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Wood Density and Mechanical Properties of *Pinus kesiya* Royle ex Gordon in Malawi

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Academic Editors: Sune Linder and Eric Jokela
Received: 24 May 2016; Accepted: 1 July 2016; Published: 7 July 2016

Abstract: Successful development of an appropriate tree breeding strategy and wood utilization requires information on wood properties. This study was therefore conducted to assess wood density and mechanical properties of *Pinus kesiya* Royle ex Gordon grown in Malawi. Wood samples from six families of *P. kesiya* at the age of 30 years were used for the study. The estimated mean wood density, Modulus of Elasticity (MoE), Modulus of Rupture (MoR) and moisture content were 0.593 ± 0.001 g/cm^3, 13.46 ± 0.07 GPa, 113.67 ± 0.57 MPa and 12.08% ± 0.03%, respectively. There were statistically significant ($p < 0.001$) differences in wood density and mechanical properties along the radial direction and stem height. Wood density and mechanical properties increased from pith to bark and decreased from the butt upwards. There were no significant ($p > 0.05$) differences in wood density and mechanical properties among the families. This is an indication that any tree among the families can be selected for tree improvement programs if density is considered as a variable. Wood density had a strong positive significant linear relationship with both MoE ($r = 0.790$; $p < 0.001$) and MoR ($r = 0.793$; $p < 0.001$). This suggests that it has the potential to simultaneously improve the wood density and mechanical properties of this species. Therefore, controlling wood density for the tree improvement program of *P. kesiya* in Malawi would have a positive impact on mechanical properties.

Keywords: *Pinus kesiya*; modulus of elasticity; modulus of rupture; wood density; tree improvement

1. Introduction

Pinus kesiya Royle ex Gordon is a softwood tree species of the family Pinaceae. It is one of the most valuable tree timber species in the tropics. Its world-wide demand is attributed to its high quality timber on account of the durability of the wood it produces [1]. *Pinus kesiya* is native to the Himalaya region (Asian): Burma, India, China, Laos, Philippines, Thailand, Tibet, and Vietnam and it grows well at altitudes from 300 to 2700 m above the sea level [2]. It has been successfully established as exotic in many countries of the world including Malawi, where it is raised as one of the fastest timber species. The tree grows to a height about 45 m with a straight, cylindrical trunk. It has a thick, reticulate and deeply fissured bark and pruinose branchlets with a waxy bloom [1].

It is vital to record the wood parameters prior to large scale expansion of plantations outside its natural range. The information on wood parameters can facilitate tree growth and wood quality in forest management and wood utilization. Wood quality assessment involves the consideration of wood density and mechanical properties [3]. Certain wood properties are reported to be good indicators of timber properties and uses. Modulus of Elasticity (MoE) and Modulus of Rupture (MoR) are important properties for the use of wood as structural material. MoE is an indication of stiffness of board or structural member while MoR is an indication of strength [4]. Reports from several researchers indicate that wood density is the most important property controlling MoE and MoR [5–7]. Therefore, the determination of MoE and MoR together with wood density is important to understand their relationships. The relationship among these properties are species specific [8]; for instance, other researchers [9,10] reported a strong relationship between wood density and mechanical properties in *Pinus patula*. On the other hand, other researchers [11] reported a weak relationship between wood density and mechanical properties in *Pinus resinosa* and there was no relationship between wood density and stiffness in *Pinus radiata* [12]. The relationships are of great importance in machine stress grading (placement of pieces of lumber of similar mechanical properties into different categories) and in tree breeding programs. They are used to predict the outcome of one parameter when the corresponding parameter has been improved [13].

Pinus kesiya plantations were established in Malawi in order to provide raw materials for sawn timber and to reduce pressure on tree species from the natural forest. Regardless of the establishment of these fast growing *Pinus kesiya* plantations adequate information about its wood density and mechanical properties are necessary for the Foresters to make wise management decision and grow trees of high quality wood that can lead to greater profitability for the forestry industry [14]. Despite these facts, no information is available on wood density and mechanical properties for *Pinus kesiya* grown in Malawi. Just like many other species, research on *Pinus kesiya* has concentrated on growth variables like height, diameter and volume [15,16]. Therefore, the main objective of this study was to assess wood density and mechanical properties of *Pinus kesiya* grown in Malawi. Specifically, the study aimed at: estimating and determining the variation of wood density and mechanical properties along the radial direction and stem height, determining the relationship between wood density and mechanical properties, and assessing the quality of timber produced from *Pinus kesiya* in Malawi based on their mechanical properties for grading purpose. The study provides information to wood industry experts on the potential use and sustainable use of the species when processing logs for timber. It also provides information to tree breeders to establish and refine breeding and deployment programs of the species. Finally, the study provides foundation for machine grading of *Pinus kesiya* timber in Malawi.

2. Materials and Methods

2.1. Study Area

The study was conducted in Chongoni Forest Plantation in Dedza, Malawi (Figure 1). It is situated about 85 km southeast of the capital, Lilongwe and lies on latitudes 14°10′ S and 14°21′ S and longitudes 34°09′ E and 34°17′ E. It is located between 1570 m and 1690 m above the sea level and receives about 1200 to 1800 mm rainfall per annum, with a mean annual temperature ranging from 7 °C to 25 °C.

2.2. Plant Material and Sampling

The materials for the study were collected from a *Pinus kesiya* seed orchard which was planted in 1984 at a spacing of 2.75 m × 2.75 m with seed source from Zimbabwe. The orchard consisted of 18 families which was planted in a completely randomized design in four replicates. All the silvicultural treatments (weeding, slashing, pruning and thinning) were done on the instruction of the breeder.

Six of the 18 families were chosen and a total of ninety straight boled trees (15 trees from each family) with no major defects were randomly selected. Logs of 50 cm length were cut at 1.3 m, 3.3 m, 5.3 m and 7.3 m above the ground per tree. The logs were further cut into 20 mm × 20 mm × 320 mm small wood specimens. A total of 1080 small wood specimens were collected, three specimens per log (inner, middle, and outer). A lot of care was taken to avoid any defects of the specimens. The average height and diameter at breast height of the trees expressed with standard deviations were 25.9 ± 2.8 m and 32.0 ± 3.9 cm, respectively. The north side of each tree was marked before felling. The trees were harvested in May 2014.

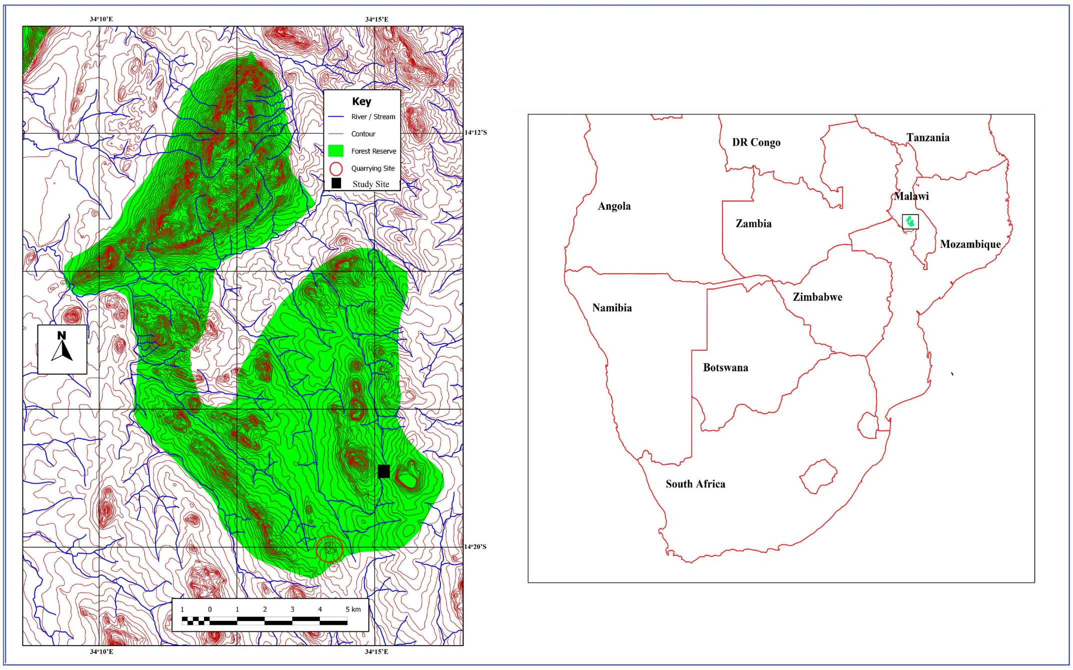


Figure 1. Location of Chongoni Forest Plantation in Southern Africa.

2.3. Sample Processing and Measurement

Each specimen was weighed using a digital scale and measurements were recorded as green mass (m_g). The specimens were then oven-dried at 105 °C to constant weight. Moisture content (MC) and wood density (ρ) were calculated using Equations (1) and (2):

$$\mathrm{MC} = \frac{\mathrm{m_g} - m_{od}}{m_{od}} \times 100 \quad (1)$$

$$\rho = \frac{m_{od}}{V_o} \quad (2)$$

where, m_{od} is the oven dry mass (g) and V_o is the wood oven dry volume, obtained by displacement method by immersing the specimen in a beaker. Then the specimens were subjected to bending test using Instron Tester over a span length of 300 mm. Load was applied to the center of the specimen at a constant speed of 0.11 mm/s. Load of the force plate and the corresponding deflection was recorded from the dial gauge for each sample (the recording was continued until it failed to support one tenth of the maximum load or deflected by more than 60 mm). MoR and MoE were calculated as:

$$MoR = \frac{3PL}{2bh^2} \quad (3)$$

$$MoE = \frac{P_1 L^3}{4d_1 bh^3} \quad (4)$$

where P is maximum load (N), d_1 is Load at the limit of proportionality (N), L is Span length (mm), b is width of the specimen, h is thickness of the specimen, and d_1 is the deflection at the limit of proportionality (mm). The average moisture content of the specimens was about 12%.

2.4. Statistical Analysis

Wood density, MoE and MoR data were tested for normality and homogeneity with Kolmogorov-Smirnov D and normal probability plot tests in SAS software version 9.1.3 [17]. After the two criteria were met the data were subjected to analysis of variance (ANOVA) using the same SAS software version 9.1.3 [17] with stem height and radial direction as fixed factors and family as random effect factor. Differences between treatments means were separated using Fischer's least significant difference (LSD) at the 0.05 level. Regression analysis was performed to determine the relationship between wood density and the mechanical properties.

Based on previous research [18], the boundary between juvenile wood and mature wood for *Pinus kesiya* grown in Malawi is ring number 10 from the pith. Therefore, data for juvenile wood and mature wood was subjected to analysis of variance, using SAS PROC GLM type 3 method, to find out if the variation of the mechanical properties were significantly different or not. Differences between treatment means were also separated using Fisher's least significant difference at the 0.05 level.

Grade yield for the specimens were checked using the grading standard of mechanical properties of timbers from South African standard for pine, South East Asia and Pacific Regions for softwood species, and the European standard for softwood species (Table 1).

Table 1. Mechanical grades of timber for South African Pine, South East Asia and Pacific Regions softwood species, and European Standard for softwood species.

Grading Standard	Grade	MoE (GPa)	MoR (MPa)
South African standard for pine	xxx	<7.8	
	S5	7.8–9.5	
	S7	9.6–11.9	
	S10	⩾12.0	
South East Asia and Pacific Regions standard for softwood species	I	<7.45	<58.9
	II	7.45–10.3	58.9–82.4
	III	10.4–13.2	82.5–107.0
	IV	13.3–16.2	107.1–130.9
	V	⩾16.3	⩾131.0
European standard for softwood species	C14	7	
	C16	8	
	C18	9	
	C20	9.5	
	C22	10	
	C24	11	
	C27	11.5	
	C30	12	
	C35	13	
	C40	14	
	C45	15	
	C50	16	

Source [10,19,20].

3. Results and Discussion

3.1. Wood Density, Modulus of Elasticity and Modulus of Rupture

A summary of the results on wood density, MoE and MoR along the radial direction and stem height are presented in Table 2. The results indicate that there were statistically significant ($p < 0.001$) differences in wood density, MoE and MoR along the radial direction. Wood density, MoE and MoR increased from pith to bark. The increase in wood density from the pith to bark is due to the increasing age of the cambium [21]. The present results are in agreement with previous researches [3,7,21–23]. Variation along the radial direction is the most studied within tree variability in wood, which is usually reflected as radial pattern of change in wood characteristic of juvenile and mature wood. The radial change in wood properties varies in magnitude and type in different species [24–26]. The present study also confirms that the magnitude of wood density and mechanical properties varied from pith to bark.

Table 2. Variation of wood density, Modulus of Elasticity (MoE) and Modulus of Rupture (MoR) among the families, along the stem height and along the radial direction with standard errors.

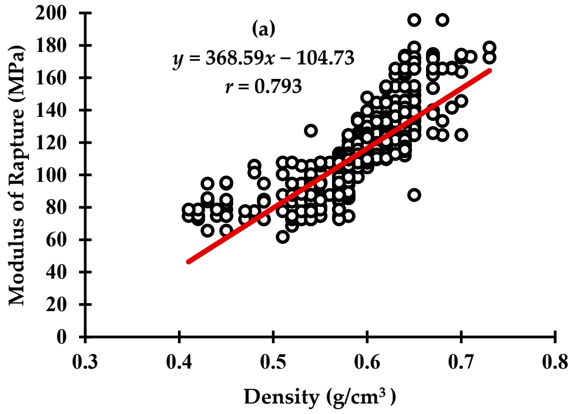
Variable	Description	*n*	Density (g/cm³)	MoE (GPa)	MoR (MPa)
Family	A (ZW701)	180	0.590 ± 0.044 a	13.81 ± 0.20 a	118.25 ± 1.77 a
	B (ZW703)	180	0.593 ± 0.003 a	13.53 ± 0.20 a	114.40 ± 1.35 a
	C (ZW705)	180	0.580 ± 0.003 a	13.20 ± 0.18 a	110.03 ± 1.30 a
	D (ZW709)	180	0.599 ± 0.003 a	13.27 ± 0.12 a	112.76 ± 1.28 a
	E (ZW712)	180	0.592 ± 0.002 a	13.45 ± 0.15 a	113.72 ± 1.37 a
	F (ZW716)	180	0.602 ± 0.003 a	13.49 ± 0.13 a	112.89 ± 1.14 a
Stem height (m) above the ground	1.3	270	0.597 ± 0.002 a	13.74 ± 0.14 a	116.93 ± 1.21 a
	3.3	270	0.594 ± 0.002 a,b	13.56 ± 0.13 a,b	115.05 ± 1.14 a,b
	5.3	270	0.591 ± 0.003 a,b	13.43 ± 0.15 a,b	113.94 ± 1.09 a,b
	7.3	270	0.587 ± 0.003 b	13.12 ± 0.13 b	108.77 ± 1.05 b
Radial direction	Inner (Ring 1–5)	360	0.574 ± 0.002 b	11.80 ± 0.12 b	106.32 ± 0.90 b
	Middle (Ring 12–18)	360	0.593 ± 0.002 a	14.19 ± 0.12 a	115.99 ± 0.99 a
	Outer (Ring 21–28)	360	0.601 ± 0.002 a	14.39 ± 0.12 a	118.70 ± 1.03 a
	Mean		0.593 ± 0.001	13.46 ± 0.07	113.67 ± 0.57
	CV %		6.57	6.35	5.95
	R^2		0.869	0.837	0.863

Note: n = sample size (number of wood specimen); Different letters within a column in the same variable significantly differ ($p < 0.001$); CV = coefficient of variation; R^2 = coefficient of determination.

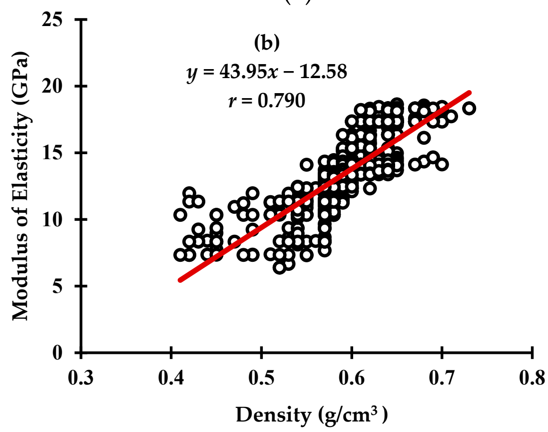
The results also show that there were statistically significant ($p < 0.001$) differences in wood density, MoE and MoR along the stem height. There was a decrease in wood density, MoE and MoR from base to top. However, there were not statistically significant ($p > 0.05$) differences in wood density, MoE and MoR up to 6m height. This indicates that for uniformity of density and mechanical properties in processed lumber of *P. kesiya* in Malawi, logs of 6 m long or less must be used. According to other researchers [27] juvenility increases from bottom to top and as juvenility increases, density decreases. Due to maturity of wood tissues in the bottom portion, density showed a decreasing trend towards the top portion. This implies that the high-density wood from butt end logs should be used for structural purposes where high strength is required. The present results are comparable with those reported by [22,28], working with *Tectona grandis* and *Gmelina arborea* respectively. Other researchers [7,23] also reported similar observation for *Populus euramericana* and *Nauclea diderichii* wood plantations. The observed decrease in wood density from bottom to top agrees with the auxin gradient theory [29]. According to the theory, the endogenous auxin arising in the apical region of growing shoots stimulates cambial division and xylem differentiation. Therefore, high production of early wood near the crown contributes significantly to low wood density at the top. There were no significant ($p > 0.05$) differences in wood density, MoE and MoR among families. This is an indication that any tree among the families can be selected for tree improvement programs if wood density, MoE or MoR are considered as variables.

3.2. The Relationship Between Wood Density and Mechanical Properties

Correlation, graphical representation and regression equations results of wood density and mechanical properties are presented in Figure 2. The results show that wood density had a strong significant linear relationship with MoE ($r = 0.790$, $p < 0.001$) and MoR ($r = 0.793$, $p < 0.001$). This implies that wood density can be used as a parameter for predicting mechanical properties. In other words, this shows that wood density is a good indicator of mechanical properties of wood; therefore, controlling density would have a positive impact on mechanical properties. The present results are in line with those of other researchers [22,30] who reported a strong positive relationship between wood density and mechanical properties in *Tectona grandis* and *Gigantochloa levis*, respectively. The positive relationship between wood density and mechanical properties in *Eucalyptus tereticornis* [31] also support the findings of the present study.



(**a**)



(**b**)

Figure 2. Relationship between (**a**) wood density and MoR; and (**b**) wood density and MoE.

3.3. Grade Yield of Juvenile and Mature Woods

Summary results for the mechanical properties and grade yields for juvenile wood and mature wood are presented in Table 3 and Figure 3, respectively. The results show that there were statistically significant ($p < 0.001$) differences between mature wood and juvenile wood in mechanical properties. Mature wood had higher values in mechanical properties than juvenile wood. This indicates that mature wood is superior in stiffness and strength than juvenile wood. Similar results were reported by other researchers [10] working with *Pinus patula* grown in Malawi.

Figure 3 shows grade yield for both juvenile wood and mature wood according to MoE and MoR using grading standard of mechanical properties of timbers from South African standard for pine, South East Asia and Pacific regions, and the European standard for softwood species. The results clearly show that mature wood yielded more grades with higher values of MoE and MoR than juvenile wood. This implies that mature wood and juvenile wood should be used for different purposes to avoid underutilization. According to other researchers [10], uniform use of juvenile wood and mature wood for structural purposes would be potentially dangerous because juvenile wood has inferior mechanical performance. Therefore, lumber strength can be improved by processing logs of old trees and minimize the use of the interior portion of the log.

Based on the results in Table 3, mature wood for *Pinus kesiya* grown in Malawi can be allocated into grades S10, IV and C40, while juvenile wood can be allocated into grades S7, III and C27 using grading standard of mechanical properties of timbers from South African standard for pine, South East Asia and Pacific regions, and the European standard for softwood species, respectively. This indicates that wood products from *P. kesiya* grown in Malawi such as lumber, composite panels and structural composite lumber products can compete successfully with same products in the huge construction markets of Southern Africa, Asia and Europe.

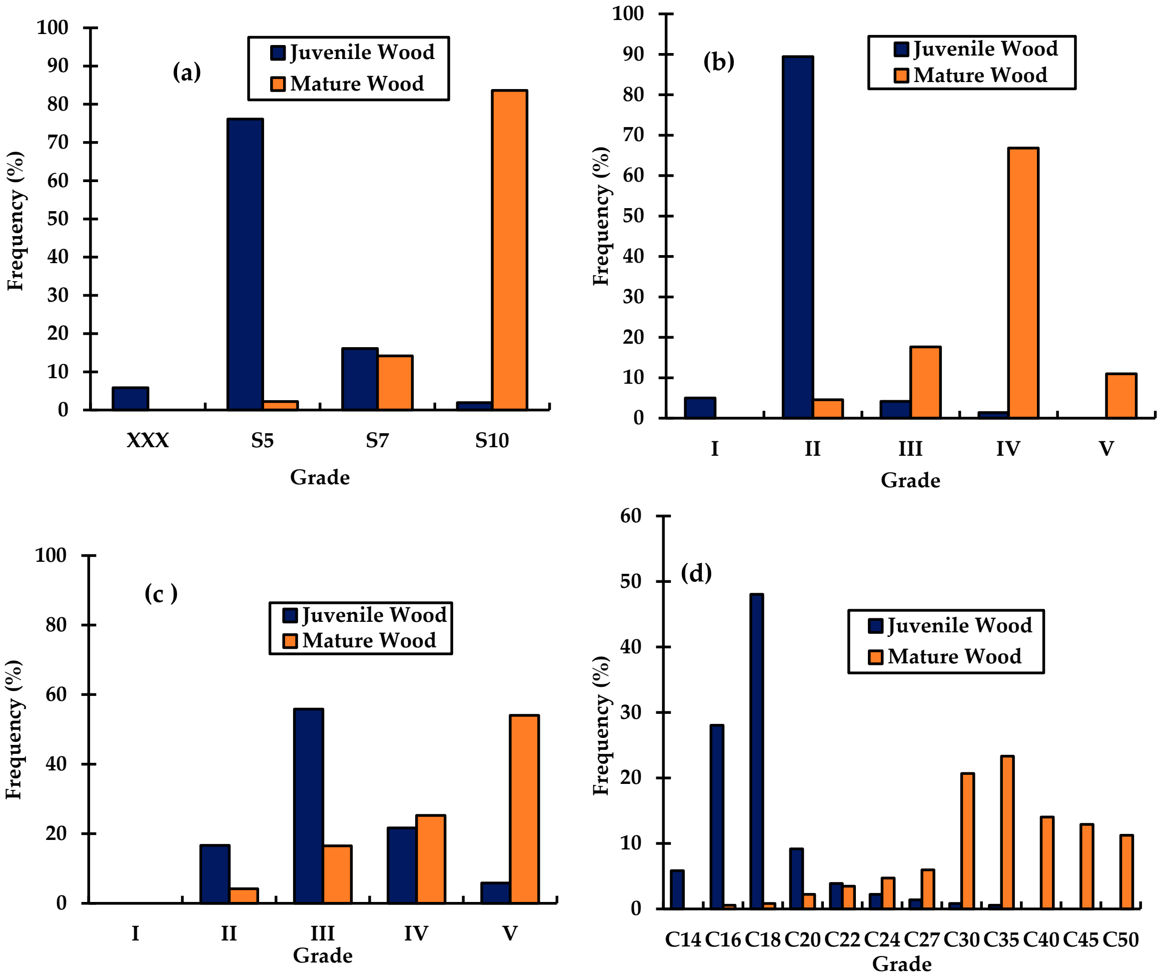


Figure 3. Specimen grade allocation for Juvenile wood and Mature wood in terms of (**a**) MoE for South African Standard for Pine; (**b**) MoE and (**c**) MoR according to South East Asia and Pacific Regions; (**d**) MoE according to European Standard for softwood species.

Table 3. Mechanical properties of juvenile and mature woods of *P. kesiya* specimens in Malawi.

Description	MoE (GPa)	MoR (MPa)
Juvenile Wood	11.80 ± 0.12 b	106.32 ± 1.0 b
Mature Wood	14.29 ± 0.12 a	117.35 ± 1.0 a
Mean	13.46 ± 0.12	113.67 ± 1.0
CV (%)	6.46	6.28
R^2	0.813	0.816

Different letters within a column significantly differ ($p < 0.001$); CV = coefficient of variation; R^2 = coefficient of determination.

The procedure in establishment of grades of lumber are: testing of small wood specimens according to the guidelines, establishing strength values and allowable properties, establishing visual grades rules, and, lastly, verifying grades using in-grade testing [10,32]. This research has clarified the variation of mechanical properties, and thus has established the first step in assigning allowable mechanical properties for *P. kesiya* grown in Malawi. Therefore, testing using the "in grade approach" (use of full size lumber samples) is recommended to compare the results. This will help in assignment of standard grades that will ensure the efficient utilization of *P. kesiya* structural lumber in Malawi.

4. Conclusions

The study has shown that there were statistically significant differences in wood density and mechanical properties (MoR and MoE) along the radial direction and stem height. Wood density and mechanical properties increased from the pith to the bark and decreased from the butt upwards. Therefore, for uniformity of density and mechanical properties in processed lumber of *P. kesiya* in Malawi, logs of 6 m long or less must be used. There were no significant differences in wood density and mechanical properties among families. This is an indication that any tree among the families can be selected for tree improvement programs if density is considered as a variable. There were statistically significant differences between mature wood and juvenile wood in mechanical properties. Mature wood had higher superior mechanical performance than juvenile wood. Wood density had a strong positive significant linear relationship with mechanical properties. This suggests that it is potentially possible to simultaneously improve wood density and mechanical properties of *P. kesiya* in Malawi. Therefore, controlling wood density would have a positive impact on mechanical properties. Furthermore, the present results are a foundation that will provide a technical basis for the machine grading of *P. kesiya* structural lumber in Malawi.

Acknowledgments: The first author was funded by MEXT for a PhD course at Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University, Fukuoka, Japan.

Author Contributions: E.M. and J.M. conceived and designed the experiments; E.M. performed the experiments, analyzed the data and wrote the paper; J.M. contributed substantially to the interpretation of the results and to writing the paper.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of variance
FFPRI	Forestry and Forest Products Research Institute
GLM	Generalized Linear Model
LSD	Least Significant Difference
MC	Moisture Content
MoE	Modulus of Elasticity
MoR	Modulus of Rupture
PROC	Procedure
SAS	Statistical Analysis System

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