

INVESTIGATION OF GAMMA RADIATION SHIELDING PROPERTIES OF *ACACIA MANGIUM* WOOD FROM SABAH, MALAYSIA

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ABSTRACT

Gamma radiation shielding properties of *Acacia mangium* wood (ages 3 - 15 years) were investigated at 662 keV (^{137}Cs). Mass attenuation coefficients, linear attenuation (μ), and half-thickness were measured; the attenuation properties were discussed include linear attenuation (μ) and mass attenuation (μ/ρ). Additionally, the paper will explore the feasibility of substituting traditional shielding materials, such as concrete and copper, with these tropical wood species for low-energy gamma-ray diagnostic applications. Two mathematical models have been developed to predict wood density based on variations in relaxation length and half-thickness values. The results indicate that the three-year-old *Acacia mangium* tree has the longest relaxation length at 83.33 cm and the lowest density at 0.43 g/cm³. In contrast, the 15-year-old tree has the shortest relaxation length of 28.56 cm and the highest density at 0.76 g/cm³. Furthermore, the results show that the 3-year-old *Acacia mangium* tree's wood has the maximum half-thickness value (57.75 cm), while the fifteen-year-old tree's wood has the lowest half-thickness value (about 19.85 cm). A good agreement (greater than 85% in most cases) was observed between the measured values and predicted ones. A strong linear correlation was observed between the measured density and the age of the tree ($R^2 = 0.824$), as well as between the estimated density and the age of *Acacia mangium* trees ($R^2 = 0.952$). *Acacia mangium* shows potential as a sustainable gamma shielding material for low-energy applications.

KEYWORDS: *Acacia mangium*, wood density, relaxation length, half thickness value, linear attenuation coefficient.

INTRODUCTION

Wood is not a solid and homogeneous substance like a piece of metal. Some wood materials with a thin lead coating have earlier been tried for shielding X-ray facilities. Therefore, wood's ability to insulate against radiation can be investigated on its own. In this respect,

the investigation of wood materials' capacity to absorb various wavelengths of radiation has allowed for the examination of different types of wood materials based on their hardness. Radiation densitometry is a commonly used technique for assessing density characteristics of wood samples. Understanding the characteristics of wood and how it behaves under physical, chemical, and biological processes has been made easier with the help of gamma radiation technology (Rajasekhar et al. 2014). Linear attenuation coefficients are influenced by the densities of woods, exhibiting a linear proportionality. A higher attenuation coefficient indicates a greater density of wood. Both attenuation coefficients and density are key characteristics for assessing the radiation attenuation capabilities of different wood species (Aung and Tun 2019). Forest managers and wood processors utilize wood density to accurately align raw materials with their final products (Wu et al. 2020). Timber serves as a significant source of foreign revenue in Malaysia, and creating wood composites as cost-effective materials for radiation shielding will undoubtedly enhance the economic value of timber. The attenuation coefficient is inversely related to gamma energy and directly related to the density of various wood types (Rajasekhar et al. 2014).

Additionally, wood density is a crucial factor in measuring carbon in forests (Phillips et al. 2019). X-ray densitometry is used to give an optical radiographic reading of wood density but does not give an actual reading value. The mass attenuation of gamma radiation results from the various types of interactions it has with matter, including the photoelectric effect, pair production, and the Compton effect. These interactions occur as gamma radiation engages with the atoms in a material, which consequently reduces the transmitted intensity. The density, absorbing layer thickness, and material cross-sectional characteristics all affect the transmitted intensity (Rajasekhar et al. 2015). Accuracy determination of mass attenuation coefficients is essential before a given material is used as gamma ray shield. Half-thickness value is a useful parameter for understanding the interaction of gamma rays. It determines the thickness required to reduce the intensity to a safe level (Yadeta 2024). The interaction of gamma rays with materials is a well-understood process, allowing for the investigation of the interior of bulky objects due to their ability to penetrate to considerable depths (typically several centimeters, depending on the material and their energy) (Sharma et al. 2017). The density of *Acacia mangium* wood is determined by this method using gamma radiation, which serves as a rapid yet reliable assessment of the wood's quality, applications, and uses (Tabet and Abdul Aziz 2009). The gamma ray method is distinguished from other various methods due to its accuracy, effective penetration, and non-intrusive nature (Weng & Ma 2019). The study site, Kinarut Eco Forest Park, located in Kinarut, Sabah, Malaysia, spans approximately 400 hectares and is characterized by extensive and prominent acacia coverage, offering a contrasting environment for further comparative analysis (Anthony 2012). The objective of this study was to assess the density and half-thickness value of *Acacia mangium* wood at eight different ages from Kinarut Eco Forest Park in Sabah, as well as to examine its gamma radiation shielding properties for low-energy applications. Wood has not received much attention when it comes to radiation shielding, despite its extensive use in construction and design. Most existing wood studies that are now available either have a small sample diversity or do not validate their findings by comparing them to theoretical data (Türker & Kılınçarslan 2025).

The principle used to measure density with gamma radiation is simply to pass radiation

through a material attenuating the radiation. In this case gamma particles. This principle is described by Lambert equation (Tabet & Abdul Aziz 2009) as:

$$I = I_0 e^{-(\mu/\rho) \rho x} \quad (1)$$

where: I = radiation intensity after attenuation (counts/s), I_0 = radiation intensity before any attenuation (counts/s), μ/ρ = mass attenuation coefficient (cm^2/g), ρ = density (g/cm^3), x = absorber thickness (cm).

With known values of μ/ρ and x and acknowledging the existence of some amount of background radiation I_a , Eq. 1 may be rearranged as:

$$\rho = \frac{\ln \left[\frac{I_0 - I_a}{I - I_a} \right]}{\left(\frac{\mu}{\rho} \right) x} \quad (2)$$

Eq. 2 assumes a point source of radiation that produces a collimated beam passing through a thin slab of wood material. Additionally, the attenuation coefficient μ , varies with the energy of the gamma rays; for a specific material, different gamma ray energies correspond to distinct values of μ .

Theoretical calculation

The attenuation of gamma radiation occurs due to various energy exchange mechanisms, including photoelectric attenuation and the Compton effect, as it interacts with the atoms in a material. This interaction leads to a reduction in transmitted intensity. The transmitted intensity is influenced by the density and thickness of the absorbing layer, as well as the cross-sectional properties of the material (Louis 2004). When gamma radiation with an initial intensity (I_0) strikes a material of thickness (x), the attenuation of the gamma radiation is described by Eq. 3. The attenuation of gamma radiation can also be expressed using a quantity known as the half-thickness length, $X_{1/2}$, defined that $I(X_{1/2}) = I_0/2$. Eq. 3 may also be written as Eq. 4 and Eq. 5. The attenuation coefficient μ and the relaxation length L are determined by plotting $\ln(I_0/I)$ against x for each wood sample (Louis 2004).

$$I = I_0 e^{-x/L} \quad (3)$$

$$\ln(I/I_0) = -\mu x \quad (4)$$

$$X_{1/2} = 0.693 / \mu \quad (5)$$

where: x is the thickness and L is the relaxation length, μ is the attenuation coefficient.

MATERIAL AND METHODS

The wood samples were collected from Kinarut plantation, Sabah, Malaysia. Eleven wood trunks from *Acacia mangium* trees of varying ages were measured at breast height diameter (BHD) for this study, as shown in Fig. 1. Each wood disc was meticulously cut into 13

rectangular blocks, with thicknesses ranging from 1 cm to 13 cm. wood samples were prepared in accordance with the ISO 4471:1982 methodology for physical characterization. A radiation source of 30 millicuries an energy of 0.662 MeV and a 2-inch sodium iodide (NaI) scintillation detector are used. Radiation is emitted from a 0.25-inch-diameter source and must be shaped into a slot source for measuring density. Samples with a maximum width of 3 inches can be accommodated in the sample holder located on the stage.



Fig. 1: a) Trunk diameters of *Acacia mangium* trees at ages 3, 5, 7, 9, 11, 13, and 15 years, presented from top to bottom, b) samples of *Acacia mangium* wood, aged 10 years, are being prepared from the pith to the bark.

Fig. 2 shows the experimental setup and sample stage. We conducted the current experiment with narrow beam geometry. The distance between the source and detector was set at 30 cm to enable significant transmission (Rumana 2019). Emergent radiation was measured without an absorber and then with an absorber for a thousand seconds. The recorded data included measurements of the linear attenuation coefficient, mass attenuation coefficient, and half-thickness value, which were then represented graphically.

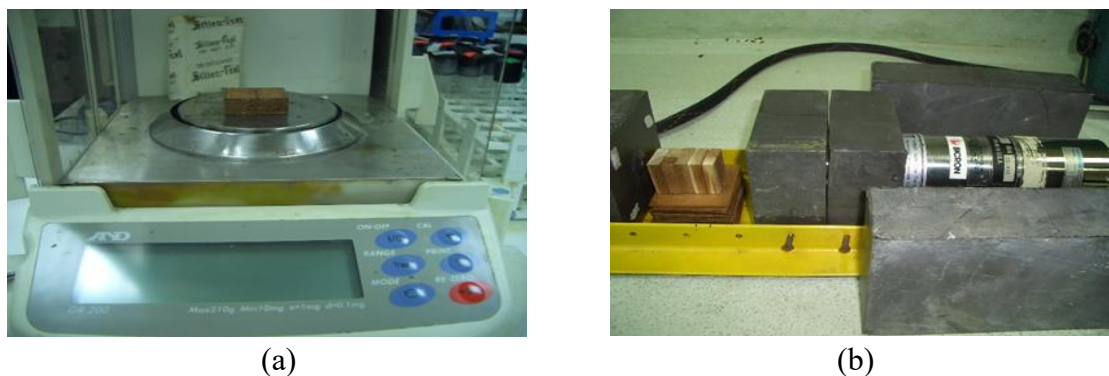


Fig. 2: a) *Acacia mangium* sample 3 cm x 2.5 cm x 1 cm for mass measurement, b) samples stage of gamma radiation equipment.

RESULTS AND DISCUSSION

In this study measured and estimated density, relaxation lengths and half-thickness value of different ages of *Acacia mangium* wood were studied using gamma radiation from ^{137}Cs sources. The mass attenuation coefficient μ , density ρ , relaxation length L , and half thickness

value $X_{1/2}$ for the respective wood samples under study are presented in this section.

Fig. 3 presents the graph of $\ln(I_o/I)$ plotted against the thickness x of eight different ages of *Acacia mangium* wood samples, from which the corresponding relaxation lengths L were derived. The lines were approximated by using the least squares method. Fig. 4 shows an exponential relationship between relaxation length L and density ρ . Fig. 5 is a plot of the density against $\ln L$, resulting in straight-line graph passing through the density axis with the intercept value of 1.234. From Fig. 4 could be expressed respectively as Eq. 6. Applying the numerical value, Eq. 7 becomes. Eq. 8 will be designated as Model 1.

$$L = L_o e^{-C\rho} \quad (6)$$

$$\rho = \ln L_o / C - \ln L / C \quad (7)$$

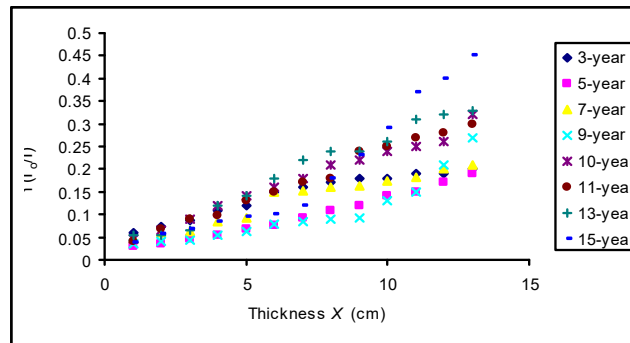


Fig. 3: A plot of $\ln I_o / I$ against thickness for eight ages of *Acacia mangium* trees.

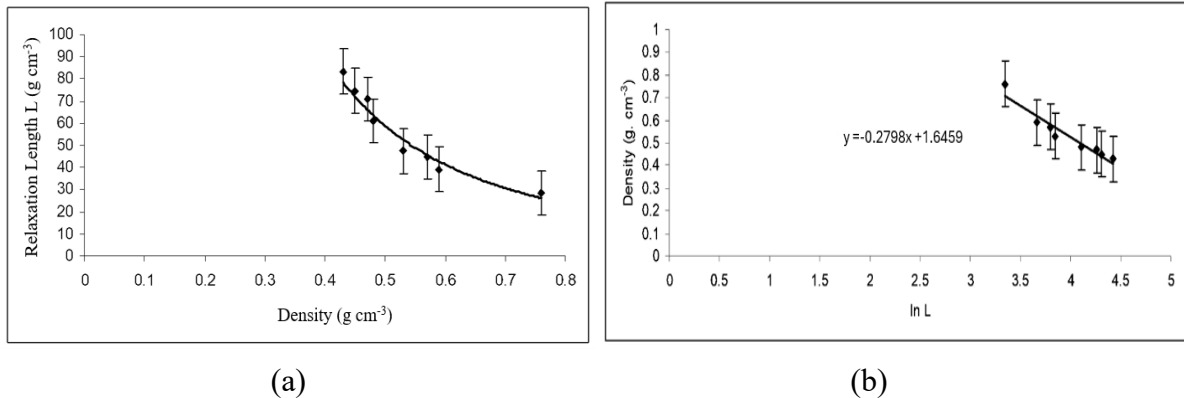


Fig. 4: a) Variation of relaxation length with density, b) variation of density with $\ln L$.

This model is illustrated by the straight-line graph shown in Fig. 4b. The slope of the graph indicates that $1/C$ equals 0.279. Consequently, the reciprocal of this slope yields a value of C as 3.584, which we consider the coefficient of relaxation for the wood sample. The intercept provides the value of L_o / C as 1.645. The ratio of the intercept to the slope results in $\ln L_o$:

$$\ln L_o = 1.645 / 0.279 = 5.896 \quad (8)$$

$$L_o = e^{5.896} = 363.58 \text{ cm} \quad (9)$$

L_o is assumed to be the relaxation length of an arbitrary wood sample of negligible density. Eq. 8 (Model 1) gives the required model for predicting the density of any wood samples.

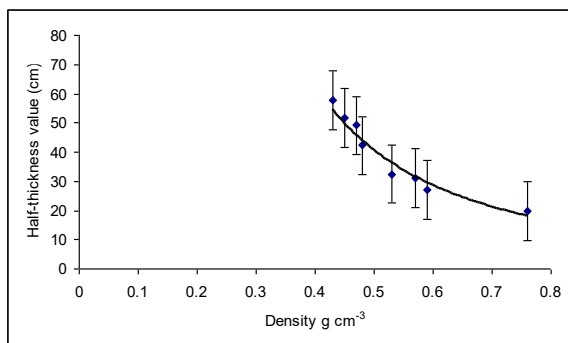
The estimated density of wood samples of age 3 years can be calculated as shown in Eq. 10, while the measured density for the same sample was 0.43 g.cm^{-3} as shown in Tab. 1.

$$\rho = -0.279 * 4.42 + 1.645 = 0.41 \text{ g.cm}^{-3} \quad (10)$$

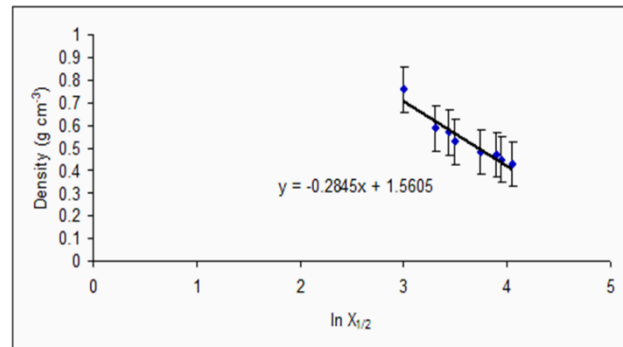
Tab. 1: Study findings regarding the density, relaxation length, half-thickness, and mass attenuation coefficient of *Acacia mangium* wood.

Age (year)	Density ρ (g cm^{-3})	Relaxation Length L (cm)	$\ln L$	Half-Thickness $\chi_{1/2}$ (cm)	$\ln \chi_{1/2}$	Attenuation Coefficient α	Mass attenuation coefficient μ ($\text{cm}^2 \text{g}^{-1}$)
3	0.43	83.33	4.42	57.75	4.05	0.021	0.027
5	0.45	74.62	4.31	51.71	3.94	0.013	0.030
7	0.47	70.92	4.26	49.14	3.89	0.014	0.030
9	0.48	60.97	4.11	42.25	3.74	0.016	0.034
10	0.53	47.39	3.85	32.48	3.49	0.021	0.039
11	0.57	44.80	3.80	31.07	3.43	0.022	0.039
13	0.59	39.21	3.66	27.17	3.30	0.026	0.043
15	0.76	28.65	3.35	19.85	2.98	0.035	0.046
	Std.Dev. 0.1071	Std.Dev 19.1609	Std.Dev 0.3675	Std.Dev 13.3015	Std.Dev 0.2846	Std.Dev 0.0071	Std.Dev. 0.0068
	Mean= 0.535	Mean= 56.23	Mean=3.79	Mean=38.92	Mean=3.72	Mean=0.021	Mean=0.03

Fig. 5a shows an exponential relationship between the half-thickness values and density ρ , while Fig. 5b a plot of density against $\ln \chi_{1/2}$ resulting in straight-line graph passing through the density axis with the intercept value of 1.56. According to Louis (2004), half-thickness value can also be used to calculate density.



(a)



(b)

Fig. 5: a) Variation of half-thickness value as a function of density of *Acacia mangium*, b) variation of density with $\ln \chi_{1/2}$ of the *Acacia mangium*.

In relation to the half-thickness value, Eq. 11 and 12 can be represented. Eq.11 yields Model 2 as Eq. 13:

$$\chi_{1/2} = \chi_{1/2}^o e^{-D\rho} \quad (11)$$

$$\rho = \ln \chi_{1/2}^o / D - \ln \chi_{1/2} / D \quad (12)$$

$$\rho = -0.282 \ln \chi_{1/2}^0 + 1.550 \quad (13)$$

Fig. 6a shows the reciprocal of the slope of the graph gives the numerical value of D as 3.546, which could be regarded as the coefficient of half-thickness value for the wood material. The intercept of the graph gives the value of the $\ln \chi_{1/2}^0 / D$. The quotient of the interception and slope gives $\ln \chi_{1/2}^0$ as the following:

$$\ln \chi_{1/2}^0 = 1.550 / 0.282 = 5.496 \quad (14)$$

$$\chi_{1/2}^0 = e^{5.496} = 243.7 \text{ cm} \quad (15)$$

The $\chi_{1/2}^0$ assumed to be the half value thickness for the arbitrary wood that has negligible density (Tabet & Abdul Aziz 2009). Using Model 2 (Eq. 12), the estimated density of wood samples of age 3-year-old can be calculated as the following, while the measured density for the same sample was 0.43 g.cm^{-3} .

$$\rho = -0.282 \times 4.05 + 1.550 = 0.40 \text{ g.cm}^{-3} \quad (16)$$

In Tab. 2, we present a comparison of experimental results and the estimated values of density in *Acacia mangium* wood and the percentage error for each case. The negative value of percentage error means that the estimated density is smaller than the measured density for the same growth age, while the positive percentage error indicates that the estimated density is bigger than measured density using both models.

Tab. 2: Experimental results and the estimated values of density in *Acacia mangium* wood.

Age of tree (year)	Model 1 $\rho \text{ (g cm}^{-3}\text{)}$			Model 2 $\rho \text{ (g cm}^{-3}\text{)}$		
	Measured	Estimated	Error (%)	Measured	Estimated	Error (%)
3	0.43	0.41	-4.65	0.43	0.40	- 6.97
5	0.45	0.49	8.88	0.45	0.43	- 4.44
7	0.47	0.50	6.38	0.47	0.45	-4.25
9	0.48	0.53	10.41	0.48	0.49	2.08
10	0.53	0.57	7.54	0.53	0.56	5.66
11	0.57	0.58	1.75	0.57	0.58	1.75
13	0.59	0.60	1.69	0.59	0.61	3.38
15	0.76	0.66	- 13.15	0.76	0.70	- 7.89
Std. dev	0.1071	0.0641		0.1071	0.1025	
Mean	0.535	0.550		0.535	0.527	

Fig. 6a shows the variation of measured density with the tree age in *Acacia mangium* wood, while Fig. 6b shows the relationship between estimated density and tree age. A very strong correlation, ($R^2 = 0.99$) was established between relaxation length and half-thickness value in this study as shown in Fig. 6c.

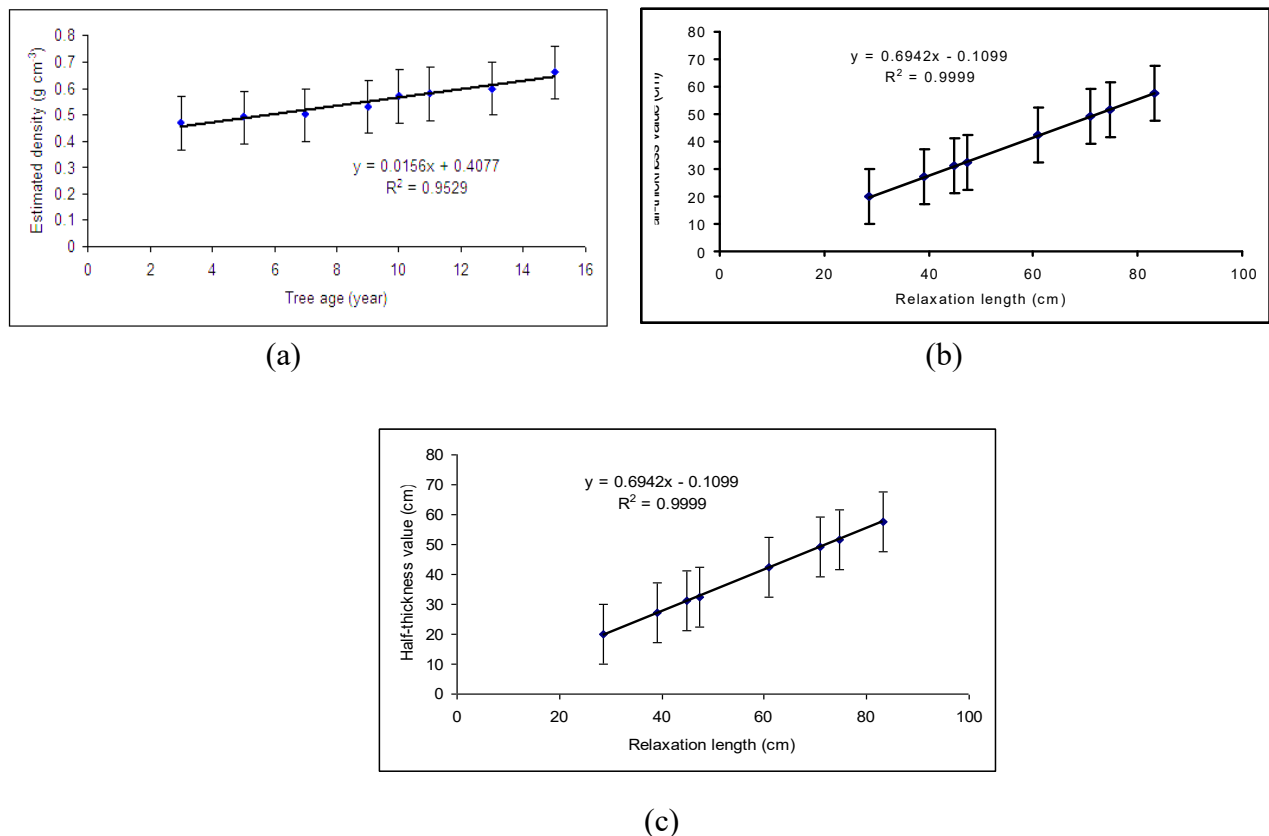


Fig. 6: a) The relationship between tree ages and measured density, b) tree age and estimated density and c) relaxation length and half-thickness value of *Acacia mangium* wood.

DISCUSSION

Wood density is a key factor in deciding whether some wood is suitable for a certain end use and shows a strong link with other wood attributes like strength and stiffness (Vega et al. 2024). Accurate measurement of wood density is fundamental to improving the efficiency of timber utilization (Todoroki et al. 2021). Higher wood density indicates stronger wood strength and an increased energy demand for drilling through the wood (Yao et al. 2024). Instead, stiffness is increasingly considered to be a better indicator as it is the characteristic that most often governs the design of the timber structure. From tree breeding prospective, density has some advantages in that it has been shown to be a highly heritable trait. At the same time, a trait whose value in mature wood is highly correlated with its value in juvenile material also presents advantages in a breeding program, in that such programs can be shorted. However, density remains an important indicator of wood strength. Information of the density of *Acacia mangium*, especially in Sabah, Malaysia, is limited. To redress this information gap, the density of eight ages of *Acacia mangium* wood was examined using gamma ray attenuation technique as a more accurate method to estimate the wood density.

This study utilized gamma radiation from a ¹³⁷Cs source to measure and estimate the density, relaxation lengths, and half-thickness of *Acacia mangium* wood at different ages. Fig. 5 shows that the relaxation duration of the attenuated gamma radiation increases for low-density

values of the *Acacia mangium* wood samples under investigation, while the relaxation length decreases for higher values of wood samples density. *Acacia mangium* tree of age 15-year-old has the least relaxation length of 28.65 cm and half-thickness value of 19.85 cm, while the 3-year-old tree has the highest relaxation length and half-thickness value of 83.33 cm and 57.75 cm, respectively as shown in Tab. 2. Attenuation is influenced by several factors, including density and atomic cross-section. Therefore, denser materials attenuate radiation more effectively than less dense materials (Louis 2004).

Materials with large particles size have greater pore spaces than the small particle size material (Molteberg 2004). Large-size particles will attenuate or scatter less radiation than small-size particle materials, for radiation passing through the pore spaces encounter little resistance. The results show that denser wood, 13- and 15-year-old *Acacia mangium* trees offer greater attenuation of radiation than the young tree, 3 and 5-year-old. That may be attributed to the fact that, in denser woods, component material is more closely packed than in young wood. Woods at the bark regions of the trees are characterized by long fibres, implying large particle size and pore spaces (Bonham and Barnett 2001). Wood density is influenced by both genetic factors and the growth environment of trees (Castro et al. 2021). The other important factor is also the area of the vessel. The wood in the bark region of *Acacia mangium* has a greater vessel area than the wood in the pith region and therefore attenuates less gamma radiation than the small hole area at pith region. This fact clarified that the relaxation length of wood was due to the non-crystalline region. Interestingly, *Acacia mangium* trees with smaller growth age and low crystallite size exhibited relaxation length with maximum value as shown in Tab. 1. The density value of completely dry wood samples can be used for classifications since density is a function of half thickness value and relaxation length of a material. A very good linear correlation was found between measured density and the age of tree and between estimated density and *Acacia mangium* tree age. We also conclude that the two models were developed for predicting the density of wood samples aligning with the findings of (Louis 2004). Fig. 7a shows the 3D module of wood samples at a distance 10.0 mm from the pith center illustrating the real depth of the hole of the *Acacia mangium* samples of 10-year-old, while Fig. 7b shows the 3D module of wood sample at distance 40.0 mm from the pith center of 10-year-old sample.

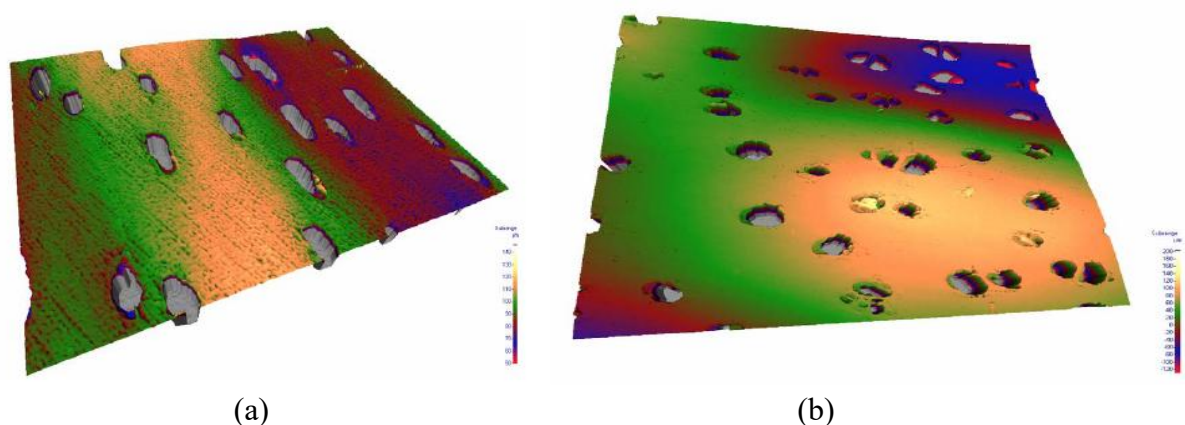


Fig. 7: a) The Pseudo colored 3D module wood at 10 mm from the pith center. The deepest hole with yellow color, b) pseudo colored 3D module wood at 40 mm from pith.

CONCLUSIONS

To obtain accurate values for the total mass attenuation coefficients of a material, it is essential to ensure that the source, sample, and detector are well collimated. This study focuses on achieving gamma radiation attenuation using wood materials. It was found that *Acacia mangium* wood of age 3-year-old has the highest relaxation length (83.33 cm) and half-thickness value (57.75 cm). Trees of 15-year-old have the least relaxation length and half-thickness of 28.65 cm and 19.85 cm, resp. This result suggests that *Acacia mangium* wood at the age of 15-year-old and more can be used with other best-known radiation protective shield that reduces to a safe level the accessible radiation from any radioactive source. In this study, the measured and calculated values of attenuation coefficients show good agreement for a source-to-detector geometry of 30 cm with a collimator. A very good linear correlation ($R^2=0.8243$) was found between measured density and the age of tree and ($R^2=0.952$) between estimated density and *Acacia mangium* tree age.

The results of this study can be utilized to comprehend accurate and effective methods of density measurement and analysis for tropical wood materials. Moreover, to design and choose an appropriate biological shielding, it is necessary to know its nuclear, structural and physical properties and the characteristics of radiation impinging on wood. For future research, it is recommended to expand the investigation to include older hardwood trees, specifically by analyzing both lower diagnostic energy ranges (below 200 keV) and higher industrial energy levels (above 1500 keV).

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