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SOME PHYSICAL AND MECHANICAL PROPERTIES OF COCONUT PALM (*COCOS NUCIFERA*) STEM IN HAINAN ISLAND, CHINA

QUANJI LU, HUICHUAN JIANG, JIANING LI, MIN LI, GUANJUN LI
[1]RUBBER RESEARCH INSTITUTE, CHINESE ACADEMY OF TROPICAL AGRICULTURAL SCIENCES
[2]STATE KEY LABORATORY INCUBATION BASE FOR CULTIVATION & PHYSIOLOGY OF TROPICAL CROPS
CHINA

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ABSTRACT

The physical and mechanical properties of 40-year-old coconut stem were investigated in different radial directions and height positions. The results showed that in the radial direction, the properties of the number of vascular bundles (NVB), density, shrinkage, compressive strength parallel to the grain (CS), modulus of rupture (MOR), and modulus of elasticity (MOE) decreased continuously from the outer area to the inner area, except for the water absorption (WA) value which increased from the outer area to the inner area. The density and MOE decreased from the bottom to the top in the height direction while NVB and WA increased. The shrinkage, CS, and MOE first increased and then decreased from the bottom to the top. NVB in coconut stem affects the density and determines the main mechanical properties of CS, MOR, and MOE. The analysis of variance (two-way ANOVA) showed a significant difference in density, NVB, WA, CS, MOR, and MOE in radial direction and height position. These findings can be useful for the development of new applications for coconut stems, such as in construction, landscaping, or furniture manufacturing, as well as for improving our understanding of their structural characteristics.

KEYWORDS: Physical properties, mechanical properties, vascular bundles, coconut stem, Hainan Island.

INTRODUCTION

The global warming crisis has become one of the most critical issues that has made researchers pay more attention to environmental issues. There is great interest in using wood from plantation trees as an alternative wood material for wood products because it is more sustainable than wood from natural forests (FAO 2018; Srivaro et al. 2019).

The coconut tree (*Cocos nucifera*) is one of the monocotyledonous species available worldwide, with a global planted area of about 12 million hectares, most likely distributed in the Philippines, Malaysia, Indonesia, Sri Lanka, Thailand and Vietnam in Southeast Asia (Fathi 2014; Srivaro et al. 2021). In China, there are approximately 34,000 hectares of coconut plantations. More than 90% of the replanted coconut wood has been discarded by landfill or incineration, which is not only a huge waste but also leads to environmental pollution risks (Wei et al. 2011; Wang 2016). Coconut trees are used as an alternative raw material for timber production with high potential commercial value. Therefore, the effective utilization of coconut wood has become one of the urgencies for the coconut wood industry in China. The study on the utilization technology of coconut wood with an effective method to improve the efficiency of the coconut wood industry, which can not only partially alleviate the contradiction between the wood supply and demand of wood, but also increase the economic value and social benefits (Xia et al. 2007; Lu et al. 2021; Zheng et al. 2023).

Coconut wood is a hard surface and durable material with a special decorative appearance on the periphery zone. It is suitable for housing components such as trusses, purlins, walls, joists, doors, window frames and jalousies (Grimwood and Ashman 1975; Killmann and Fink 1996; Arancon 2009; Kolya et al. 2022). It is crucial to investigate the significant variability in the physical and mechanical properties of coconut wood within the trunk, as this can lead to cracking or other quality defects in the products. As coconut trees are monocotyledonous plants, their wood tissues consist predominantly of fiber and parenchyma cells (Meylan 1978; Fathi 2014; Kolya and Kang 2021). Physical and mechanical properties are very important for coconut wood. The properties of coconut wood are mainly influenced by the proportion of fiber cells like other monocotyledon species such as oil palm and bamboo (Meylan 1978; Killmann 1983; Loh et al. 2011; Fathi 2014; Dixon et al. 2015; Yan and Fei 2019). It has been reported that the characteristics and distribution of the fiber cells in coconut wood vary within the trunk, resulting in a large variation in its properties. Wood from the periphery zone and the bottom of the trunk is usually stronger than other parts (Meylan 1978; Fathi and Frühwald 2014). Previous researchers have also found that the properties of coconut wood vary with different planted varieties, areas, and growth ages (Gnanaharan and Dhamodaran 1989; Fathi 2014). The physical properties of coconut wood depend on its density and moisture content. The trunk of coconut wood has a very high variability in dry density of 253-1059 kg/m^3. The main reason for the variability in density is the variability in the number and distribution of vascular bundles, fiber cell dimensions, cell wall thickness and cell wall thickness of the parenchyma as ground tissue (Fathi 2014; Srivaro et al. 2020a; Srivaro et al. 2022a).

There are few studies on the properties of coconut wood. The significant variation in the physical and mechanical properties of coconut stems needs to be investigated for the utilization of coconut wood for wood products in Hainan Island, China. In this study, we

analyzed the anatomical characteristics (number of vascular bundles) and physical and mechanical properties of coconut wood in different radial directions (from outer to inner) and height directions (from bottom to top). The results are extremely helpful to understand the grading of coconut wood in practice and to promote the economic value of coconut wood in the furniture industry.

MATERIAL AND METHODS

Materials

The coconut tree (Hainan Tall coconut, approximately 40 years old) was taken from the plantation area located in Danzhou City (19° 49' 0" N and 109° 51' 0" E), Hainan province, China, for this experiment. Three representative trees were selected as experimental targets with heights of 12.0 to 13.5 m and DBH values of 20 to 30 cm. The tree was sawed into five sawn logs from the 1 m height above the ground to the top with an interval of 2 m along the height direction and marked for H1, H3, H5, H7, and H9, respectively. All sawn logs with 2 m long were seen with the sawing pattern as shown in Fig. 1 for preparation specimens. The height direction is defined as the direction from the bottom to the top, and the radial direction as the direction from the outer to the inner area.

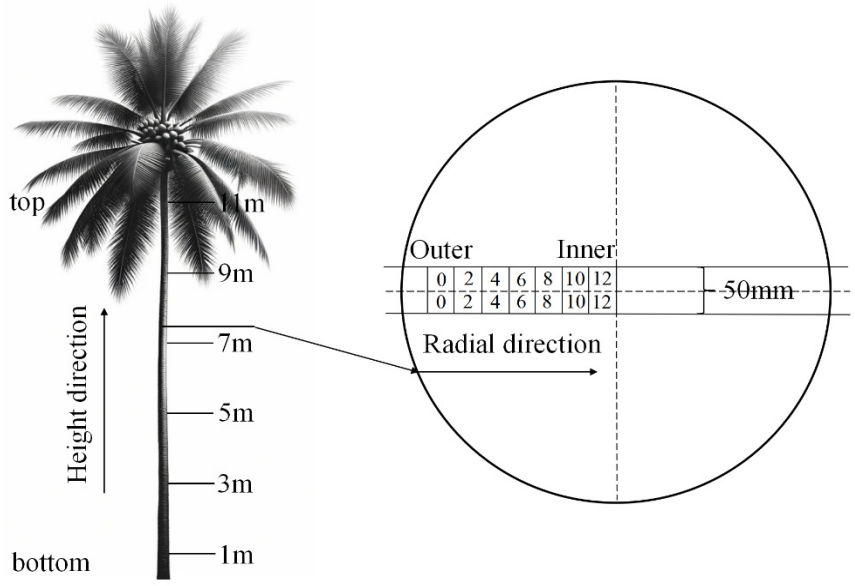

Fig. 1 (a) Fig. 1 (b)

Fig. 1: Test samples distribution at different height position and radial direction of coconut stem.

Drying treatment

The specimens were dried in the electronic oven at a temperature of 65°C to the final moisture content of approximately 12%, then cut into the requirement dimension of specimens for measurement. These specimens were conditioned at a temperature of 20°C and relative humidity of 65% for about 30 days before being tested.

Physical properties measurement

The weight and dimensions of specimens at a 12% moisture content were measured. For water absorption (WA) measurement, specimens were soaked in 20°C distilled water for about 7 days until the weight consistency and then taken out for measuring the final weight. For air drying shrinkage property, the reduced ratio of wood dimension from wet to air-drying wood (approximately 12% moisture content) are measured in radial, tangential, and volumetric. Oven drying shrinkage is the reduced ratio of wood dimension from wet to oven drying wood (weight consistency with the drying condition at 103°C) measured in radial, tangential, and volumetric directions.

The specimen dimensions for density, water absorption, and dry shrinkage properties tests are 20 mm (radial) × 20 mm (tangential) × 20 mm (longitudinal). Specimens were measured using the testing methods described in GB/T1933-2009 (Method for determination of the density of wood), GB/T1934.1-2009 (Method for determination of the water absorption of wood) and G/BT 1932-2009 (Method for determination of the shrinkage of wood).

Mechanical properties measurement

Destructive tests were conducted to measure the compressive strength parallel to grain (CS) and bending properties. Bending properties involve the modulus of elasticity (MOE) and modulus of rupture (MOR). The dimensions of CS, MOE, and MOR specimens were 20 mm (radial) × 20 mm (tangential) × 30 mm (longitudinal), 20 mm (radial) × 20 mm (tangential) × 300 mm (longitudinal) and 20 mm (radial) × 20 mm (tangential) × 300 mm (longitudinal), respectively. The specimens were determined in accordance with the Chinese national standard GB/T 1935-2009 (Method of testing in compressive strength to grain of wood), GB/T 1936.1-2009 (Method of testing in bending strength of wood), and GB/T 1936.2-2009 (Method for determination of the modulus of elasticity in static bending of wood).

Vascular bundles measurement

The dimensions of the specimens for calculating the number of vascular bundles were 20 mm (radial) × 20 mm (tangential) × 20 mm (longitudinal). The image in cross-section was captured using a digital camera at ×10 magnification, and the image was analyzed with image Digimizer software for calculating the number of vascular bundles based on 4 cm^2 cross-section area.

Statistical analysis

R software (Version 4.3.2) was used for two-way ANOVA analysis. The data distributions were examined for normality and homogeneity of variance.

RESULTS AND DISCUSSION

Vascular bundles (VB) and density

In Fig. 2, we can see the distribution of vascular bundles (VB) in the coconut stem. The number of vascular bundles (NVB) gradually decreased from the outer area to the inner area along the radial direction, while it increased from the bottom to the top along the height direction. Tab. 1 shows the effects of different heights and positions on the number of vascular bundles. The results showed that different heights and positions had significant effects on the NVB ($p < 0.001$). At a height of 5 m, the outer area had the largest NVB with 367/4 cm^2, while the core area had the smallest NVB with 55/4 cm^2 at a height of 1 m. Previous studies have also shown a gradual decrease in the NVB from the outer area to the inner area in theradial direction and a gradual increase from the bottom to the top in the height direction (Fathi 2014). It is important to note that the distribution of NVB remains constant at a height of more than 5 m. The reason for having more NVB at the bottom than at the top is that, during the life cycle of the coconut wood, the NVB remains constant, but the parenchyma cells split over time. As the tree grows, the parenchyma cells split more in the bottom position, resulting in a larger wood diameter of wood and a lower relative proportion of VB.

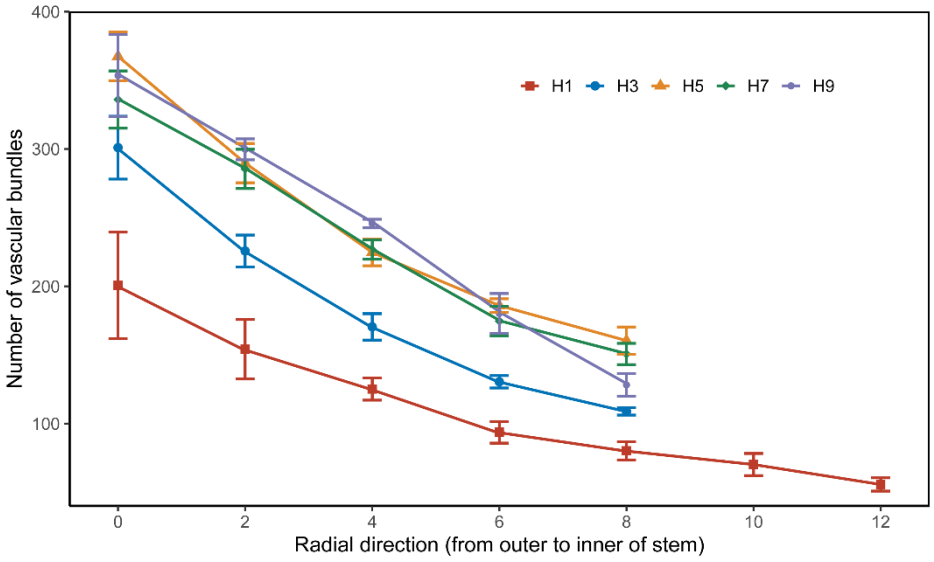

Fig. 2: Distribution of vascular bundles in the coconut stem.

Tab. 1: ANOVA analysis results of physical and mechanical properties of coconut wood in different heights and radial positions.

Variable	Variance sources	Sum Sq	Mean Sq	F value	Pr (>F)	Significance
NVB	position	599655	85665	182.6	<2e-16	***
	height	192115	48029	102.4	<2e-16	***
DENSITY	position	2599368	433228	201.4	<2e-16	***
	height	798654	199663	92.82	<2e-16	***
VS	position	95.4	23.858	3.041	0.0277	*
	height	118.8	29.712	3.787	0.0104	*
RVS	position	21.54	5.386	3.022	0.02838	*

	height	28.72	7.18	4.029	0.00759	**
TVS	position	27.2	6.8	3.038	0.0278	*
	height	30.27	7.568	3.381	0.0176	*
WA	position	45.81	6.544	105.8	<2e-16	***
	height	33.73	8.433	136.4	<2e-16	***
CS	position	8254	1650.8	47.27	<2e-16	***
	height	9439	2359.8	67.58	<2e-16	***
MOR	position	5872	1174.4	23.75	3.64E-14	***
	height	3427	856.7	17.33	4.53E-10	***
MOE	position	293267483	58653497	57.02	<2e-16	***
	height	222204165	55551041	54	<2e-16	***
Different symbols (***, **, *) indicate significant difference at the 0.001, 0.01, 0.05 level respectively according to ANOVA.						

Wood density significantly determines the physical and mechanical properties of wood. As shown in Fig. 3, the density distribution of coconut wood gradually decreased along the radial direction from the outer area to the inner area at different heights.

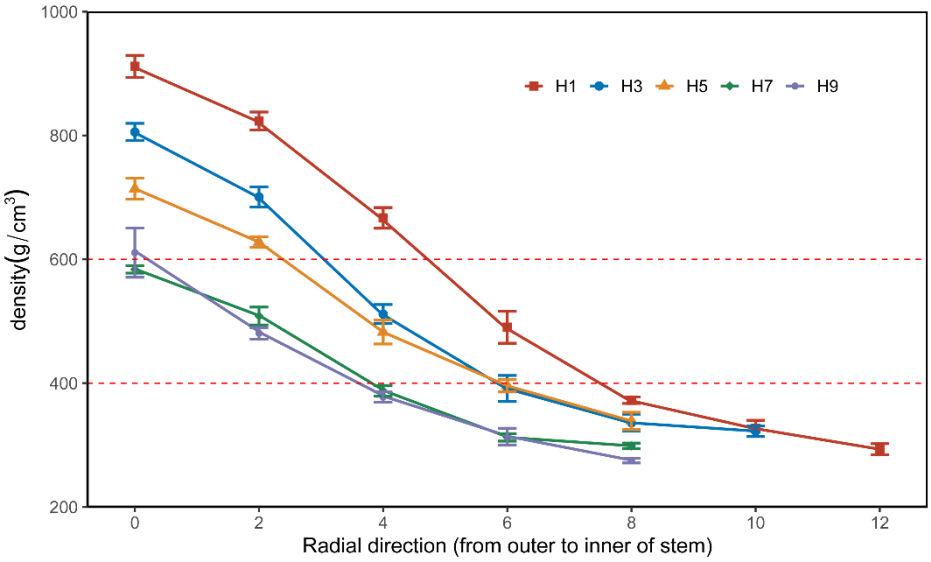

Fig. 3: Density distribution in the coconut stem.

The density ranged from 275 kg/m^3 to 920 kg/m^3, with the highest density being 920 kg/m^3 in the outer area at 1 m height, and the lowest density being only 275 kg/m^3 in the core area at 9 m height. The ratio of the highest density to the lowest density exceeded 3. The difference in density between the inner and the outer areas is obvious, which corresponds to the anatomical structure (Fig. 4). The results of ANOVA analysis (Tab. 1) showed that different heights and positions had significant effects on vascular bundle density ($p < 0.001$). In Fig. 4, the anatomical structures in the outer area were denser and more rigid with more vascular bundles distributed than those in the inner area.

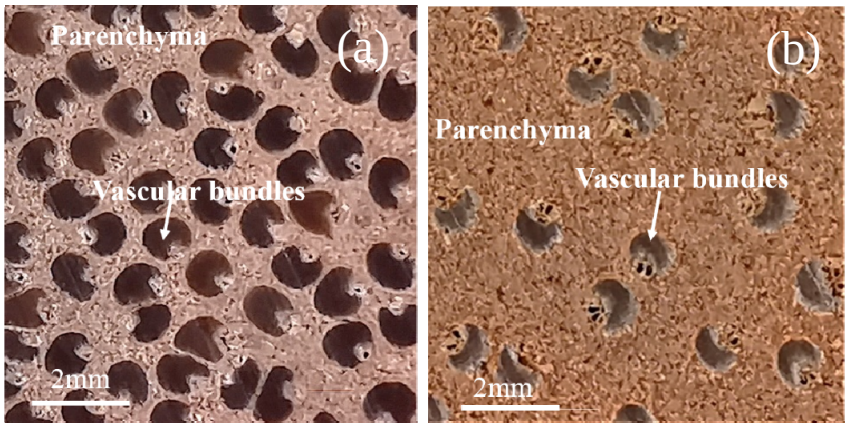

Fig. 4: Images of the distribution of vascular bundles and parenchyma cells on the outer (a) and inner (b) of the coconut stem.

It has been shown that the anatomical structure of coconut wood consists of vascular bundles surrounded by thin-walled parenchyma cells. The vascular bundles are thick-walled fiber cells, and the density of coconut wood has a close positive correlation with the distribution of vascular bundles (Killmann and Fink 1996; Fathi and Frühwald 2014; Srivaro et al. 2020b). In general, the density of fibers is much higher than that of parenchyma cells, VB in the outer area are more than in the inner area should be with higher density (Fathi 2014; Srivaro et al. 2018; Srivaro et al. 2020a). In this study, the density is closely correlated with the NVB in the radial direction, but the results show that the density of coconut gradually decreases in the height direction, from the bottom to the top, contrary to the NVB. This means that the NVB is not the only factor that determines the density of coconut wood, so when studying the relationships between NVB and density, the dimensions of the vascular bundles (diameter and cross-sectional area) and the thickness of the cell walls need to be considered.

The density of coconut wood is less than 600 kg/m^3, which males it unsuitable for structural applications (Arancon 2009; Srivaro et al. 2022b). In this study, it was found that for a given density, all the wood above 7 m in height had a density less than 600 kg/m^3. This means that only a small proportion of the wood at the bottom of the outer area can be used for structural applications. It is essential to establish a density distribution model of coconut wood in different positions for the sawing style scheme to implement a highly efficient sawing and classification method for coconut wood utilization.

Drying shrinkage

Shrinkage is an important wood property that determines its dimensional stability. In Fig. 5, we can observe the wood shrinkage of coconut wood according to radial directions and height positions.

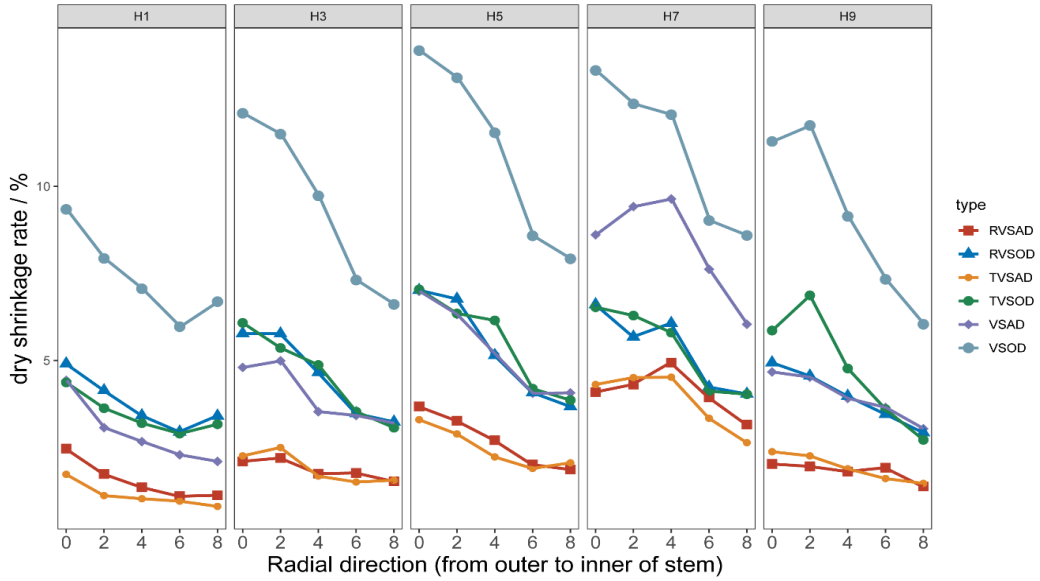

Fig. 5: Drying shrinkage change of coconut stem. RVSAD - radial air drying shrinkage, TVSAD - tangential air drying shrinkage, VSAD - volumetric air drying shrinkage, RVSOD - radial oven drying shrinkage, TVSOD - tangential oven drying shrinkage, VSOD - volumetric oven drying shrinkage.

In the radial direction, the average air-dried radial, tangential and volumetric shrinkage gradually decreased from the outer to the inner regions with values ranging from 1.11% to 4.93%, 0.83% to 4.52% and 2.10% to 6.99% respectively. The largest shrinkage occurred in the outer region at a height of 7 m, while the smallest shrinkage occurred in the inner area at a height of 1 m. Similarly, the average oven-dried radial, tangential, and volumetric shrinkage decreased from the outer to the inner regions in the radial directions, ranging from 2.95% to 7.02%, 2.90% to 7.04% and 6.04% to 13.90%, respectively.

In the height direction, there was initially a gradual increase in the average air-dried radial, tangential and volumetric shrinkage. The peak of the average air-dried radial, tangential, and volumetric shrinkage values was found to be 4.94%, 4.52% and 9.64%, respectively, in the central area at the height of 7 m. Similarly, the average oven-dried radial, tangential, and volumetric shrinkage showed a pattern of initial increase followed by decrease from the bottom to the top position. The highest values observed were 7.02%, 7.04% and 13.90% in the outer region at a height of 5 m.

The radial and tangential shrinkage of coconut wood were not significantly different. The tangential shrinkage of conventional wood is nearly twice the radial shrinkage. The probable reason for this is that coconut wood, unlike conventional wood, consists of vascular bundles and parenchyma cells distributed in the cross-section. There may be no structural difference between radial and tangential directions, resulting in a slight difference between radial and tangential shrinkage. Previous studies have reported that the drying shrinkage of coconut wood is related to its density, with higher densities having greater drying shrinkage (Fathi 2014).

Water absorption (WA)

Water absorption (WA) is the capacity of wood to absorb and hold water inside. The results of WA of coconut wood at different heights and radial directions are shown in Fig. 6, the average WA of coconut wood gradually increased from the outer to the inner for all heights.

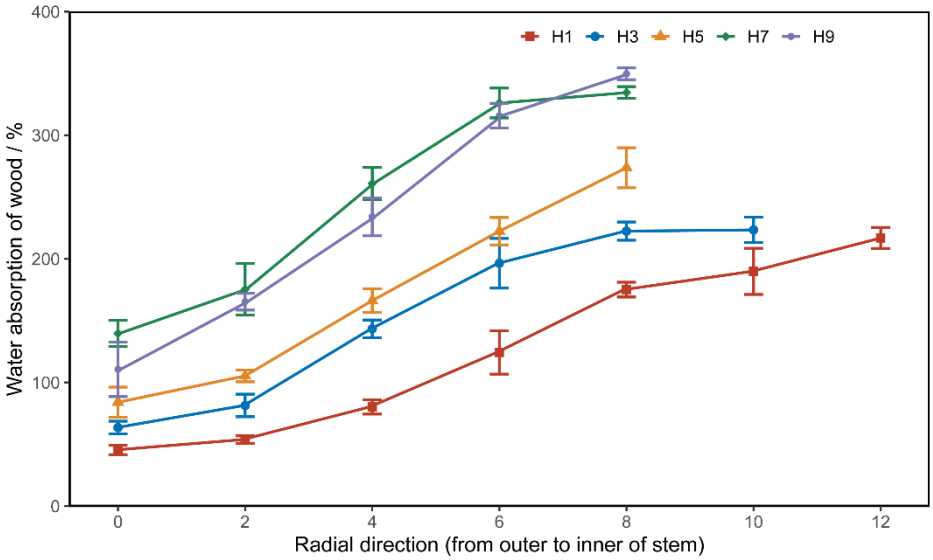

Fig. 6: Water absorption change of coconut stem.

The trends of the WA value were opposite to the density distribution with a range from 43% to 360%. The highest WA value was 360% in the pith area of the 9 m height position and the lowest was only 43% in the outer area of the 1 m height position. The ratio of the highest WA to the lowest was greater than 5. There was a significant difference in WA in radial direction (Tab. 1). Similarly, in the height direction, the difference in WA was also evident, but the change was slower as it increased along the height direction. Like bamboo and oil palm, coconut wood is composed of vascular bundles and parenchyma. Parenchyma is a thin-walled cell with larger intercellular spaces than fiber cells, making it an ideal moisture-storage space. Consequently, the parenchyma cells in coconut wood have the potential to hold more water than the vascular bundles. The WA of coconut wood should be lower due to the higher density in the bottom or outer area, which contains more vascular bundles.

There are differences in the density of coconut wood at different locations. Low density means that the wood contains fewer vascular bundles and more parenchyma, resulting in wood with a higher water storage capacity or higher moisture content. This observation supports previous work (Srivaro et al. 2018). However, the mean WA of 7-m-height coconuts was slightly higher than that of 9 m height coconuts, suggesting that the structure of coconut needs further investigation.

Compressive strength of coconut wood

The compressive strength parallel to the grain (CS) is the capacity of wood to bear external pressure load along the grain direction. The results of ANOVA analysis (Tab. 1) showed that different heights and positions had significant effects on the CS of coconut wood ($p < 0.001$). Fig. 7 showed the trends of the CS of coconut wood at different positions.

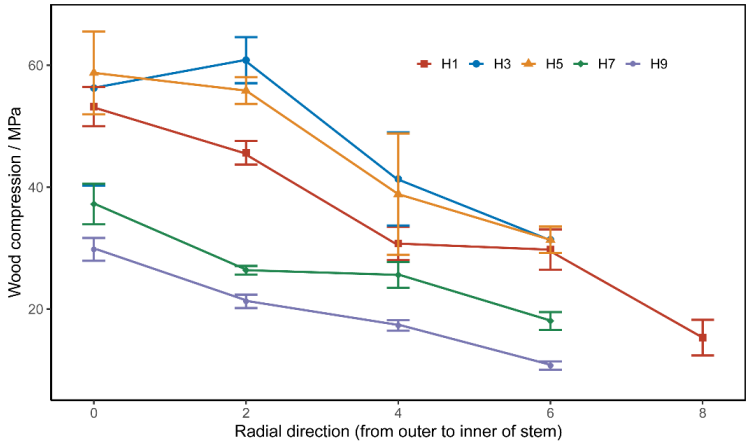

Fig. 7: Compressive strength parallel to grain of coconut stem in different position.

In the radial direction, the CS of coconut wood was found to have a higher value in the outer area than in the inner area. The maximum value of 60.8 MPa was found in the outer area of the 3 m height position, and the minimum value of 10.7 MPa was found in the core area of the 9 m height position. On the other hand, the CS first increased and then decreased from the bottom to the top in the height position. Previous research reported that the fraction of fibers determines the CS of coconut wood (Srivaro et al. 2020). The CS is dominated by the fiber density. However, vascular bundles oriented in the axial direction in coconut tissues also affect the CS. The greater CS was found in the position where more fibers and vascular bundles were arranged in a highly parallel arrangement in the axial direction (Srivaro et al. 2018).

Modulus of rupture and modulus of elasticity

The modulus of rupture (MOR) is a measure of the capacity of wood to resist failure in bending. As shown in Fig. 8, the average MOR of coconut wood decreased from the outer to the inner area, ranging from 14.2 MPa to 55.2 MPa in the radial direction. The ANOVA analysis results (Tab. 1) showed that different heights and radial positions had significant effects on the MOR of coconut wood ($p < 0.001$). The maximum value was 55.2 MPa in the outer area of the 5 m height position, and the minimum value was 14.2 MPa in the inner area of the 9 m height position.

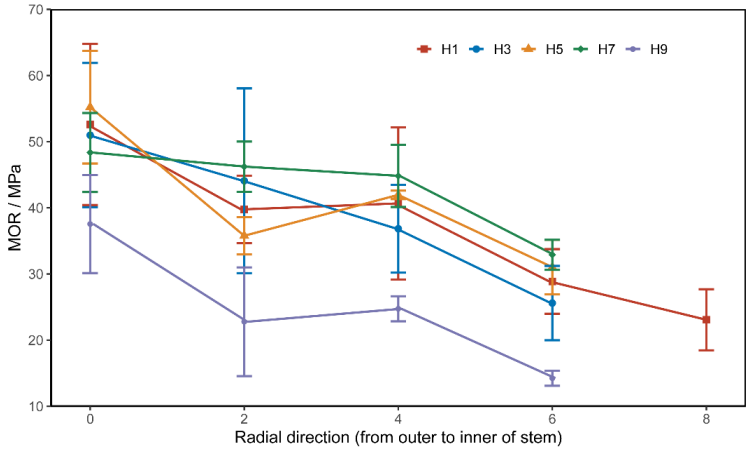

Fig. 8: MOR of coconut stem in different position.

The modulus of elasticity (MOE) is a measure of the ability of wood to resist elastic deformation (i.e., temporary deformation) when subjected to stress. MOE is an important determinant of the performance and value of solid lumber. The results of ANOVA analysis (Tab. 1) showed that different heights and positions had significant effects on the MOE of coconut wood ($p < 0.001$). As shown in Fig. 9, the average MOE of coconut wood decreased progressively from the outer to the inner area in the radial direction. The highest value of 12500 MPa was observed at the outermost height position of 1 m while the lowest value of 2000 MPa was recorded at the innermost position of 9 m. The average MOE value showed a gradual decrease towards from the bottom to the top in the height direction, in line with the density change. Although there was a noticeable contrast between different height positions, no significant difference was found between the heights of 1 m and 3 m. Similarly, there was no significant difference between the heights of 5 m and 7 m height.

In general, MOR and MOE were affected by density and both values increased with increasing density (Sudo 1980). As mentioned above, vascular bundles oriented in the axial direction in coconut tissues also affect the MOR and MOE, while the cell wall structure needs to be considered, which is worthy of future investigation.

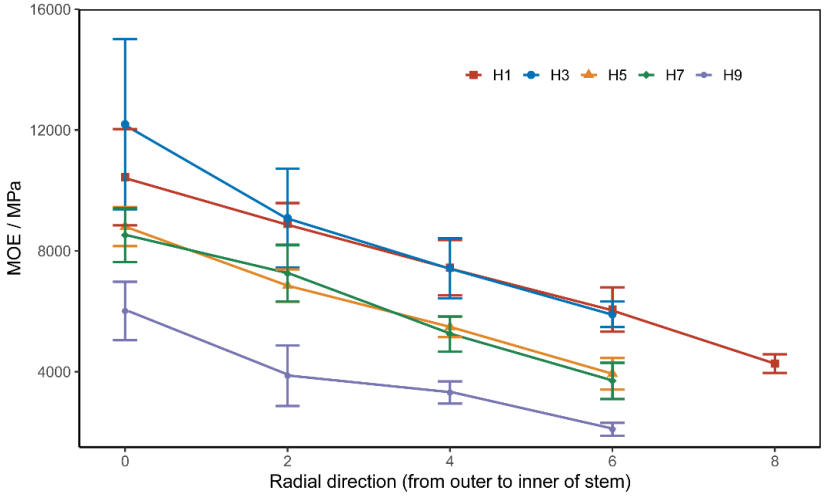

Fig. 9: MOE of coconut stem in different position.

CONCLUSIONS

The number of vascular bundles distributed in the coconut stem affects the density, which determines the main physical and mechanical properties. The number of vascular bundles gradually decreased from the outer to the inner area in the radial direction. Simultaneously, it increased from the bottom to the top in the height direction. In the radial direction, the values of coconut density, shrinkage, CS, MOR and MOE decreased continuously from the outer to the inner area. In contrast, the values of WA increased from the outer to the inner area. In the height direction, the values of coconut density and MOR decreased from the bottom to the top, while the values of WA increased. However, the values of shrinkage, CS and MOE first increased and then decreased from the bottom to the top. Analysis of variance (two-way ANOVA) showed a

significant difference in density, number of vascular bundles, WA, CS, MOR and MOE in radial and height direction. MOR and MOE were determined by density and both values increased with increasing density in this study. However, vascular bundles oriented in the axial direction in coconut tissue also affect MOR and MOE. Meanwhile, the cell wall architecture needs to be considered, which is worth investigating in the future.

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QUANJI LU, HUICHUAN JIANG*, JIANING LI, MIN LI, GUANJUN LI
[1]RUBBER RESEARCH INSTITUTE, CHINESE ACADEMY OF TROPICAL AGRICULTURAL SCIENCES
HAIKOU 571101
CHINA
[2]STATE KEY LABORATORY INCUBATION BASE FOR CULTIVATION & PHYSIOLOGY OF TROPICAL CROPS
HAIKOU 571101
CHINA
*Corresponding author: jianghc@126.com