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Investigating Physical and Mechanical Properties of Mahogany Root Wood (*Khaya ivorensis*) for its Utilization

Istraživanje fizičkih i mehaničkih svojstava drva korijena afričkog mahagonija (*Khaya ivorensis*) radi njegove uporabe

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ABSTRACT • *The growing need for wood in construction and furniture production has led to a gradual increase for interest in other tree components, such as the use of root wood. However, to evaluate the quality of wood, one must consider its mechanical, anatomical, and physical characteristics. African mahogany (Khaya ivorensis) is a hard and durable wood that has been over-exploited. However, its other tree components, such as root wood, are available and considered waste left to rot. This study investigated the physical and mechanical properties of mahogany root wood and known properties of other wood species as an alternative base for wood resources. Root samples were extracted from three trees with three roots each, with average diameters of 54.3 cm, 23.3 cm, and 20.6 cm for trees 1, 2, and 3, respectively, and prepared according to BS 373 standard. All tests were investigated at the Kumasi CSRI (FORIG) laboratory. The results indicated that the root wood of the species dried at 17 - 20 % MC proved to be as good a material as its stem wood and branch wood counterparts in terms of physical and mechanical properties. Basic density values averaged 508 kg/m^3, 531 kg/m^3, and 569 kg/m^3 across the roots. The green moisture content was 80 %, 76 % and 70 % for tree 1, 2, and 3, respectively. Average shrinkage was 0.84 %, 4.58 %, and 6.28 %, respectively, in longitudinal, tangential, and radial direction. MOE recorded 6724.4 MPa, 9276.0 MPa and 10010.0 MPa, MOR was 54.3 MPa, 76.1 MPa, and 78.5 MPa, compressive strength parallel to the grain was 41.8 MPa, 54.4 MPa, and 59.2 MPa, shear strength values ranged from 14.3 MPa, 15.4 MPa, to 17.2 and Janka hardness from 3.81 kN to 4.01 kN for tree 1, 2, and 3. Most of the recorded root wood results were similar to those of the stem and branch wood, indicating that it was equally fit for structural purposes.*

KEYWORDS: *African mahogany (Khaya ivorensis); root wood; physical and mechanical properties*

SAŽETAK • *Sve veća potreba za drvom u graditeljstvu i proizvodnji namještaja dovela je do postupnog porasta zanimanja za ostale dijelove stabla, a time i do potrebe iskorištavanja korijena. Međutim, kako bi se procijenila*

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kvaliteta drva korijena, moraju se uzeti u obzir njegova mehanička, anatomska i fizička svojstva. Afrički mahagonij (Khaya ivorensis) tvrdo je i izdržljivo drvo koje se prekomjerno iskorištava. Međutim, drugi dostupni dijelovi njegova stabla, poput korijena, smatraju se otpadom ostavljenim da trune. Ovom studijom istražena su fizička i mehanička svojstva drva korijena afričkog mahagonija kao alternativne baze drvne sirovine u usporedbi s poznatim svojstvima drugih vrsta drva. Uzorci korijena uzeti su od tri stabla prosječnog promjera 54,3 cm (stablo 1.), 23,3 cm (stablo 2.) i 20,6 cm (stablo 3.) te su od njih pripremljeni uzorci za ispitivanje svojstava drva prema standardu BS 373. Sva ispitivanja provedena su u laboratoriju Kumasi CSRI (FORIG). Rezultati su pokazali da se drvo korijena osušeno na 17 – 20 % sadržaja vode u smislu fizičkih i mehaničkih svojstava pokazalo jednako dobrim materijalom kao i drvo debla i grana. Nominalna gustoća drva za pojedine je uzorke korijena prosječno iznosila 508 kg/m³, 531 kg/m³ i 569 kg/m³. Sadržaj vode u korijenu stabala 1., 2. i 3. u sirovom je stanju bio 80 %, 76 % i 70 %. Prosječno utezanje u uzdužnom, tangentnom i radijalnom smjeru iznosilo je 0,84 %, 4,58 % i 6,28 %. MOE je bio 6724,4 MPa, 9276,0 MPa i 10010,0 MPa; MOR je iznosio 54,3 MPa, 76,1 MPa i 78,5 MPa; čvrstoća na tlak paralelno s vlakancima bila je 41,8 MPa, 54,4 MPa i 59,2 MPa; vrijednosti smične čvrstoće kretale su se od 14,3 MPa, 15,4 MPa do 17,2 MPa, a tvrdoća po Janki za drvo korijena stabala 1., 2. i 3. iznosila je od 3,81 kN do 4,01 kN. Većina zabilježenih rezultata za svojstva drva korijena bila je slična onima za drvo debla i grana, što potvrđuje prikladnost tog drva za konstrukcijske namjene.

KLJUČNE RIJEČI: *African mahogany (Khaya ivorensis); drvo korijena; fizička i mehanička svojstva*

1 INTRODUCTION
1. UVOD

Mahogany wood was one of the first to be identified as a durable wood, and it can be found in northern Ghana. Its structural and aesthetic value is enormous. It is one of the exotic species with multi-functional uses, and its products may be found in every home in Ghana (Asare *et al.,* 2022). *Khaya ivorensis* is ranked as one of the best-known and most valuable tropical timbers on the international market, as indicated in the ITTO (2004) report.

Mahogany is distributed across Africa, Benin, Ghana, the Ivory Coast, Sudan, Togo, D.R. Congo, and Uganda. It grows in savannah and semi-deciduous forests, particularly the drier ones, however in the latter, it is typically found near water courses in regions with 1200–1800 mm of annual rainfall and a three–five-month dry season (Opoku *et al*., 2012).

The mahogany tree grows well in Ghana; it is observed that it is mainly found by river banks and lowland areas in the northern parts of the country, with large crown sizes producing a lot of canopies for relaxation, especially when grown in the community and along the major roads to serve as carbon sequestration to reduce environmental pollution (Nusir *et al.,* 2002). It is always well protected when planted in the community to prevent ruminants' destruction, as the leaves appear to be their delicacy.

Mahogany falls into the category of medium hardwood, in terms of density, stiffness, shear, compressive and good bending strength and it is simple to season and resistant to termite, bacterial, and fungal decay. The uses of mahogany in this part of the country are not different from what is established in other areas of the country and beyond. It is believed to be superior to teak wood in many ways, such as its ability to take a beautiful polish and other finishes and its widespread use in furniture, construction, turnery, panelling, tool handles, cooking utensils, and musical instruments. Other uses include car body building, floor joists, roof members, window and door frames, and veneer, among other industrial uses (Stephen *et al.,* 2016).

According to records, the West and Central African subregion is home to four main species of mahogany from the family Meliaceae: *Khaya anthotheca, Khaya ivorensis, Khaya grandifoliola*, and *Khaya senegalensis* (Bonsu *et al*., 2020).

All these species perform various functions in the wood industry. They are well known for their natural beauty when used for decoration works as well as their durability standards for structural works, and this has significantly increased the demand for these species, rendering them endangered amongst others, not losing sight of usage in the traditional areas for the treatment of ailments.

The demand for wood is driven by its use in construction, furniture, paper production, and energy (as fuelwood). With global population growth, urbanisation, and increasing consumerism, wood consumption continues to rise. Unsustainable harvesting contributes to deforestation, biodiversity loss, and climate change, making it critical to address both the demand and supply sides of the issue. Adopting sustainable forestry practices, including certified logging (e.g., FSC certification) and afforestation, ensures wood is sourced responsibly. Alternative materials like bamboo, engineered wood, recycled plastics, or metal can replace wood in construction, furniture, and packaging. Promoting recycling of paper and wood products reduces the need for virgin wood. Repurposing construction materials can extend their lifecycle. Advances like lab-grown wood or bioplastics offer promising ways to reduce dependence on natural wood. By integrating these solutions, the demand for wood can be met more sustainably, reducing environmental impact and ensuring resources for future generations (Antwi *et al.,* 2024).

The properties of mahogany root wood have not been thoroughly researched, even though some work has been done on species other than mahogany root wood. This study aims to study its properties for utilising the roots of harvested mahogany trees in the wood industry to promote a continued and sustainable wood resource base in the wake of the high demand for limited resources for local use.

In the savanna zones in Ghana, sometimes mahogany trees are uprooted either by storm or by erosion, yet the phenomenon of abandoning the roots is common after harvesting their trunks for lumber and the branches for charcoal and fuel wood; this may be attributed to a lack of knowledge on its alternative uses. It was also realised that 99.5 percent of the trees harvested, using the chainsaw machine could not produce shoots for regeneration; these suggest that the stumps and roots are left to waste; the course of the stumps inability to produce new shoots is yet to be established by research. Therefore, more studies must be conducted to find alternative uses for the unused parts of the species for economic benefits, which is the idea behind this research. The objective of this study is to investigate the physical and mechanical properties of mahogany (*Khaya ivorensis*) root wood for its utilisation.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Study area and description
2.1. Područje i opis istraživanja

The Savannah region in Ghana was chosen for the study due to its large forest cover. It is one of the regions with vast forest land and Mole forest reserves located in the western part of the country toward the border with the Cote d'Ivoire.

The Savannah region is located nearby the Sahel and Sahara and it is significantly drier than the southern parts of Ghana. The predominant type of vegetation is grassland, particularly savanna, with pockets of drought-tolerant trees such as shea, dawadawa, ebony, nim, and baobabs. The dry season is considered to be from December to April. The average annual rainfall during the wet season, roughly from May to November, is between 750 and 1050 mm (30 and 40 inches). The end of the dry season brings the highest temperatures, while December and January bring the lowest. However, between December and the beginning of February, the hot Harmattan wind from the Sahara blows regularly. The temperature range is 14 °C (59 °F) at night to 40 °C (104 °F) during the day.

Data for this investigation were collected from Wangasi-Tudu, 55 km from Kpalbe in the north-east Gonja district in the savannah region with coordinates with latitude 9^0 9` N and longitude $1^0$ 36` W with elevation of 202 meters above sea level, with the digital address S J 15243-0154 where research materials were harvested.

2.2 Sampling
2.2. Uzorkovanje

Three (3) mature African mahogany trees yielded nine straight root boles for the study, with an average diameter of 16 cm to 20 cm and 24 cm. The trees were obtained from cassava and yam farmland in the same locality within the open forest area. The sample preparation process from logging to conversion is demonstrated in Figures a) - i). A purposive sampling technique was employed, targeting roots with a diameter greater than 16 cm, measured 75 cm from the stem and the overall straightness, and defect-free of the root bole. This approach ensured the selection of samples that met specific size criteria relevant to the study.

The samples were prepared in the Wood Technology Workshop of the Department of Wood Science and Technology Education of Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development and the Anatomy laboratory at the Forestry Research Institute of Ghana, the Council for Scientific and Industrial Research of Ghana.

The samples were prepared in the dimensions shown in Table 1 for physical and mechanical tests according to the standards stated in Table 1. In total, sixty samples were tested for each property.

Table 1 Description of test samples
Tablica 1. Opis ispitnih uzoraka

Tests conducted *Provedena ispitivanja*	**Properties evaluated** *Ispitana svojstva*	**Standards used** *Primijenjene norme*	**Samples geometry** *Dimenzije uzoraka* mm	**Quantity of samples** *Broj uzoraka*
Physical properties *Fizička svojstva*	Moisture content / *sadržaj vode* Density / *gustoća* Shrinkage / *utezanje*	ASTM D4442-07 ASTM D2395-07 ASTM D1037-07	20 × 20 × 20 20 × 20 × 20 25 × 25 × 30	60 60 60
Mechanical properties *Mehanička svojstva*	Modulus of elasticity / *modul elastičnosti* Modulus of rupture / *modul loma* Compressive strength / *čvrstoća na tlak* Shear strength / *smična čvrstoća* Hardness (radial\tangential) / *tvrdoća (radijalna/tangentna)*	BS 373: 1957 BS 373: 1957 BS 373: 1957 BS 373: 1957 BS 373: 1957	20 × 20 × 300 20 × 20 × 300 20 × 20 × 60 50 × 50 × 50 50 × 50 × 150	60 60 60 60 60

Figure 1 Root wood samples preparation for physical and mechanical tests
Slika 1. Priprema uzoraka drva korijena za ispitivanje fizičkih i mehaničkih svojstava

The samples were air-dried at room temperature for three months and all particles on their edges were trimmed to keep the edges clean. Afterwards, they were transferred to a conditioning room, where the moisture was reduced to a uniform moisture content of 12 %. Each sample was labelled and grouped according to each test, e.g. R1, R2, R3…

2.3 Determination of basic density and moisture content
2.3. Određivanje nominalne gustoće i sadržaja vode

The basic density and moisture content were determined according to ASTM D 2395-07 and ASTM D4442-07, respectively. The same samples were used for both tests. Each strip was sawn into 20 mm × 20 mm sections and cross-cut into 20 mm cubes. The mass of the samples was taken immediately after preparation using a digital electronic balance (VWR Science Education RS232) with a precision of 0.001 g to obtain the initial mass (W_1). The samples were soaked in water for 24 hours to obtain the swollen volume (V_1) determined by the immersion method. Afterwards, the wood samples were oven-dried at (103 ± 2) °C with intermittent weighing until a constant mass (oven-dry mass) (W_0) was attained according to ASTM D 2395-07. The test was carried out under ambient temperature conditions of 20 °C. The duration of the basic density test was 24 hours. The basic density (BD) of the samples was calculated from oven-dry mass and swollen volume, as shown in Figures 2e-h.

2.4 Determination of shrinkage
2.4. Određivanje utezanja

Shrinkage was evaluated using 25×25×30 mm specimens. The four-sided specimen sizes were measured at 0.0001m accuracy of volume, then computed through weighing of specimens to obtain the initial weight, and then submerged horizontally under 25mm depth of clean water at room temperature for 72 hours. The specimens were then removed and put in a kiln until they attained the mandatory twelve per cent (12 %) moisture content. Volumetric shrinkage was calculated by Eq (1)

$$Volumetric\,shrinkage = \frac{Vf - Vo}{Vo} \times 100\,\% \qquad (1)$$

Where: Vo – initial volume of the specimen
Vf – final volume of the specimen

2.5 Testing instrument for mechanical properties
2.5. Uređaj za ispitivanje mehaničkih svojstava

Mechanical properties were tested using an automatic universal testing machine (UTM-Hegewald &

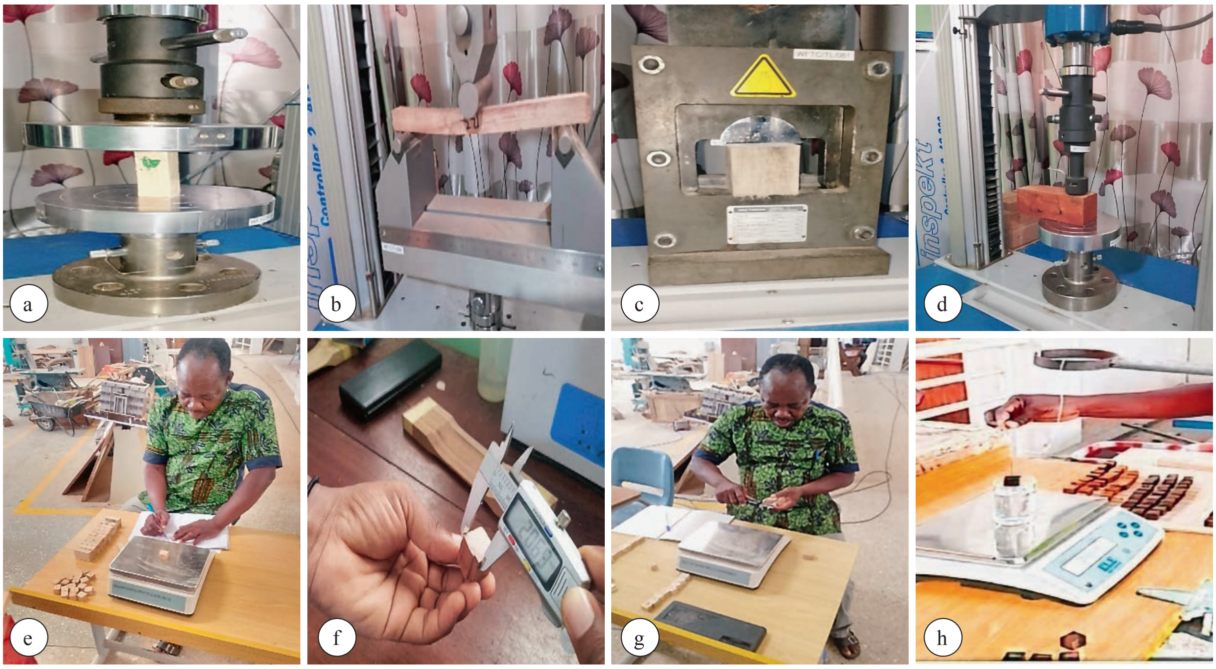

Figure 2 Testing of physical and mechanical properties of root wood
Slika 2. Ispitivanje fizičkih i mehaničkih svojstava drva korijena

Peschke mpt GmbH series no 10-030-000b2v1. 50 KN) according to standard BS 373 (1957). The testing machine consists of a jig where the samples are loaded for testing, and a head that moves up or down to exert stress on the sample. The computer used for this setup has the program "Winsoft", which senses deflection and stress and displays the load-by-deflection curve on the monitor concurrently with the test. The instrument was adjusted for the loading rate, and the sample dimensions by ISI 1708 (ISI, 1986).

Compressive strength was measured using the parallel to longitudinal grain method. Each sample was examined to ensure that the rectangular test pieces were smooth, parallel and expected to the axis. Plates containing the test component were parallel to each other throughout the test. Several checks were made to make sure that the correct conclusions were drawn, as shown in Figure 2a.

For static bending tests (modulus of elasticity and modulus of rupture), a three-point bending (central loading) system (Figure 2b) was used. The machine automatically applied the loading at a speed of 6.5 mm/min. Loading speed was maintained until the test sample failed. The computer component of the UTM recorded the maximum load at failure and the maximum load at the limit of proportionality between the outer points of loading. The tests were completed in (90 ± 30) seconds.

For the shear test samples, the load was applied at a speed of 0.635 mm/min. Shear strength was carried out in a longitudinal direction, parallel to the grain (Figure 2c). The samples were subjected to load until failure. The tests were completed in (90 ± 30) seconds.

For Janka hardness tests, a steel ball with a diameter of (11.3 ± 2.5) mm was located at one end of a steel bar, which was the fixture. The application of a load causes the hemispherical end (steel ball) to penetrate the test segment. The max force necessary to press the hemispherical end of the steel ball into the test piece to a depth of 5.64 mm is automatically recorded by the machine. The Janka hardness was calculated as the maximum force to imprint the steel ball into the wood. Both radial and tangential surfaces were tested, as shown in Figure 2 d.

2.6 Statistical procedures
2.6. Statistički postupci

Data were imported into the statistical software Origin (Version: Origin (Pro) 2021) for statistical analysis. Descriptive and inferential statistics were used to summarise the data numerically and graphically. Single factor one-way analysis of variance (ANOVA) was used to determine the significant difference within each root wood. The Turkey multiple comparison test and HSD post hoc were used to test the statistical significance of each pair of means and the variation in the physical and mechanical properties of the mahogany root wood. A 95 % confidence level was used to test the differences between all mean values.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Physical properties
3.1. Fizička svojstva

The results of the basic density for Root 1, Root 2, and Root 3 show that Root 3 recorded the highest basic density of 569 kg/m³, while Root 1 recorded the lowest density of 508 kg/m³, as indicated in Figure 3 and Table 2. The ANOVA test shows that the roots significantly affect the basic density at a level of significance of 5 %. However, Turkey's multiple comparison tests show substantial density differences. This result is consistent with a similar result reported by Amoah *et al.* (2012b), who found that the Iroko root wood had the highest average density (760 kg/m³), ranging between 694 and 813 kg/m³. Again, the findings that Root 3 recorded the highest basic density (568.51 kg/m³) and Root 1 recorded the lowest (508.03 kg/m³) align with similar studies that highlight the influence of genetic and environmental factors on the basic density of wood. Variations in density among roots are commonly attributed to differences in wood anatomy, moisture distribution, and growth conditions, as supported by studies examining inter- and intra-tree wood property variations. This supports the study of Wiemann and Williamson (1988), who found significant variability in wood density across different parts of trees, emphasizing that root wood often exhibits lower densities due to increased porosity and moisture content. Similarly, Panshin and de Zeeuw (1980) identified that roots generally have a different structural composition compared to stems, leading to variation in density and mechanical properties.

Results of the green moisture content for Root 1, Root 2, and Root 3, respectively, show Root 1 with the highest moisture content of 80 % and Root 3 with the

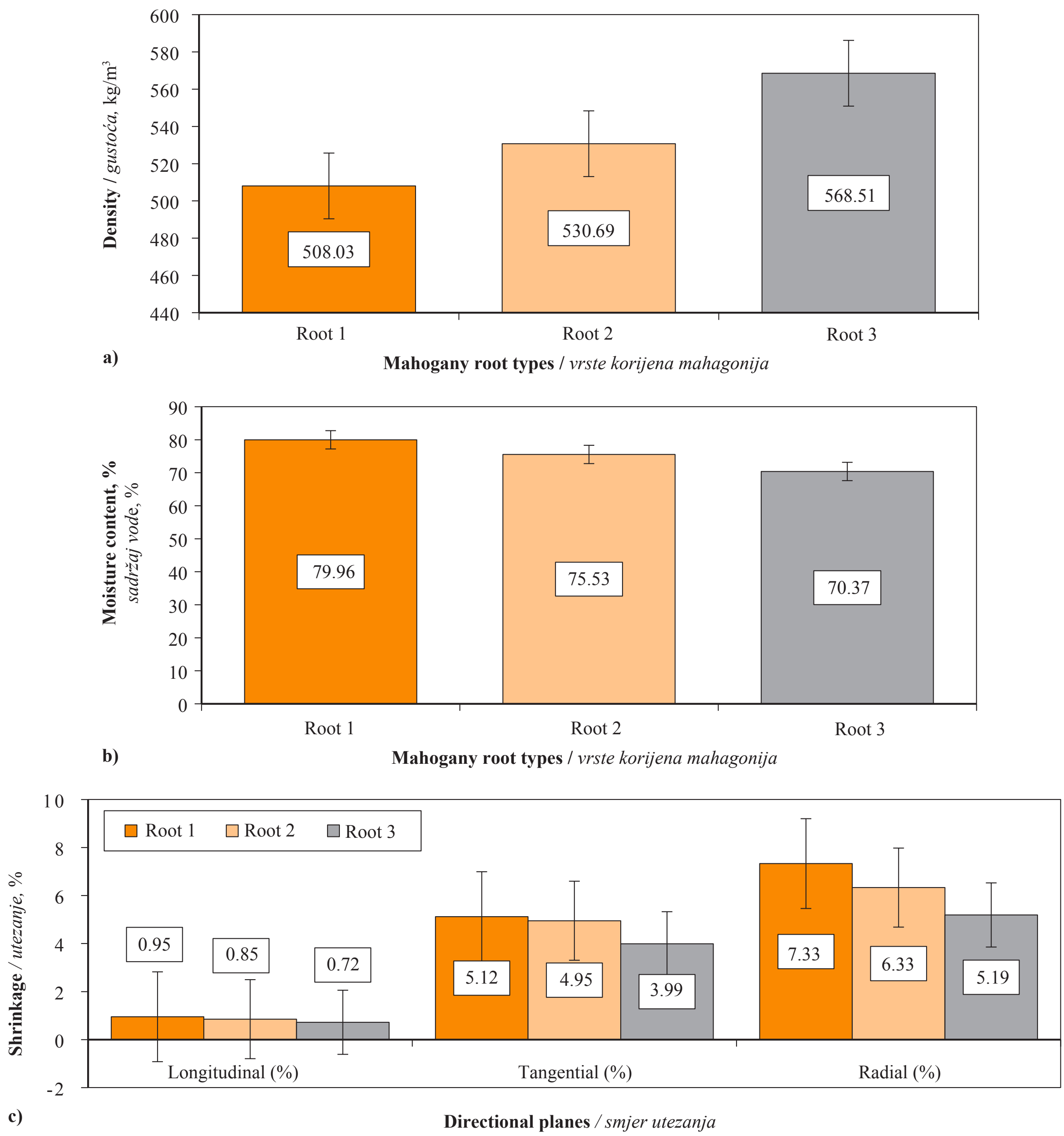

Figure 3 Average density, green moisture content, and shrinkage of mahogany root wood (Error bars = standard deviation)
Slika 3. Prosječna gustoća, sadržaj vode drva u sirovom stanju i utezanje korijena mahagonija (traka pogreške prikazuje standardnu devijaciju podataka)

lowest moisture content of 70 %. Furthermore, Turkey's multiple comparison tests show significant differences in moisture content between the three roots. These results can be compared with the findings of Hales and Miniat (2017), and Zhang *et al*. (2014), who reported that the moisture content of Chinese fir **(***Cunninghamia lanceolata***)** has a significant relationship with the strength of the wood. Their findings highlighted that variations in moisture content substantially affect the mechanical properties, including strength and stiffness, making moisture control crucial in the utilisation of this species.

The results demonstrate that Root 1 exhibits the highest shrinkage across longitudinal, tangential, and radial dimensions, likely due to differences in wood density, moisture content, or anatomical structure at the cellular level. High shrinkage values suggest that Root 1 may have a higher proportion of moisture-retentive tissues or a more variable grain structure, leading to greater dimensional changes during drying.

In contrast, Root 3 shows the lowest shrinkage**,** which could be attributed to a denser or more uniform cell structure, lower initial moisture content, or enhanced resistance to deformation under drying conditions. The reduced shrinkage values in Root 3 indicate better dimensional stability, making it potentially more suitable for applications requiring minimal warping or distortion. This variation highlights the importance of material selection based on shrinkage characteristics for specific woodworking or construction applications.

The shrinkage of Root 1, Root 2, and Root 3 shows a level of variability from 5.1 % to 54 %. This could be explained by root type and plane direction. However, the results of the ANOVA indicated a significant difference of shrinkage between the roots, while the Turkey multiple comparison tests prove that there was no significance. In their study, Glass *et al.* (2021) concluded that wood shrinks relatively little longitudinally or in a direction perpendicular to the grain. However, for most wood species, the average volumetric shrinkage from green to oven-dry is between 0.1 % and 0.2 %. However, depending on the species, it shrinks (swells) tangentially slightly more than radially. The study results are in line with Yang *et al.* (2016), who researched the moisture content and tensile strength of four tree roots *Betula platyphylla, Quercus mongolica, Pinus tabulae form, and Larix gmelinii*, with moisture content ranging from 26.00 to 33.00 %, 24.70 to 31.30 %, 37.00 to 45.00 % and 20.40 to 35.70 %, respectively.

Table 2 ANOVA test for physical properties of mahogany root wood
Tablica 2. ANOVA test rezultata fizičkih svojstava drva korijena mahagonija

Properties / *Svojstva*	***df***	***F*-value**	***P*-value**	**Var., %**
Density / *gustoća*	2	39.649	0.001**	
Moisture content *sadržaj vode*	2	75.095	0.001**	
Shrinkage / *utezanje*				
- Root type (RT) - *vrsta korijena (RT)*	2	4.550	0.012**	5.1
- Plane direction (PD) - *smjer utezanja (PD)*	2	101.876	0.001**	54.4
- RT × PD	4	1.053	0.382ns	2.4

** = significant at p<0.05, ns = not significant / ** = *značajno pri p < 0,05, ns = nije značajno*

3.2 Mechanical properties of mahogany root wood
3.2. Mehanička svojstva korijena mahagonija

3.2.1 Modulus of elasticity
3.2.1. Modul elastičnosti

The Modulus of Elasticity (*MOE*) results for Root 1, Root 2, and Root 3 are shown in Figure 4, accordingly. The results show that Root 3 recorded the highest *MOE* of 10010 MPa, while Root 1 recorded the lowest *MOE* value of 6724.4 MPa. The ANOVA results for the modulus of elasticity for roots 1, 2, and 3, respectively, are significant; Root 3 recorded the highest *MOE*, while root 1 recorded the lowest *MOE*. The reason could be the difference in root diameter resulting from the formation and maturity. The current results can be compared with the findings of Appiah-Kubi *et al.* (2016) on plantation-grown African mahogany (*Khaya ivorensis*) with *MOE* of 8603 MPa at the bottom, 10051 MPa at the middle, and 8718 MPa at the top of the stem wood with mean densities of 554, 518 and 491 kg/m^3, respectively. França *et al.* (2024) reported that the mean values of African mahogany *MOE* and *MOR* were 6367 MPa and 55.93 MPa, respectively.

3.2.2 Modulus of rupture
3.2.2. Modul loma

For Root 1, Root 2, and Root 3, the corresponding modulus of rupture (*MOR*) was obtained. The results show that Root 3 recorded the highest *MOR* of 78.48 MPa, while Root 1 recorded the lowest *MOR* value of 54.25 MPa. At the five percent significance level, the modulus of rupture for roots 1, 2, and 3 shows that they are significant, with Root 3 recording the highest value of 78.48 MPa, while Root 1 recorded the lowest *MOR* of 76.11 MPa. The current results are consistent with the findings of Ashaduzzaman *et al.* (2011), who investigated big-leaf mahogany (*Swietenia macrophylla king*) with *MOR* of 79.12 and 73.59 MPa, respectively. The results are also in accordance with the results of Amoah *et al.* (2012), who recorded that the *MOR* values of the branch, stem, and root wood ranged from 55 to 91, 60 to 88, and 56 to 90 MPa, respectively, and the *MOR* of the root wood was 74 MPa, varying between 53 and 85 MPa.

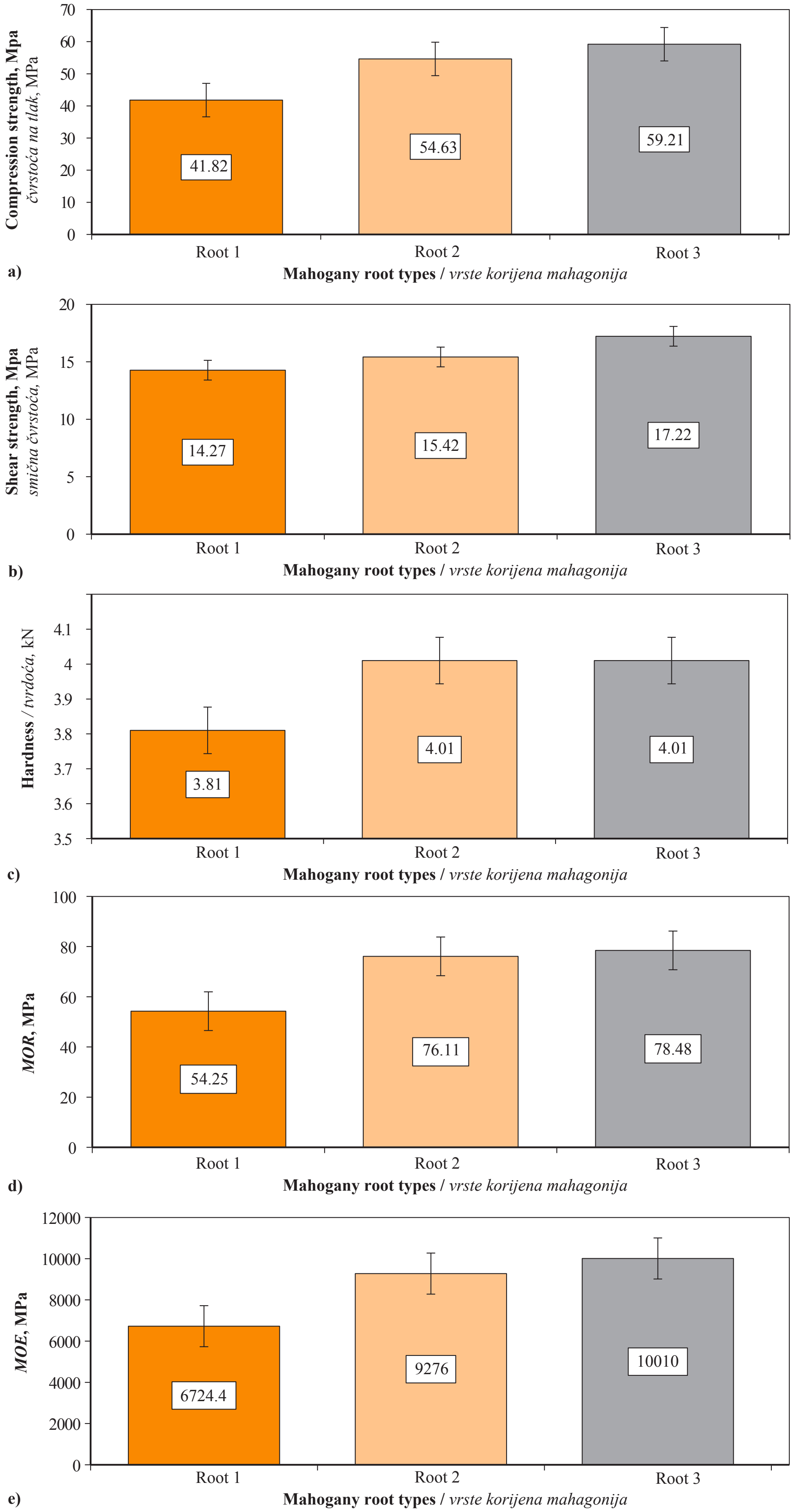

Figure 4 Average mechanical properties of mahogany root wood (Error bars = standard deviation)
Slika 4. Prosječna čmehanička svojstva korijena mahagonija (traka pogreške prikazuje standardnu devijaciju)

3.2.3 Compressive strength parallel to the grain
3.2.3. Čvrstoća na tlak paralelno s vlakancima

Figure 4 shows the results of the compressive strength parallel to the grain (*COM*) for R1, R2, and R3, respectively. R3 recorded the highest *COM* of 59.21 MPa, while R1 recorded the lowest *COM* of 41.82 MPa. The ANOVA test shows that the *COM* differences are significant between the roots. These variations could be attributed to the difference in properties within and between trees, the growth pattern, and environmental factors. The results are similar to those of Anoop *et al.* (2014), who reported that the compressive strength parallel to the grain varied significantly among different tropical wood species, reflecting how material properties are influenced by density and anatomical structure. Their findings showed that denser wood species tend to have higher compressive strength values, aligning with trends in our results where Root 3, likely denser, recorded the highest compressive strength (59.21 MPa), while Root 1, less dense, had the lowest (41.82 MPa). This correlation supports the significance of wood density in mechanical performance.

Table 2 indicates the ANOVA results, showing that, at a 5 % significance level, the root type significantly affects *MOE*. The results of Turkey's multiple comparison tests, as presented in Table 3, confirm that the *MOE* differences between the root types are significant.

The table also presents the ANOVA results for *MOR*, showing that, at a 5 % significance level, root type significantly affects *MOR*. Similarly, Turkey's multiple comparison tests reveal that the differences in *MOR* between the root types are significant. Results of the ANOVA (Table 3) indicate that root type significantly affects compressive strength at a 5 % significance level. Furthermore, Turkey's multiple comparison tests suggest that the differences in compressive strength between the root types are significant. The shear strength results for Root 1, Root 2, and Root 3 are presented in Figure 4. Root 3 recorded the highest shear strength of 17.22 MPa, while Root 1 recorded the lowest shear strength of 14.27 MPa as presented in Figure 4.

Table 3 ANOVA test for mechanical properties of mahogany root wood
Tablica 3. ANOVA test rezultata mehaničkih svojstava korijena mahagonija

Properties / *Svojstva*	***df***	***F*-value**	***P*-value**
MOE	2	133.498	0.001**
MOR	2	492.841	0.001**
COM	2	289.059	0.001**
Shear strength *smična čvrstoća*	2	37.376	0.001**
Hardness / *tvrdoća*	2	1.017	0.368ns

** = significant at $p < 0.05$, ns = not significant; *MOE* – modulus of elasticity; *MOR* – modulus of rupture; *COM* – compressive strength parallel to the grain.
*** = značajno pri p < 0,05, ns = nije značajno; MOE – modul elastičnosti; MOR – modul loma; COM – čvrstoća na tlak paralelno s vlakancima*

The ANOVA results (Table 3) indicate that root type significantly affects compressive strength at a 5 % significance level. Furthermore, Turkey's multiple comparison tests confirm that the differences in compressive strength between root types are significant. The ANOVA results show that root type significantly affects shear strength at a 5 % significance level. Additionally, Turkey's multiple comparison tests confirm that the differences in shear strength between the root types are significant. The ANOVA results indicate that root type has no significant effect on hardness at a 5 % significance level. Consistently, Turkey's multiple comparison tests show that the differences in hardness between the root types are insignificant.

3.2.4 Shear strength parallel to the grain
3.2.4. Smična čvrstoća paralelno s vlakancima

The results of the ANOVA for the shear strength of Root 1, Root 2, and Root 3, respectively, are significantly different between roots. Root 3 recorded the highest shear strength (17.22 MPa), while Root 1 recorded the least (14.27 MPa). This could be caused by genetic and growth factors as the root bole increases density and all mechanical test conducted increased. Mascarenhas *et al.* (2022) measured similar parameters of shear strength (10.4 MPa) when he researched the wood quality of *Khaya senegalensis*, while the average shear strength of the current study was 9.95 MPa.

3.2.5 Hardness
3.2.5. Tvrdoća

The ANOVA table shows that hardness values for Root 1, Root 2, and Root 3 show that Root 2 and Root 3 had the highest values, followed by Root 1; nonetheless, there was no discernible variation in hardness amongst the roots. This means that mahogany roots have similar hardness properties regardless of the environment and other genetic factors. It could also be the morphological structure of the roots and other anatomical structures within the tree, such as the fibre length and other chemical deposits. The current results fall in line with the parameters measured by França *et al.* (2024) on African mahogany, with results in Janka hardness, tangential, and radial, 4.58 kN, and 3.55 kN, respectively. However, the mahogany wood was lower in compressive strength parallel and perpendicular to the grain (46.19 MPa) (8.07 MPa) than the other mahogany wood. Mascarenhas *et al.* (2022) measured Janka hardness of 342 kN in their studies.

4 CONCLUSIONS
4. ZAKLJUČAK

The study on mahogany root wood was conducted to utilise roots that are usually abundant after felling and cutting their stems for wood and as an alternative to mahogany stem wood to increase the demand for mahogany wood to serve small-scale industries.

The study revealed a close relationship between the mahogany root wood and the stem wood of the same species for all the parameters measured, except hardness, which had a slightly lower value.

The root wood of *K. ivorensis* trees, based on density and strength properties, would be classified for use in class 3 and 4 according to EN 252 (CEN 2014) and considered appropriate for analogous applications of hardwood species (*Pterocarpus soyauxii*, *Diospyros spp*., *Tectona grandis, Dalbergia iatifolia*) often utilised as structural supports (beams and columns), bridges, flooring, railway sleepers, utility poles, mine props, boat building, as well as highly-priced furniture and cabinets.

Root wood exhibited high values in both physical and mechanical properties, which are the basis for wood utilisation and, therefore, can be used for structural and non-structural applications.

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