm², compression parallel to grain 43–68(–96) N/mm², shear 6–15 N/mm², cleavage 9–23 N/mm, Janka side hardness 5690–7470 N and Janka end hardness 5740–7470 N (Protabase, 2010).

Treculia africana (African breadfruit) is a large, slow-growing, evergreen tree with a dense, spreading crown; usually growing 15–30 m tall but with some specimens up to 50 m. The bole is fluted. It is a very valuable food crop in Africa, providing a nutritious protein and oil rich food. It is thus often grown in and around African villages where it is commonly harvested for its edible seeds, which are sold in local markets. Trees are often protected when land is cleared for agriculture (Ken Fern, 2022).

The heartwood is yellow with very narrow pale sapwood that is very dense, fairly elastic and flexible, rather heavy, with a fine, even structure. It is suitable for furniture, carving, turnery and inlay wood, as well as for pulp and papermaking. The wood is used for fuel and making charcoal (Ken Fern, 2022). The wood density of the species is 674 kg/m³ (Keay, 1989). The wood is fairly elastic and flexible (Torelli & Čufar, 1995) and has an even structured fine grain, and saws and planes very easily.

Sterculia tragacantha (African tragacanth) is a tree to about 28 m high, the bole sometimes with buttresses, girth up to 1.5 m by 10–15 m long, bearing a crown of pseudo-whorled branches. It used for building materials (made from the bark), fibre (wood), pulp and paper (wood), carpentry and related applications (gum, wood), farming, forestry, hunting and fishing equipment (gum) (Burkill, 1985).

Nesogordonia kabingaensis (danta) is a medium-sized to large tree up to 45(–50) m tall, mostly evergreen but sometimes briefly deciduous. The bole is usually straight and cylindrical, branchless for up to 25 m and 80(–120) cm in diameter, with narrow buttresses up to 3 m high (Oyen, 2005).

The heartwood is pale brown to purplish brown with a tendency to become lighter on exposure to light, distinctly demarcated from the pale brown to pink sapwood, which is 2–5(–10) cm thick. The grain is straight or interlocked, the texture fine. At 12% moisture content the modulus of rupture is 108–183(–231) N/mm², modulus of elasticity (7800–)10,900–16,200 N/mm², compression parallel to grain 45–75 N/mm², shear 8–16 N/mm², and cleavage 13–31 N/mm (Oyen, 2005).

The species *Nauclea diderrichii*, *Mansonia altissima*, *Nesogordonia kabingaensis*, *Cassia simea*, *Afzelia africana* and *Milicia excelsa* are all well known, while *Treculia africana* and *Sterculia tragantha* are less familiar. They grow in the natural forests in Nigeria, and due to the afforestation and reforestation efforts of the government and private individuals a number of plantations of the species are being established. The trees are very important in Nigeria and elsewhere because the woods are hardwood and naturally durable, and thus suitable for various construction purposes.

The general objective of this study is to establish the relationship between the density and shrinkage/swelling of the wood of the selected species, and thus its specific objectives are as follows: determination of density, evaluation of the radial, tangential and volumetric shrinkage of the wood and their correlations with the density.

2 MATERIALS AND METHODS
2 MATERIALI IN METODE

2.1 DETERMINATION OF WOOD DENSITY
2.1 DOLOČANJE GOSTOTE LESA

Two discs, 20 cm long were cut from each of the species at the base and top. Selection of representative samples for test was carried out from the central planks obtained from each of the discs to give 16 planks from where test samples for all the experiments were obtained. Ten samples were collected for each of the species from the bark to the pith resulting in eighty (80) test samples. For the determination of density, test samples of dimensions 20 x 20 x 60 mm were produced from the central planks. The test samples were oven-dried to a constant weight, and the density was thus determined as given below in accordance with the American Standard for Testing Materials (ASTM D) 2395 (1983):

$$D = \frac{M}{V}\left(\frac{kg}{m^3}\right) \tag{1}$$

Where:
D = density
M = weight of the wood
V = volume of wood

2.2 DETERMINATION OF PERCENTAGE SHRINKAGE
2.2 DOLOČANJE KRČENJA

Test specimens of 20 x 20 x 60 mm were produced, which were then properly aligned and denoted 'T' and 'R' for tangential and radial planes, respectively. They were soaked in water for 48 hrs in order to get them conditioned to moisture above the fibre saturation point (FSP). Specimens were removed one after the other, and their dimensions in wet condition were taken to the nearest millimetre with the aid of a vernier calliper. The percentage shrinkages along the two planes were measured after specimens had been oven-dried as

$$S = \frac{D_S - D_O}{D_S} x100 \quad (2)$$

Where:
S = shrinkage %
D_S = dimensions at saturated condition
D_O = dimensions at oven dry condition

Volumetric shrinkage is approximately equal to the sum of radial and tangential shrinkage, as given below:

$$S_v = S_R + S_T \quad (3)$$

Where:
S_V = volumetric shrinkage
S_R = radial shrinkage
S_T = tangential shrinkage

This is in accordance with the approximations done by Dinwoodie (1989).

$$Anisotropy = \frac{S_T}{S_R} \quad (4)$$

2.3 EXPERIMENTAL DESIGN AND DATA ANALYSIS
2.3 EKSPERIMENTALNA ZASNOVA IN ANALIZA PODATKOV

The design adopted for the experiment was a completely randomized design with ten replications each and the data obtained were subjected to analysis of variance (ANOVA), correlation, linear and non-linear regression.

3 RESULTS AND DISCUSSION
3 REZULTATI IN RAZPRAVA

3.1 DENSITY
3.1 GOSTOTA

The highest mean density was observed in *Milicia excelsa* with 900.63±50.13 kg/m³, followed by *Afzelia africana*, *Nesogordonia kabingaensis* and *Nauclea diderichii* with 831.25±41.67 kg/m³, 808.75±20.88 kg/m³ and 801.88±46.40 kg/m³, respectively. The mean density for *Cassia simea* was 781.88±27.71 kg/m³, *Mansonia altissima* 593.13±65.98 kg/m³, and *Sterculia tragacantha* 481.25±111.73 kg/m³, while the least density was observed in *Treculia africana* with 463.75±67.88 kg/m³.

According to Brandon (2005), who classified wood species based on their density (the density of seasoned timber is usually measured for classification purposes at 12% air-dry MC) as follows: exceptionally light – under 300 kg/m³, light – 300 to 450 kg/m³, medium – 450 to 650 kg/m³, heavy – 650 to 800 kg/m³, and very heavy – 800 to 1000+ kg/m³. Based on this classification, *Milicia excelsa*, *Afzelia africana*, *Nesogordonia kabingaensis* and *Nauclea diderichii* are termed very heavy density wood while *Cassia simea* to be heavy and *Mansonia altissima*, *Sterculia tragacantha* and *Treculia africana* have medium density wood (Table 1).

According to Jane (1970), wood from different parts of a tree is noted to show differences in density, and according to Panshin and de Zeeuw (1980) this variation exists horizontally from the pith to the periphery, and vertically from the base to the crown of the tree. According to the United nations Food and Agriculture Organization (1985), timber should be graded hard, intermediate or soft, corresponding to high, medium and low densities. The technical limits between the grades are: high density above 500 kg/m³, medium density between 500

Table 1. Mean values of the parameters from the eight hardwood species; density = oven dry density, ST, SR, SV – tangential, radial and volumetric shrinkage.
Preglednica 1. Povprečne vrednosti parametrov lastnosti lesa za osem tropskih listavcev; density – gostota lesa v absolutno suhem stanju, ST, SR, SV – tangencialni, radialni in prostorninski skrček, anisotropy – anizotropija krčenja.

Species	Density (kg/m³)	S_T (%)	S_R (%)	S_V (%)	Anisotropy
Nauclea diderrichii	801.88^a±46.40	4.44^a±1.42	4.36^a±1.64	8.79^a±1.67	1.32^a±1.00
Mansonia altissima	593.13^c±65.98	3.96^a±1.34	5.20^{ab}±1.74	9.16^a±1.55	0.88^a±0.49
Treculia africana	463.75^b±67.88	3.30^a±1.23	3.91^a±1.49	7.21^{ab}±1.42	1.08^a±0.76
Sterculia tragacantha	481.25^b±111.73	3.92^a±1.59	3.71^a±1.06	7.64^{ab}±0.96	1.24^a±0.71
Nesogordonia kabingaensis	808.75^a±20.88	7.74^b±1.40	6.98^b±1.63	14.71^c±2.28	1.15^a±0.20
Cassia siamea	781.88^a±27.71	3.77^a±3.21	3.65^a±1.56	5.11^b±2.65	2.09^a±0.10
Afzelia africana	831.25^a±41.67	4.30^a±2.01	3.12^a±2.24	7.42^{ab}±3.02	2.01^a±1.57
Milicia excelsa	900.63^d±50.13	4.34^a±0.90	3.98^a±1.02	8.32^a±1.34	1.17^a±0.45

Values with the same letters are not significantly different from one another.
Vrednosti z isto črko niso značilno različne.

and 350 kg/m³, low density less than 350 kg/m³, and only high density timber is acceptable for structural purposes.

Chaffe (1991) reported that high cellulose content in wood is a good indication of high density and low lignin content. Density varies greatly depending on the anatomical structure of the wood.

However, the results of ANOVA show that there is a significant difference among the wood species (Table 2) regarding density. The results of correlation analysis indicated that there was a positive correlation between density and tangential shrinkage (0.236) at a 0.01 level of probability, and a positive but not significant correlation among density, radial shrinkage and volumetric shrinkage (Table 3).

Table 2. Analysis of variance of all parameters.
Preglednica 2. Analiza variance vseh parametrov.

		F-values				
SV	df	density	SR	ST	SV	Anisotropy
Species	7	79.07*	5.8112*	5.9619*	19.756*	0.76ns
Error	72					
Total	79					

* = significant at 0.05 level of probability
ns = not significant at 0.05 level of probability
* = značilno pri stopnji verjetnosti 0,05
ns = ni značilno pri stopnji verjetnosti 0,05

3.2 RADIAL SHRINKAGE
3.2 RADIALNO KRČENJE

The highest mean radial shrinkage was observed in *Nesogordonia kabingaensis* with 6.98±1.63%, followed by *Nauclea diderichii*, *Milicia excelsa* and *Mansonia altissima* with 4.36±1.64%, 3.98±1.02% and 3.96±1.34%, respectively. The mean RS for *Cassia simea* was 3.65±1.56%, *Afzelia africana* 3.12±2.24%, *Sterculia tragacantha* 3.71±1.06% and for *Treculia africana* 3.30±1.23% (Table 1).

Ogunsanwo (2000), in his work on *Triplochiton scleroxylon*, and Choong et al. (1989) as well as Poku et al. (2001), all reported significant differ-

Table 3. Pearson correlation matrix for the tested parameters.
Preglednica 3. Matrika s Pearsonovimi korelacijskimi koeficienti za testirane parametre.

	D	S_R	S_T	S_V
D	1.00			
S_R	0.107	1.00		
S_T	0.236*	0.232*	1.00	
S_V	0.191	0.671**	0.644**	1.00

** Correlation is significant at the 0.01 level
* Correlation is significant at the 0.05 level
** Korelacija je značilna na ravni 0,01
* Korelacija je značilna na ravni 0,05

Table 4. Linear and non-linear models of the relationship between oven dry density and shrinkage (S_T, S_R, S_V – tangential, radial and volumetric shrinkage) for each of the species.
Preglednica 4. Linearni in nelinearni modeli za proučevanje zveze med gostoto lesa in krčenjem (S_T, S_R, S_V – tangencialni, radialni in prostorninski skrček) vsako vrsto.

Species	Models	ST	SR	SV
Nauclea diderrichii	Simple Linear	y = -7.967x + 837.2 R^2 = 0.059	y = 17.77x + 724.4 R^2 = 0.396	y = 11.42x + 701.3 R^2 = 0.169
	Exponential	y = 837.9e-0.01x R^2 = 0.063	y =726.9e0.022x R^2 = 0.397	y =707.6e0.014x R^2 = 0.164
	Logarithmic	y = -11.4ln(x) + 817.6 R^2 = 0.025	y = 58.76ln(x) + 720.1 R^2 = 0.341	y = 88.21ln(x) + 611.5 R^2 = 0.142
	Polynomial	y = -10.58x2 + 55.96x + 781.2 R^2 = 0.234	y = -0.392x2 + 21.43x + 716.9 R^2 = 0.397	y = 3.413x2–48.16x + 952.8 R^2 = 0.232
	Power	y = 817.3x-0.01 R^2 = 0.028	y = 722.9x0.073 R^2 = 0.343	y = 634.1x0.108 R^2 = 0.137
Mansonia altissima	Simple Linear	y = 11.73x + 546.6 (R^2 = 0.056)	y = 12.85x + 530.1 R^2 = 0.053	y = 22.32x + 388.6 R^2 = 0.275
	Exponential	y = 537.4e0.023x R^2 = 0.057	y = 520.8e0.025x R^2 = 0.053	y = 398.2e0.042x R^2 = 0.265
	Logarithmic	y = 47.69ln(x) + 529.6 R^2 = 0.052	y = 12.85x + 530.1 R^2 = 0.053	y = 226.1ln(x) + 95.09 R^2 = 0.318
	Polynomial	y = -1.357x2 + 24.15x + 520.9 R^2 = 0.057	y = 19.12x2–176.5x + 974.9 R^2 = 0.165	y = -16.05x2 + 330.1x–1049. R^2 = 0.534
	Power	y = 519.3x0.094 R^2 = 0.054	y = 505.8x0.097 R^2 = 0.035	y = 226.3x0.434 R^2 = 0.309
Treculia africana	Simple Linear	y = 32.89x + 355.1 R^2 = 0.377	y = -7.649x + 493.6 R^2 = 0.028	y = 17.56x + 337.1 R^2 = 0.136
	Exponential	y = 364.4e0.07x R^2 = 0.366	y = 494.0e-0.01x R^2 = 0.036	y = 357.4e0.034x R^2 = 0.114
	Logarithmic	y = 55.04ln(x) + 403.3 R^2 = 0.178	y = -6.03ln(x) + 471.4 R^2 = 0.001	y = 113.5ln(x) + 241.6 R^2 = 0.128
	Polynomial	y = 33.18x2–161.3x + 586.5 R^2 = 0.882	y = -9.652x2 + 69.81x + 357.6 R^2 = 0.219	y = 3.794x2–34.50x + 508.3 R^2 = 0.144
	Power	y = 404.4x0.115 R^2 = 0.168	y = 471.4x-0.02 R^2 = 0.004	y = 295.9x0.224 R^2 = 0.107
Sterculia tragacantha	Simple Linear	y = -22.10x + 568.1 R^2 = 0.099	y = 60.91x + 255.1 R^2 = 0.332	y = -2.491x + 534.2 R^2 = 0.013
	Exponential	y = 595.0e-0.06x R^2 = 0.084	y = 232.0e0.185x R^2 = 0.303	y = 534.4e-0.00x R^2 = 0.013
	Logarithmic	y = -34.2ln(x) + 522.4 R^2 = 0.054	y = 244.2ln(x) + 170.3 R^2 = 0.420	y = -18.9ln(x) + 553.5 R^2 = 0.015
	Polynomial	y = -9.615x2 + 37.15x + 505.6 R^2 = 0.138	y = -74.71x2 + 621.7x–721.9 R^2 = 0.672	y = 2.589x2–40.01x + 667.6 R^2 = 0.032
	Power	y = 521.5x-0.10 R^2 = 0.047	y = 178.4x0.745 R^2 = 0.387	y = 555.3x-0.03 R^2 = 0.015

Species	Models	ST	SR	SV
Nesogordonia kabingaensis	Simple Linear	y = -7.817x + 869.2 R^2 = 0.273	y = -5.706x + 848.5 R^2 = 0.200	y = -5.892x + 895.4 R^2 = 0.413
	Exponential	y = 871.2e-0.01x R^2 = 0.273	y = 848.7e-0.00x R^2 = 0.196	y = 899.3e-0.00x R^2 = 0.408
	Logarithmic	y = -57.0ln(x) + 924.6 R^2 = 0.276	y = -41.9ln(x) + 889.2 R^2 = 0.206	y = -83.0ln(x) + 1031. R^2 = 0.431
	Polynomial	y = 0.335x2–12.78x + 886.9 R^2 = 0.273	y = 0.259x2–9.625x + 862.6 R^2 = 0.202	y = 0.580x2–22.30x + 1008. R^2 = 0.440
	Power	y = 932.8x-0.07 R^2 = 0.276	y = 891.8x-0.05 R^2 = 0.201	y = 1062.x-0.10 R^2 = 0.426
Cassia siamea	Simple Linear	y = -3.671x + 795.7 R^2 = 0.181	y = -6.415x + 807.8 R^2 = 0.063	y = -5.760x + 815.4 R^2 = 0.064
	Exponential	y = 795.1e-0.00x R^2 = 0.180	y = 807.4e-0.00x R^2 = 0.063	y = 814.5e-0.00x R^2 = 0.062
	Logarithmic	y = -18.0ln(x) + 800.0 R^2 = 0.329	y = -22.6ln(x) + 812.9 R^2 = 0.041	y = -43.0ln(x) + 856.9 R^2 = 0.099
	Polynomial	y = 0.745x2–12.59x + 811.8 R^2 = 0.280	y = -6.455x2 + 52.86x + 680.5 R^2 = 0.148	y = 10.06x2–131.3x + 1192. R^2 = 0.379
	Power	y = 799.4x-0.02 R^2 = 0.324	y = 812.4x-0.02 R^2 = 0.041	y = 857.6x-0.05 R^2 = 0.095
Afzelia africana	Simple Linear	y = 1.969x + 822.7 R^2 = 0.009	y = 4.403x + 817.5 R^2 = 0.056	y = 3.310x + 806.6 R^2 = 0.057
	Exponential	y = 821.4e0.002x R^2 = 0.010	y = 4.403x + 817.5 R^2 = 0.056	y = 805.3e0.004x R^2 = 0.064
	Logarithmic	y = 18.81ln(x) + 805.6 R^2 = 0.047	y = 24.28ln(x) + 808.6 R^2 = 0.176	y = 31.82ln(x) + 770 R^2 = 0.111
	Polynomial	y = -4.708x2 + 49.52x + 722.5 R^2 = 0.222	y = -3.664x2 + 41.90x + 752.7 R^2 = 0.331	y = -1.561x2 + 28.64x + 717.5 R^2 = 0.209
	Power	y = 804.7x0.023 R^2 = 0.050	y = 807.8x0.029 R^2 = 0.187	y = 770.2x0.039 R^2 = 0.120
Milicia excelsa	Simple Linear	y = 21.91x + 805.4 R^2 = 0.157	y = 8.825x + 865.4 R^2 = 0.032	y = 15.17x + 774.3 R^2 = 0.165
	Exponential	y = 809.2e0.024x R^2 = 0.163	y = 865.7e0.009x R^2 = 0.032	y = 782.6e0.016x R^2 = 0.169
	Logarithmic	y = 93.44ln(x) + 765.4 R^2 = 0.166	y = 40.23ln(x) + 846.3 R^2 = 0.047	y = 115.7ln(x) + 657.0 R^2 = 0.169
	Polynomial	y = -9.791x2 + 105.7x + 633.4 R^2 = 0.177	y = -19.18x2 + 160.7x + 582.8 R^2 = 0.165	y = -2.082x2 + 47.29x + 654.6 R^2 = 0.170
	Power	y = 774.2x0.103 R^2 = 0.172	y = 848.0x0.043 R^2 = 0.047	y = 687.5x0.127 R^2 = 0.173

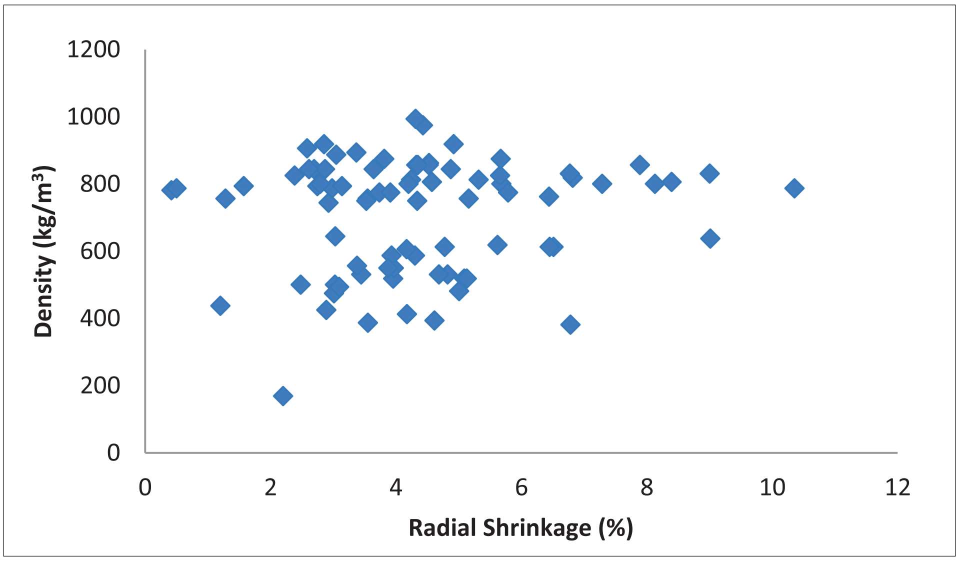

Figure 1. Wood density and radial shrinkage of the eight tropical wood species.
Slika 1. Gostota lesa in radialno krčenje osmih tropskih lesnih vrst.

ences between radial and tangential shrinkage on lesser-used hardwood species from Ghana. Lausberget et al. (1985), reported that this could have been caused by the presence of ray cells on the radial plane, with their horizontally aligned cells producing a restraining effect on radial shrinkage. However, Panshin and de Zeeuw (1980) noted that it is related to the rapid reduction of the microfibril angle in the cell wall.

The results of the analysis of variance of radial shrinkage show that there were significant differences among the wood species at a 0.05 level of probability (Table 2). However, the results of correlation analysis indicate that there was strong and positive significant correlation between radial and tangential shrinkage (0.644**) at a 0.05 level of probability (Table 3), but of all the models developed none of them has a good fit because of the low R^2 for all the species (Fig. 1 and Table 4)

The observed changes in wood dimensions as a result of shrinkage are unequal along the three structural directions. This behaviour of wood has been documented widely by various authors (Panshin and de Zeeuw 1980; Dinwoodie, 1981; Lausberg et al., 1995; Ogunsanwo, 2000). However, Panshin and de Zeeuw (1980) noted that the geometric disposition of cells along the principal directions is mainly responsible for this observation.

Osadare (2001) observed that the noticeable variations in wood properties are influenced principally by (i) the changes in activities of cambium as it grows older, (ii) genetic constitutions which govern the form and growth of the tree, and (iii) environmental influences. However, the interaction of these factors made it difficult to attribute the observed variations in wood properties to only a single factor. The variability of wood characteristics within individual trees is basically related to changes resulting from ageing of the cambium and modifications imposed on the cambial activity by the environmental conditions, genetic and silvicultural effects, as noted by Evans (1991).

3.3 TANGENTIAL SHRINKAGE
3.3 TANGENCIALNO KRČENJE

The highest tangential shrinkage was observed in *Nesogordonia kabingaensis* with 7.74±1.40%, followed by *Mansonia altissima* (5.20±1.74%), *Nauclea diderichii* (4.44±1.42%) and *Milicia excelsa* (4.34±0.90%). The mean tangential shrinkages for *Sterculia tragacantha*, *Afzelia africana*, *Treculiaafricana* were 3.92±1.59%, 4.30±2.01% and 3.91±1.49%, respectively, while the least tangential shrinkage was observed in *Cassia simea* with 3.77±3.21% (Table 1). According to the classification of Bolza and Keating (1972), TEDB (1994) and Upton and Attah (2003), the tangential shrinkage values are classified as small (3.5-5.0%), medium (5.1-6.0%), large (6.1-8.0%) and very large (above 8.0%)

The results of the analysis of variance of tangential shrinkage show that there were significant differences among the wood species at a 0.05 level of probability (Table 2), while the follow-up analy-

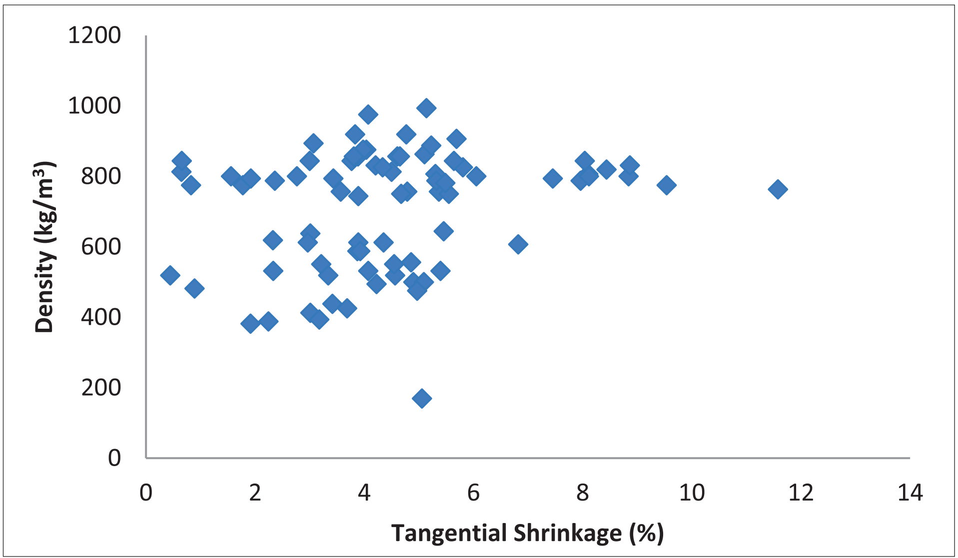

Figure 2. Wood density and tangential shrinkage of the eight tropical wood species.
Slika 2. Gostota lesa in tangencialno krčenje osmih tropskih lesnih vrst.

sis shows that there was no significant difference among the species except for *Nesogordonia kabingaensis* (Table 1). However, the results of the correlation analysis indicated that there was a strong and positive significant correlation between tangential shrinkage and radial shrinkage (0.232*) at the 0.01 level of probability, and a positive but not significant correlation between tangential and volumetric shrinkage (Table 3). Likewise, of all the models developed none of them had a good fit with the data because of the low R^2 for all the species (Fig. 2 and Table 4).

The greatest dimensional shrinkage occurs along the tangential plane, followed by shrinkage along the radial plane while longitudinal shrinkage has been widely reported to be the smallest, ranging from 0.1 to 0.3% (Desch, 1988; Dinwoodie, 1989). The suitability of wood for various end uses has been linked with the tangential/radial shrinkage ratio (ST/SR), also known as anisotropy. Panshin and de Zeeuw (1980) noted that a low value of T/R is synonymous with high suitability of wood for end uses. In this study, it is observed that the anisotropy found for the eight species is low, as can be seen in Table 1.

3.4 VOLUMETRIC SHRINKAGE
3.4 PROSTORNINSKO KRČENJE

The highest volumetric shrinkage was observed in *Nesogordonia kabingaensis*, at 14.71±2.28%, followed by *Mansonia altissima* (9.16±1.55%) *Nauclea diderichii* (8.79±1.67%) and *Milicia excelsa* (8.32±1.34%). The mean volumetric shrinkages for *Sterculia tragacantha*, *Afzelia africana*, and *Treculia Africana* were 7.64±0.96%, 7.42±3.02% and 7.21±1.42%, respectively. The least volumetric shrinkage was observed in Cassiasimea, at 5.11±2.65% (Table 1). Poku et al. (2001), recorded volumetric shrinkages of 7.51%, 11.51% and 6.21% for *Alstonia boonei. Pterocarpus macrocarpus* and *Ricinodendron hendelotti*, respectively, while Kiaei and Samariha (2011) obtained 12.39% for *Ulmus glabra* grown in Iran.

The wide disparity among the eight species could be attributed to their densities and probably the presence of more biomass in latewood cells, as noted by Chudnoff (1976). However, many other factors, such as spiral grain and latewood proportion, also affect the variation in the shrinkage of wood (Pilura et al, 2005; Walker, 2006)

The results of the analysis of variance of tangential shrinkage show that there were significant differences among the wood species at a 0.05 level of probability (Table 2). Moreover, none of the models developed in this work had a good fit because of the low R^2 for all the species (Fig. 3 and Table 4).

4 CONCLUSIONS
4 SKLEPI

The use of the eight tropical hardwood species for this study has provided useful information

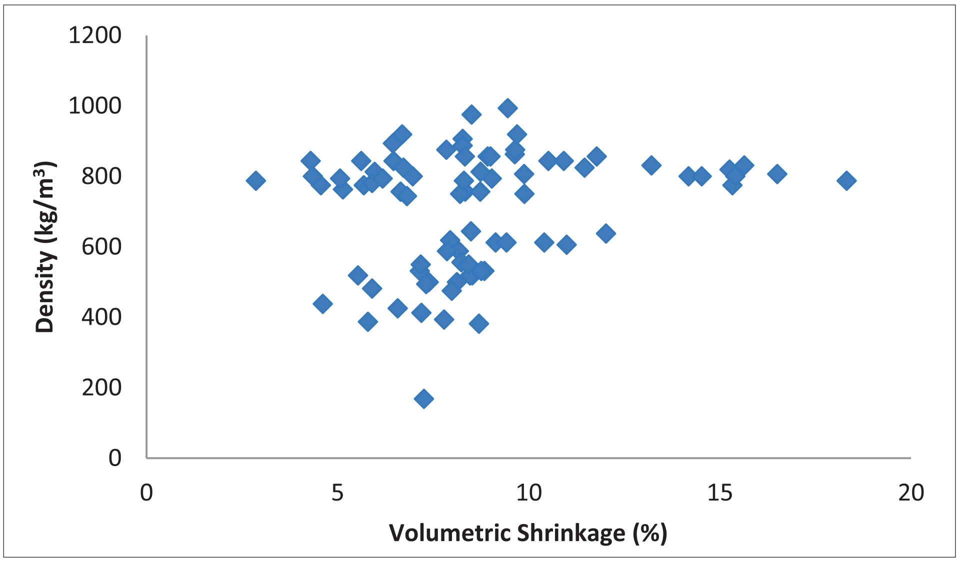

Figure 3. Wood density and volumetric shrinkage of the eight tropical wood species.

Slika 3. Gostota lesa in prostorninsko krčenje osmih tropskih lesnih vrst.

regarding the density, shrinkage and anisotropy of the wood and the relationships among them.

Based on the findings of this study, the following conclusions were made. *Nesogordonia kabingaensis* shrinks more than the other species studied. Along the radial and tangential plane, there was a positive correlation between wood density, radial, tangential, and volumetric shrinkage but a weak coefficient of fitness R^2 for the linear and non-linear models for all the species. Statistically significant differences among the eight species could not be established for all the studied parameters.

5 SUMMARY
5 POVZETEK

Izbrali smo les osmih tropskih vrst: *Nauclea diderichii*, *Mansonia altissima*, *Treculia africana*, *Sterculia tragacantha*, *Nesogordonia kabingaensis*, *Cassia simea*, *Afzelia africana*, *Milicia excelsa* in raziskali gostoto, radialno, tangencialno in volumsko krčenje ter anizotropijo krčenja ter povezave med njimi. Večina vrst je uveljavljenih, samo *Treculia africana* in *Sterculia tragantha* sta z vidika lastnosti lesa manj znani.

Za določanje gostote lesa v absolutno suhem stanju so bili izdelani testni vzorci dimenzij 20 x 20 x 60 mm iz centralnih desk spodnjega dela debel. Testni vzorci so bili posušeni v laboratorijskem sušilniku do konstantne mase, gostota lesa pa je bila tako določena v skladu z ameriškim standardom za testiranje materialov (ASTM D) 2395 (1983). Izdelani so bili orientirani vzorci velikosti 20 x 20 x 60 mm; za merjenje tangencialnih in radialnih skrčkov. Les so namočili v vodo za 48 ur, da je dosegel vlažnost nad točko nasičenja celičnih sten (FSP). Dimenzije v mokrem stanju so bile natančno določene s pomočjo Venierovega merilnika. Odstotek krčenja vzdolž obeh ravnin je bil izmerjen po tem, ko so vzorci v sušilniku dosegli ravnovesno, absolutno suho stanje.

Največjo povprečno gostoto je imel les vrste *Milicia excelsa* z 900,63±50,13 kg/m³, sledijo *Afzelia africana*, *Nesogordonia kabingaensis* in *Nauclea diderichii* z 831,25±41,67 kg/m³, 808,75±20,88 kg/m³ oziroma 801,88±46,40 kg/m³. Povprečna gostota za les vrst *Cassia simea* je bila 781,88±27,71 kg/m³, *Mansonia altissima* 593,13±65,98 kg/m³, *Sterculia tragacantha* 481,25±111,73 kg/m³, medtem ko je imela najmanjšo gostoto vrsta *Treculia africana* s 463,75±67,88 kg/m³ (preglednica1).

Največje povprečno radialno krčenje je bilo pri lesu vrste *Nesogordonia kabingaensis* s 6,98 ± 1,63 %, sledijo *Nauclea diderichii*, *Milicia excelsa* in *Mansonia altissima* s 4,36 ± 1,64 %, 3,98 ± 1,02 % in 3,96 ± 1,34 %. Povprečen radialni skrček pri vrsti *Cassia simea* je bil 3,65 ± 1,56 %, pri vrsti *Afzelia africana* 3,12 ± 2,24 %, pri *Sterculia tragacantha* 3,71 ± 1,06 % in pri *Treculia africana* 3,30 ± 1,23 % (preglednica 1).

Največje tangencialno krčenje je bilo zabeleženo pri vrsti *Nesogordonia kabingaensis* s 7,74 ± 1,40 %, sledijo *Mansonia altissima* (5,20 ± 1,74 %), *Nauclea diderichii* (4,44 ± 1,42 %) in *Milicia excelsa*

(4,34 ± 0,90 %), srednje tangencialno krčenje je imel les vrst *Sterculia tragacantha*, *Afzelia africana* in *Treculia africana* (3,92±1,59 %, 4,30±2,01 % in 3,91±1,49 %), medtem ko je bilo najmanjše tangencialno krčenje opaženo pri vrsti *Cassia simea* s 3,77 ± 3,21 % (preglednica1).

Največje prostorninsko krčenje so opazili pri vrsti *Nesogordonia kabingaensis* s 14,71 ± 2,28 %, sledijo *Mansonia altissima* (9,16 ± 1,55 %), *Nauclea diderichii* (8,79 ± 1,67 %) in *Milicia excelsa* (8,32 ± 1,34 %), povprečno prostorninsko krčenje za vrste *Sterculia tragacantha*, *Afzelia africana*, *Treculia africana* je bilo 7,64±0,96 %, 7,42±3,02 % oziroma 7,21±1,42 %. (preglednica 1).

Za les osmih raziskanih tropskih listavcev smo ovrednotili tudi povezave med gostoto absolutno suhega lesa in krčenjem lesa, vendar nismo mogli potrditi statistično značilne povezave.

Na podlagi raziskav ugotavljamo, da se les vrste *Nesogordonia kabingaensis* krči bolj kot les drugih vrst. Determinacijski koeficient R^2 je bil v vseh primerih prenizek, da bi lahko potrdili zvezo med gostoto lesa ter radialnim, tangencialnim in prostorninskim krčenjem.

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