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ASSESSMENT OF THE PHYSICAL AND MECHANICAL PROPERTIES OF *Pseudocedrela kotschyi* WOOD FROM GHANA'S SAVANNAH ZONE: VERTICAL VARIATION AND UTILIZATION IMPLICATIONS

OCENA FIZIKALNIH IN MEHANSKIH LASTNOSTI LESA *Pseudocedrela kotschyi* IZ OBMOČJA SAVANE V GANI: VERTIKALNE SPREMEMBE IN POMEN ZA NJEGOVO UPORABO

Bashiru WONGARA IBRAHIM[1], Bih KOFI FRANCIS[2], Issah CHAKURAH[3]

(1) Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development, Department of Wood Science and Technology, KUMASI, Ghana, wonbash@gmail.com

(2) Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development, Department of Wood Science and Technology, KUMASI, Ghana, kfbih@aamusted.edu.gh

(3) University of Cape Coast, Department of Vocational and Technical Education, Cape Coast - Ghana, academiachakurah@gmail.com

ABSTRACT

This study assessed the physical and mechanical properties of *Pseudocedrela kotschyi* wood from Ghana's Savannah zone using three mature trees from Jeyiri in the Wa East District. Specimens from the bottom, middle, and top stem sections were tested following BS 373 (1957) protocols. The results revealed significant vertical gradients in wood properties: moisture content increased with height from 44.5% to 49.54% ($p = 0.001$), while density also decreased from 747.92 kg/m^3 to 705.63 kg/m^3 ($p = 0.042$). Dimensional stability deteriorated upward, with volumetric shrinkage rising from 9.48% to 12.46% ($p = 0.005$) and volumetric swelling increasing from 10.09% to 15.41% ($p = 0.003$). All mechanical properties declined with height: the modulus of elasticity decreased from 4,801 to 4,077 MPa, the modulus of rupture from 24.26 to 19.95 MPa, compression strength from 37.82 to 33.96 MPa, and shear strength from 16.62 to 13.08 MPa. Overall, *P. kotschyi* exhibits medium-density hardwood characteristics and requires position-based utilization and grading strategies.

Keywords: *Pseudocedrela kotschyi*, wood properties, vertical variation, savannah zone, timber utilization, dimensional stability, mechanical properties, position-based grading, tropical hardwood

IZVLEČEK

V tej študiji so ocenili fizikalne in mehanske lastnosti lesa *Pseudocedrela kotschyi* iz območja Savannah v Gani z uporabo treh odraslih dreves iz Jeyirija v okrožju Wa East. Vzorci iz spodnjega, srednjega in zgornjega dela debla so bili testirani po protokolih BS 373 (1957). Rezultati so pokazali znatne vertikalne gradiente v lastnostih lesa: vsebnost vlage se je z višino povečala s 44,5 % na 49,54 % ($p = 0,001$), medtem ko se je gostota zmanjšala s 747,92 kg/m^3 na 705,63 kg/m^3 ($p = 0,042$). Dimenzijska stabilnost se je poslabšala navzgor, pri čemer se je volumetrično krčenje povečalo z 9,48 % na 12,46 % ($p = 0,005$), volumetrično nabrekanje pa z 10,09 % na 15,41 % ($p = 0,003$). Vse mehanske lastnosti so se z višino zmanjševale: modul elastičnosti se je zmanjšal s 4801 na 4077 MPa, modul lomnosti s 24,26 na 19,95 MPa, tlačna trdnost s 37,82 na 33,96 MPa in strižna trdnost s 16,62 na 13,08 MPa. Na splošno ima *P. kotschyi* značilnosti trdega lesa srednje gostote in zahteva strategije izrabe in razvrščanja na podlagi položaja.

Ključne besede: *Pseudocedrela kotschyi*, lastnosti lesa, vertikalne variacije, območje savane, izraba lesa, dimenzijska stabilnost, mehanske lastnosti, razvrščanje na podlagi položaja, tropski trdi les

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1 INTRODUCTION

1 UVOD

Timber utilization in engineering and construction applications fundamentally depends on understanding the mechanical and physical properties of the wood species involved (Jimoh and Ibitolu, 2018). However, significant knowledge gaps exist regarding these properties for several lesser-known indigenous timber species in Ghana, especially those from the Savannah ecological zone (Asase et al., 2005; Antwi-Boasiako and Boadu, 2016).

Pseudocedrela kotschyi is a deciduous hardwood tree belonging to the family Meliaceae and is widely distributed across tropical Africa, particularly within forest–savannah transition zones. In Ghana, the species is locally known as 'Bonga' and serves as an essential resource for rural livelihoods. It is used extensively for traditional medicine, local building materials, charcoal, and fuelwood (Asase et al., 2005). Despite its widespread occurrence and traditional uses, limited scientific documentation exists on the engineering properties of *P. kotschyi* wood sourced specifically from Ghana's Savannah zone.

Recent studies have attempted to address these knowledge gaps but remain geographically limited. Research on *Pseudocedrela kotschyi* has focused on its medicinal and chemical properties (Alhassan et al., 2021). Dadzie et al. (2018), in a study on similar species originating from different forest zones, reported that the wood exhibited medium strength properties. However, the unique ecological and climatic conditions within Ghana's Savannah region could significantly influence wood properties, making extrapolation from other zones unreliable.

Ghana's Savannah zone covers approximately 70% of the country's land area and holds considerable potential for the sustainable use of timber species, including *P. kotschyi* (Dadzie and Amoah, 2015). However, unsustainable logging, charcoal burning, and agricultural expansion threaten the species' population, emphasizing the need for informed utilization strategies based on comprehensive property data.

Understanding vertical variation in wood properties is crucial for optimizing timber utilization. Studies have shown that mechanical and physical properties can vary significantly within individual trees depending on height position, growth conditions, and wood maturity (Dadzie and Amoah, 2015). Such variations have important implications for strength grading, processing strategies, and end-use applications.

This study aimed to evaluate the physical and mechanical properties of *P. kotschyi* wood sourced specifically from Ghana's Savannah zone, with particular emphasis on vertical variation patterns within trees. The findings provide essential baseline data for sustainable utilization, strength grading, and evidence-based poli-

Fig. 1: Preparation of specimens for testing: A) felling of selected trees, B) measuring tree diameters, C) sawing specimens to the required sizes in accordance with selected standards, and D) prepared specimens ready for testinga

Slika 1: Priprava vzorcev za testiranje: A) sečnja izbranih dreves, B) merjenje premerov dreves, C) žaganje vzorcev na zahtevane velikosti v skladu z izbranimi standardi in D) pripravljeni vzorci za testiranje cy formulation for this lesser-known but economically important species.

2 MATERIALS AND METHODS

2 MATERIALI IN METODE

2.1 Study Area and Sample Preparation

2.1 Območje raziskav in priprava vzorcev

2.1.1 Study Area

2.1.1 Območje raziskav

The study was conducted in Jeyiri, Wa East District, Upper West Region, Ghana (10°10'N, 1°45'W). This location was selected due to its proximity to the Ambalaara Forest Reserve and the natural abundance of *P. kotschyi.* The area experiences a unimodeal rainfall regime, with annual precipitation ranging from 840 to 1400 mm and a mean temperature of approximately 31°C during the day and 26°C at night. Three mature *P. kotschyi* trees were purposively selected from natural forest stands based on stem quality and accessibility. The selected trees had diameters at breast height (DBH) of 43, 47, and 51 cm, with corresponding total heights of 7.90, 8.70, and 7.41 m, respectively. The trees were felled and immediately sectioned into three equal parts based on total height: bottom (0–33%), middle (33–66%), and top (66–100%) stem sections.

2.1.2 Sample Preparation

2.1.2 Priprava vzorcev

Wood processing and testing were conducted at the Wood and Furniture Testing Laboratory of the Forestry Research Institute of Ghana (FORIG), Kumasi. From each stem section, defect-free specimens were prepared following standardized dimensions specified in BS 373 (1957) (Figure 1). All specimens were quarter-sawn to maintain consistent grain orientation and labelled according to tree number, stem position, and test type.

2.2 Physical Properties *P. kotschyi* Wood

2.2 Fizikalne lastnosti lesa *P. kotschyi*

2.2.1 Moisture Content (MC)

2.2.1 Vlažnost lesa (MC)

Moisture content was determined using 15 replicates per stem section. Samples were weighed and oven-dried at 103 ± 2 °C for 24 hours and then cooled in a desiccator until a constant weight was achieved. Moisture content was calculated as a percentage of the oven-dry weight following the standard procedure.

$$MC\,(\%) = \left[\frac{(W_1 - W_0)}{W_0}\right] \times 100$$

where W_1 is the initial weight and W_0 is the oven-dry weight.

2.2.2 Basic Density

2.2.2 Osnovna gostota

Basic density was determined according to ASTM D143-94 (2007) using 20 × 20 × 20 mm specimens (45 samples per section). Specimens were soaked in distilled water for 72 hours to ensure that their moisture content exceeded the fibre saturation point. Dimensions were measured using digital calipers (± 0.001 mm). Samples were then oven-dried at 103 ± 2 °C to constant weight. Basic density was calculated as the ratio of oven-dry mass to saturated volume.

$\rho = Mod/Vsat$

Where, Mod = oven-dry mass

Vsat = saturated volume

2.2.3 Dimensional Stability Testing

2.2.3 Preizkus dimenzijske stabilnosti

Shrinkage and swelling tests were conducted according to BS 373 (1957) using 20 × 20 × 100 mm specimens (15 samples per stem section per test). Conditioning was carried out at 20 °C and 65% relative humidity to approximately 12% moisture content. For shrinkage testing, conditioned samples were oven-dried at 103 ± 2 °C until constant weight, and initial and final dimensions were recorded. For swelling testing, oven-dried samples were soaked in distilled water for 72 hours and dimensions were recorded again. Percentage shrinkage and swelling were calculated based on dimensional changes.

$$\text{Shrinkage}\,(\%) = \frac{D - Do}{D} \times 100$$

where D is the initial dimension (before oven-drying) and D_o is the final dimension (after oven-drying).

$$\text{Swelling}\,(\%) = \frac{Df - D}{D} \times 100$$

where D is the initial dimension (before soaking) and Df is the final dimension (after soaking).

2.3 Mechanical Properties

2.3 Mehanske lastnosti

2.3.1 Bending Properties (MOE and MOR)

2.3.1 Upogibna trdnost (MOE in MOR)

Modulus of elasticity (MOE) and modulus of rupture (MOR) were determined using three-point bending tests on 20 × 20 × 300 mm specimens (15 replicates per section). Tests were conducted using a universal testing machine with specimens placed on supports spaced 250 mm apart. Load was applied at the midpoint until failure, and maximum load and deflection were recorded.

$$MOR = \frac{3PL}{2bh^2}$$

where MOR is modulus of rupture (N/mm^2), P is the maximum load (N), L is the span (mm), b is the specimen width (mm), and h is the specimen height (mm).

MOE in three-point bending was determined in accordance with BS373 (1957).

$$MOE = \frac{p/l^3}{4\Delta/wh^3}$$

where P is the load at the limit of proportionality (N), l is the span (mm), Δ is the mid-span deflection at the limit of proportionality (mm), w is the specimen width (mm), and h is the specimen height (mm).

2.3.2 Compression Strength Parallel to the Grain
2.3.2 Tlačna trdnost vzporedno z vlakni

Compression strength was evaluated using 20 × 20 × 60 mm specimens (45 samples per stem section) following BS 373 (1957). Tests were conducted on an Instron universal testing machine, with load applied along the longitudinal axis at a uniform rate until failure (Figure 2).

Compression strength was calculated as:

$$Compression\ Strength = \frac{P}{A}$$

where p = the maximum load (N) and A is the cross-sectional area (mm^2)

2.3.3 Shear Strength Parallel to the Grain
2.3.3 Strižna trdnost vzporedno z vlakni

Shear strength parallel to the grain was evaluated using small clear wood specimens measuring **50 × 50 × 50 mm**. For each stem section, **15 replicates** were prepared. A compressive load was applied **parallel to the grain** on the radial–tangential plane of the specimens until **shear failure** occurred. The maximum load at failure was recorded and used to calculate the shear strength of the material (Figure 3).

Shear strength parallel to the grain was calculated as:

$$Shear\ Strength = \frac{P}{A}$$

where P is the maximum load (N) and A is the shear area (mm^2)

2.3.4 Hardness Testing (Janka Indentation)
2.3.4 Preizkus trdote po Janki

Janka hardness (N) was determined as the load required to embed a hardened steel ball (11.28 mm in diameter) to a depth of 5.6 mm into the radial and tangential surfaces of the specimen, following BS 373 (1957).

2.4 Statistical Analysis
2.4 Statistična analiza

Data were analysed using one-way ANOVA to evaluate axial variation between stem positions. Where significant differences were detected, Bonferroni post-hoc tests were used for pairwise comparisons. Statistical significance was set at α = 0.05. Analyses were performed using SPSS (Statistical Package for the Social Sciences).

3 RESULTS
3 REZULTATI

3.1 Physical Properties
3.1 Fizikalne lastnosti

3.1.1 Moisture Content
3.1.1 Vlažnost lesa

Moisture content analysis revealed a significant vertical gradient within *P. kotschyi* trees ($F = 85.19$, $p = 0.001$). Values increased from 44.5 ± 0.8% in the bot-

Fig. 2: Determination of compression strength parallel to the grain of *P. kotschyi* specimens using an Instron universal testing machine

Slika 2: Določanje tlačne trdnosti vzporedno z vlakni vzorcev vrste *P. kotschyi* z uporabo univerzalnega preskusnega stroja Instron

Fig. 3: Determination of shear strength parallel to the grain of *P. kotschyi* specimens using an Instron universal testing machine

Slika 3: Določanje strižne trdnosti vzporedno z vlakni vzorcev *P. kotschyi* z uporabo univerzalnega preskusnega stroja Instron

tom section to 49.54 ± 0.8% in the top section. Pairwise comparisons indicated no significant difference between the bottom and middle sections (p = 0.642), whereas both differed significantly from the top section (p = 0.001 and p = 0.039, respectively). The observed vertical moisture gradient is primarily attributed to an increasing proportion of physiologically active sapwood and higher water transport demands toward the crown (Dsouza et al., 2025). Upper stem sections typically store more free water due to greater vessel functionality, juvenile wood characteristics, and continuous involvement in transpiration processes. Consequently, the top sections of *P. kotschyi* retain significantly higher moisture content than the bottom and middle portions.

3.1.2 Density
3.1.2 Gostota

Wood density decreased from the bottom to the top of the stem, with mean values of 747.92 ±70.41, 736.01 ± 59.54, and 705.63 ± 46.64 kg/m^3 for the bottom, middle, and top sections, respectively. The observed decrease in wood density from the bottom toward the top of the stem is consistent with known anatomical and physiological gradients in hardwoods. Upper-stem regions often contain a larger proportion of juvenile wood. Juvenile wood is typically characterized by higher microfibril angle, thinner cell-walls, and shorter fibres. In many species, this correlates with lower oven-dry density compared to mature wood (Tampori et al., 2024). In addition, ANOVA analysis results indicated a significant effect of vertical position (F = 7.8, p = 0.042), although pairwise comparisons did not reach statistical significance. These findings align with recent studies reporting moderate vertical variation in density in several tropical and temperate hardwood species due to similar anatomical gradients (Alméras et al., 2025; Hein and Brancheriau, 2011).

Table 1: Statistical analysis of the physical properties of *P. kotschyi*

Preglednica 1: Statistična analiza fizikalnih lastnosti *P. kotschyi*

Properties Lastnosti	F-value F-vrednost	P-value P-vrednost	Tree sections / Drevesni deli		
			BOTTOM / Dno	MIDDLE / Srednji	TOP / Zgoraj
Moisture Content (%) Vsebnost vlage (%)	85.19	0.001**	44.5 ± 0.8	45.45 ± 1.41	49.54 ± 0.8
DENSITY kg/m³ Gostota (kg/m³)	7.8	0.042**	747.92 ± 70.41	736.01 ± 59.54	705.63 ± 46.64
Volumetric Shrinkage (%) Prostorninsko krčenje (%)	27.54	0.005**	10.09 ± 1.08	11.16 ± 1.91	11.16 ± 1.91
Volumetric Swelling (%) Prostorninsko nabrekanje (%)	15.72	0.003**	10.09 ± 1.08	12.86 ± 1.19	15.41 ± 0.94

Note: ** = significant at p < 0.05; ns = not significant
Opomba: ** = statistično značilno pri p < 0,05, ns = ni statistično značilno

3.1.3 Volumetric Shrinkage
3.1.3 Volumetrično krčenje

Volumetric shrinkage demonstrated a significant increasing trend with height (F = 27.54, p = 0.005), ranging from 10.09 ± 1.08 % at the bottom to 11.16 ± 1.91% at the top. This represents a 31% increase that exceeds typical expectations for hardwood species and has important processing implications.

The results showed a highly significant effect (F = 27.54, p = 0.005), indicating that vertical position strongly influences shrinkage behavior.

The post-hoc analysis revealed that while the bottom-middle difference was marginally significant (p = 0.086), the pattern suggests a progressive increase in shrinkage potential with height. The bottom-top comparison showed the largest difference (2.98%, p = 0.101), and the middle-top difference was 2.52% (p = 0.108).

3.1.4 Volumetric Swelling
3.1.4 Volumetrično nabrekanje

Volumetric swelling results showed the most pronounced vertical gradient among the physical properties (F = 15.72, p = 0.003), increasing from 10.09 ± 1.08% in the bottom section to 15.41 ± 0.94% in the top section. The bottom-top comparison was statistically significant (5.32% difference, p = 0.029), representing a 53% increase, with critical implications for applications where dimensional stability is critical.

3.2 Mechanical Properties
3.2 Mehanske lastnosti

3.2.1 Modulus of Elasticity (MOE)
3.2.1 Modul elastičnosti (MOE)

MOE results demonstrate a clear decreasing trend with increasing height (F = 30.84, p = 0.004), with values of 4,801.39 ± 74.21 MPa, 4,618.86 ± 131.99 MPa, and 4,077.26 ± 94.92 MPa for the bottom, middle, and top sections, respectively. The bottom–top difference of 724.13 MPa approached statistical significance (p = 0.053) and represents a practically meaningful 15% reduction in stiffness, indicating that vertical position strongly influences elastic properties.

3.2.2 Modulus of Rupture (MOR)
3.2.2 Upogibna trdnost (MOR)

MOR followed a similar decreasing pattern (F = 33.65, p = 0.003), ranging from 24.26 ± 0.9 MPa in the bottom section to 19.95 ± 0.14 MPa in the top section. The bottom–top comparison was statistically significant (4.32 MPa difference, p = 0.033), representing an 18% reduction in bending strength and indicating that vertical position significantly affects bending performance.

3.2.3 Compression Strength Parallel to the Grain
3.2.3 Tlačna trdnost vzporedno z vlakni

Compression strength parallel to the grain decreased from 37.82 ± 3.67 MPa in the bottom section to 33.96 ± 2.53 MPa in the top section (F = 19.7, p = 0.008). Although individual pairwise comparisons were not statistically significant, the overall 10% reduction is practically relevant for load-bearing applications and is consistent with expected within-stem anatomical variation.

3.2.4 Shear Strength Parallel to the Grain
3.2.4 Strižna trdnost vzporedno z vlakni

Shear strength demonstrated the largest proportional change among the mechanical properties (F = 29.1, p = 0.004), decreasing from 16.62 ± 0.59 MPa in the bottom section to 13.08 ± 0.51 MPa in the top section. The middle–top comparison was statistically significant (1.57 MPa difference, p = 0.045). Overall,

Table 2: Statistical analysis of the mechanical properties of *P. kotschyi*

Preglednica 2: Statistična analiza mehanskih lastnosti *P. kotschyi*

MECHANICAL PROPERTIES MEHANSKE LASTNOSTI	F-VALUE F-vrednost	P-VALUE P-vrednost	TREE SECTIONS / Drevesni deli		
			BOTTOM / Dno	MIDDLE / Srednji	TOP / goraj
MOE (MPa)	30.84	.004**	4801.39 ± 74.21	4618.86 ± 131.99	4077.26 ± 94.92
MOR (MPa)	33.65	.003**	24.26 ± 0.9	22.4 ± 1.36	19.95 ± 0.14
COMPRESSION (MPa) Tlačna trdnost (MPa)	19.7	.008**	37.82 ± 3.67	35.55 ± 2.65	33.96 ± 2.53
SHEAR (MPa) Strižna trdnost (MPa)	29.1	0.004 **	16.62 ± 0.59	14.65 ± 0.24	13.08 ± 0.51
HARDNESS Radial (kN) Trdota radialno (kN)	2.67	0.183ns	4.04 ± 0.03	4.01 ± 0	4 ± 0
HARDNESS Tangential (kN) Trdota tangencialno (kN)	17.17	0.011 **	4.05 ± 0.02	4.01 ± 0	4 ± 0

Note: ** = significant at p < 0.05; ns = not significant

Opomba: ** = statistično značilno pri p < 0,05, ns = ni statistično značilno the 21% reduction highlights the critical importance of considering vertical position where shear resistance is critical.

3.2.5 Hardness Properties

3.2.5 Trdota

Both radial and tangential hardness showed remarkable consistency across vertical positions, with minimal variation from 4.00 to 4.05 for both orientations. The analysis showed no significant effect for radial hardness ($F = 2.67$, $p = 0.183$), while tangential hardness showed statistical significance ($F = 17.17$, $p = 0.011$) but with differences within measurement precision limits.

4 DISCUSSION

4 RAZPRAVA

4.1 Physical Properties

4.1 Fizikalne lastnosti

The observed moisture content gradient (44.5% to 49.54%) reflects fundamental physiological processes in tree growth, with magnitudes that significantly impact timber utilization strategies. The 5% increase in moisture content from the bottom to the top is consistent with established patterns of cambial activity, where younger wood in upper-stem positions tends to retain higher moisture due to active metabolic processes (Alhassan et al., 2021). This gradient necessitates position-based drying schedules to minimize defects during processing. As shown in Table 1, density decreased with height (747.92 to 705.63 kg/m^3), which is consistent with typical hardwood patterns in which density is often higher in the lower stem due to greater extractives content and the deposition of tyloses, and lower in the upper stem because of a high percentage of juvenile wood with thinner fibre walls and a larger lumen fraction. This finding may reflect specific adaptations to environmental conditions in Ghana's Savannah zone, where water limitation promotes denser wood formation throughout the stem. These density values place *P. kotschyi* in the medium-density hardwood category, consistent with ranges reported for the species across West Africa (Louppe et al., 2008).

The dimensional stability results present the most critical challenges for processing and end-use applications. The 31% increase in volumetric shrinkage and 53% increase in volumetric swelling from the bottom to the top sections exceed the typical within-stem variation reported for many tropical hardwoods. The pronounced increase in volumetric shrinkage and swelling with stem height can be attributed to established anatomical and moisture-related gradients within hardwood stems. Upper-stem regions typically contain a higher proportion of juvenile wood, thinner cell walls, and lower cell-wall crystallinity, all of which contribute to greater dimensional movement during drying (Hashemi and Kord, 2011; Lu et al., 2021; Topaloglu and Erisir, 2018). Such marked variation necessitates position-based segregation during processing to prevent differential movement that can lead to warping, checking, and other defects (Dadzie et al., 2018).

4.2 Mechanical Properties

4.2 Mehanske lastnosti

The systematic decrease in mechanical properties with increasing stem height follows expected anatomical patterns, as mature wood at the base typically exhibits superior lignification and cell-wall development. The 15% reduction in MOE (4,801 to 4,077 MPa) and 18% reduction in MOR (24.26 to 19.95 MPa) have direct implications for structural applications. Although these values are within the range reported for comparable African timber species (Jimoh and Ibitolu, 2018), they are also consistent with findings from savannah environments, where growth conditions may affect wood properties. The 21% reduction in shear strength represents the largest proportional change among the mechanical properties, highlighting an important consideration for engineered wood products and structural elements in which shear capacity often governs design limitations. These findings support previous observations that wood properties, including chemical composition, can vary significantly in tropical species (Hay et al., 2007).

Hardness showed little variation across stem positions, which distinguishes P. kotschyi from species in which hardness more closely tracks changes in density and mechanical strength. This uniformity suggests that the wood may be suitable for surface applications regardless of stem position.

The relatively uniform Janka hardness observed along the stem of *P. kotschyi* likely reflects a stable microstructure and consistent chemical reinforcement throughout the bole rather than density-driven variability. Many tropical hardwoods maintain a constant fibre-wall morphology (cell-wall thickness, fibre lumen size, microfibril orientation) along the stem, which stabilizes indentation resistance regardless of small density fluctuations (Li et al., 2021). Unlike species where large vessel size, variable parenchyma fraction, or juvenile-to-mature wood contrasts lead to uneven hardness, *P. kotschyi* may have a dominant fibre matrix with minimal vessel or parenchyma variation along the bole, making hardness less sensitive to verti-

Table 3: Comparative density and bending properties of *P. kotschyi* and selected wood species

Preglednica 3: Primerjava gostote in upogibnih lastnosti lesa vrste *P. kotschyi* z izbranimi lesnimi vrstami

Species	Typical oven-dry density (kg m⁻³) Značilna gostota v absolutno suhem stanju (kg m⁻³)	MOE (MPa)	MOR (MPa)	Structural interpretation Strukturna razlaga	Sources (in-text citation) Viri – citati v besedilu
Triplochiton scleroxylon (Wawa)	350 – 420	5,000 – 7,000	40 – 60	Low density, moderate strength; lightweight furniture, interior use	(Jamala et al., 2013)
Terminalia superba (Ofram)	450 – 560	8,000 – 10,500	70 – 90	Efficient fibre structure; better strength–density ratio	(Okoh, 2014)
Khaya ivorensis (African mahogany)	560 – 650	9,000 – 12,000	80 – 100	Well-developed fibre walls, lower MFA	(Tekpetey et al., 2008)
Nesogordonia papaverifera (Danta)	650 – 750	11,000 – 14,000	90 – 120	Dense, mechanically efficient hardwood	(Kwaku et al., 2022)
Fagus sylvatica (European beech)	~720	12,000 – 14,000	100 – 120	Highly optimized fibre anatomy; benchmark hardwood	(Gryc et al., 2008; Skarvelis & Mantanis, 2013)
P. kotschyi	700 – 813	4,077.26 - 4,801.39	19.95 - 24.26	Medium-density hardwood with low-to-moderate bending properties; suitable for non-load-bearing structural components, furniture parts and interior applications.	Findings from present study

cal anatomical gradients (Wang et al., 2023; Zieminska et al., 2013).

Despite having a density comparable to *Nesogordonia papaverifera* and European beech, *P. kotschyi* exhibits substantially lower MOE and MOR. This confirms that **density alone is an insufficient predictor of mechanical performance**, particularly across species. Compared with Ghanaian timbers such as *Terminalia superba* and *Khaya ivorensis*, *P. kotschyi* shows a markedly lower strength-to-density ratio, indicating less efficient fibre wall reinforcement and stress transfer. The contrast with European beech further highlights the influence of **fibre wall thickness, microfibril angle, and tissue organization**, rather than bulk density, in controlling bending stiffness and strength. These comparisons support classifying *P. kotschyi* as a **medium-density, low-to-moderate strength hardwood**, suitable for non-load bearing structural components, furniture parts, and interior applications, but not for high-performance structural uses.

4.3 Density-Mechanical Property Relationships along the Stem

4.3 Razmerja med gostoto in mehanskimi lastnostmi vzdolž debla

Wood density decreased from the bottom (747.92 ± 70.41 kg m^{-3}) to the middle (736.01 ± 59.54 kg m^{-3}) and top (705.63 ± 46.64 kg m^{-3}) of the stem, with vertical position exerting a significant effect ($F = 7.8$, $p = 0.042$). Mechanical properties also declined with stem height. The modulus of elasticity (MOE) and modulus of rupture (MOR) decreased by 15% and 18%, respectively, while shear strength showed the largest proportional reduction (21%). This parallel pattern indicates that both density and anatomical maturity may contribute to mechanical performance in *P. kotschyi,* although density alone does not fully explain the observed difference. The superior mechanical properties of basal wood likely reflect a higher proportion of mature wood with greater lignification, thicker cell walls, longer fibres, and a lower microfibril angle, which enhance stiffness and strength. Upper-stem wood, although slightly denser, likely contains more juvenile tissue with less efficient load transfer, resulting in reduced MOE, MOR, and shear strength. Similar partial decoupling of density and strength has been reported for other tropical hardwoods, where anatomical maturity rather than bulk density alone governs mechanical behaviour.

In contrast, Janka hardness remained uniform along the stem despite the observed density and strength gradients. This suggests a stable, fibre-dominated microstructure and consistent chemical reinforcement throughout the bole, making indentation resistance less sensitive to vertical anatomical variation. Overall, the results indicate a moderate inverse relationship between density and the mechanical properties measured here, highlighting the greater suitability of lower-stem wood for structural applications, while upper-stem material may be more appropriate for non-load-bearing or surface uses.

5 CONCLUSIONS AND RECOMMENDATIONS

5 ZAKLJUČKI IN PRIPOROČILA

This comprehensive evaluation of *P. kotschyi* wood properties from Ghana's Savannah zone revealed significant vertical gradients that fundamentally impact utilization strategies. The study establishes that while the species exhibits medium-density hardwood characteristics suitable for various applications, position-based approaches are essential for optimal resource utilization.

Key findings include:

1. Moisture content and dimensional stability showed significant gradients with height.

2. Density showed a consistent decrease with height.

3. All mechanical properties showed consistent decreases with height.

4. Hardness remained relatively uniform throughout the stem.

Based on these findings, several practical recommendations can be made:

1. Position-based grading systems should be developed to optimize resource utilization, with bottom sections designated for structural applications and upper sections for non-structural uses.

2. Segregated processing protocols are essential, particularly for drying schedules that account for the significant moisture content and dimensional stability differences between stem positions.

3. Stabilization treatments may be necessary for upper-section timber intended for applications requiring dimensional precision.

4. Quality standards specific to *P. kotschyi* should incorporate position-based property variations to ensure appropriate material selection and performance expectations.

The study establishes that *P. kotschyi* from Ghana's Savannah zone exhibits significant axial property variations that require specialized management approaches. While the species demonstrates potential for various timber applications, successful utilization depends on understanding and accommodating these within-tree variations through appropriate processing and grading strategies. These findings provide essential baseline data to support sustainable management of this important savannah forest resource and contribute to a broader understanding of tropical hardwood property variations.

The trees analysed in this study were relatively short, with heights up to 8.7 m. This limited vertical development may have influenced the magnitude and pattern of axial variation observed. In taller, fully mature trees, gradients in moisture content, density, mechanical strength, and shrinkage/swelling are often more pronounced due to a greater proportion of mature heartwood at the base and increased sapwood in the upper bole. Therefore, while the present results provide valuable baseline data for *P. kotschyi* in Ghana's Savannah zone, caution is warranted when extrapolating these results to larger, more mature individuals. Future studies on taller trees may reveal stronger axial variation and could further refine processing, grading, and management strategies for optimal utilization of this timber species.

6 SUMMARY

This study comprehensively evaluated the physical and mechanical properties of *Pseudocedrela kotschyi* wood from Ghana's Savannah zone, focusing on vertical variation patterns within trees. Three mature trees were harvested and tested according to standardized protocols, revealing significant property gradients from the bottom to the top of the stem. Physical properties showed increasing moisture content (44.5% to 49.54%) and markedly reduced dimensional stability, with volumetric shrinkage rising from 9.48% to 12.46% and volumetric swelling increasing from 10.09% to 15.41%. Density consistently decreased with height (747.92 to 705.63 kg/m^3). All mechanical properties also decreased significantly with height: modulus of elasticity declined from 4,801 to 4,077 MPa, modulus of rupture from 24.26 to 19.95 MPa, compression strength from 37.82 to 33.96 MPa, and shear strength from 16.62 to 13.08 MPa. In addition, the hardness properties of *P. kotschyi* wood exhibited substantial uniformity along the vertical stem positions. Both radial and tangential hardness values showed minimal variation (4.00–4.05 kN), indicating a high level of consistency across the sampled sections. Overall, these findings demonstrate that *P. kotschyi* requires position-based utilization strategies, with bottom sections suitable for structural applications and upper sections better suited for non-structural uses. The results provide essential baseline data for sustainable utilization and inform the development of appropriate grading systems for this lesser-known but economically important species.

6 POVZETEK

Ta študija je celostno ovrednotila fizikalne in mehanske lastnosti lesa vrste *Pseudocedrela kotschyi* iz savanskega območja Gane, s poudarkom na vertikalnih variacijah lastnosti znotraj posameznega drevesa. Tri

zrela drevesa so bila posekana in preizkušena v skladu s standardiziranimi protokoli, pri čemer so bili ugotovljeni izraziti gradienti lastnosti od spodnjih proti zgornjim delom debla. Fizikalne lastnosti so pokazale naraščajočo vsebnost vlage (od 44,5 % do 49,54 %) ter izrazito povečanje dimenzijske nestabilnosti, saj se je volumetrično krčenje povečalo z 9,48 % na 12,46 %, nabrekanje pa z 10,09 % na 15,41 %. Gostota se je z višino nenavadno povečevala (od 705,63 do 747,92 kg/m^3). Vse mehanske lastnosti so se z višino statistično značilno zmanjševale: modul elastičnosti s 4801 na 4077 MPa, upogibna trdnost s 24,26 na 19,95 MPa, tlačna trdnost s 37,82 na 33,96 MPa ter strižna trdnost s 16,62 na 13,08 MPa. Le trdota je ostala razmeroma konstantna vzdolž celotnega debla. Ugotovitve kažejo, da les vrste *P. kotschyi* zahteva strategije izkoriščanja, ki temeljijo na položaju v deblu, pri čemer so spodnji deli primernejši za konstrukcijsko uporabo, zgornji deli pa za nekonstrukcijske namene. Rezultati zagotavljajo pomembne izhodiščne podatke za trajnostno rabo ter prispevajo k razvoju ustreznih sistemov razvrščanja za to manj raziskano, a gospodarsko pomembno drevesno vrsto.

DATA AVAILABILITY
RAZPOLOŽLJIVOST PODATKOV

The research data supporting this study are available from the corresponding author upon reasonable request. All data were collected at the Wood and Furniture Testing Laboratory of the Forestry Research Institute of Ghana (FORIG) using standardized testing protocols. Raw data include physical and mechanical property measurements from 135 specimens across three stem positions.

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