Attenuation Coefficients of Soy-Lignin Bonded *Rhizophora* spp. Particleboard as a Potential Phantom Material Using Monte Carlo GATE

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This work aimed to determine the linear and mass attenuation coefficients of soy-lignin bonded *Rhizophora* spp. particleboard intended for use as a phantom material using Monte Carlo GATE simulation. At a desired density of 1.0 g·cm^{-3}, particleboard constructed of *Rhizophora* spp. wood trunk bonded with soy flour and lignin was created. The sample's elemental composition was identified using energy dispersive X-ray spectroscopy. The GATE software was used to simulate the setup with the histories of 1 × 10^{7}, and comparison was made between the experimental and simulation data. The disparities between the linear and mass attenuation coefficients of the samples experimentally measured and calculated using GATE at low energy photons were quite small. The result revealed a good agreement between the experimental and simulation data, and the attenuation coefficients were in close proximity with XCOM of water. The outcome revealed GATE adequacy for validation of attenuation coefficient measurement in bioresources phantom material for medical physics application.

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Keywords: Monte Carlo simulation; GATE; Attenuation coefficient; Phantom material; Plant-based

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INTRODUCTION

Water is frequently utilized as phantom material because of its mass density, which is similar to that of human tissue. Because water cannot always be used as a phantom due to its shape, many water-equivalent phantoms, such as acrylic, have been developed. Due to the instability of plastic-based phantom materials, the majority of acrylic phantoms still fail to exhibit satisfactory scattering and absorption capabilities. It is also well known that solid materials, such as Perspex®, which makes up the RANDO phantom, are often utilized as phantom materials, but their mass density and attenuation characteristics have been found to be very different from those of water and human soft tissue (Khan and Gibbons 2014). In addition, many water-equivalent substances such as polystyrene, acrylic, and solid water were also created. Despite their many benefits, they do have some drawbacks, such as the difficulty to accurately simulate actual human soft tissue (Yohannes *et al.* 2012).

Further research has resulted in replacements for the widely used phantom, and more natural materials have been employed to make it. Previous studies have reported *Rhizophora*'s ability as a potential phantom material in medical physics applications (Bradley *et al.* 1991; Sudin *et al.* 1988; Yusof *et al.* 2017c). Previous studies also found that *Rhizophora* spp. showed a linear attenuation coefficient of 0.0212 mm^{-1}, which is near the value of 0.0205 mm^{-1} by water (Samson *et al.* 2020a, 2020b). The potential of *Rhizophora* spp. as phantom material is also supported by the elemental composition that mimics human soft tissues (Banjade *et al.* 2001; Marashdeh *et al.* 2011).

Previous research on *Rhizophora* spp. demonstrated the feasibility of this particular mangrove tree as a phantom material (Banjade *et al.* 2001; Abuarra *et al.* 2014; Tousi *et al.* 2014; Taghizadeh Tousi *et al.* 2015; Ababneh *et al.* 2016; Yusof *et al.* 2017a). However, because of its instability in terms of shape and homogeneity, particleboard made from wood is considerably preferable over raw wood for the fabrication of phantom material. To increase the physical and mechanical strength of particleboard made from different types of wood over the years, adhesive is frequently added to the manufacturing process. Although phenol formaldehyde resin (PF) is one of the common bonding substances used in the wood industry, many researchers have resorted to alternatives due to its recognized negative effects on the environment and human health. This phenol-based resin is highly hazardous when ingested, inhaled, or comes into contact with the eyes. It is also a probable cause of cancer (Nelson *et al.* 1986; Partanen *et al.* 1990; Gerberich *et al.* 2000; Beane Freeman *et al.* 2009).

In an effort to replace phenol-based resins and lessen the negative effects, several researchers concentrated on bio-based adhesives, and a variety of adhesives were developed and studied. Among many others, it has been established that protein- and carbohydrate-based adhesives are acceptable for use in the production of particleboard. Soy protein had been widely used as an alternative bonding agent to replace petroleum-based resins, whereas lignin as adhesive made it more accessible to the fibre during hot pressing as it redeposited during mixing (Boon *et al.* 2019). Both the adhesives are used for particle bonding and contribute to the particleboard's increased structural and mechanical durability. Particleboard's rough and irregular surface has led to increased efforts to create a better and smoother board surface, reducing the air gap between each slab. This is crucial for the dosimetry study because an air gap could result in inaccurate dose measurement. To generate correct dosimetry data when compared to human tissue, phantom material characterization is crucial. Several experiments must be conducted, including those on the physical and mechanical properties, characterization, mass density, and attenuation properties, to accommodate the unique characteristics of human phantom material (Zuber *et al.* 2020; Binti Zuber *et al.* 2024). This is critical, particularly in radiation studies where the phantom must have characteristics that are comparable to those of human tissue (Sharma *et al.* 2023), and the best comparison that can be made is with water, as provided by the Photon Cross Sections Database (XCOM) value (Marashdeh *et al.* 2011).

The mass attenuation coefficient of any material must be determined for medical physics applications because it reflects the material's properties and radiation study appropriateness. The attenuation properties of a substance are extensively studied in industrial, environmental, and agricultural studies in addition to medical research (Marashdeh *et al.* 2015). Ionizing radiation's ability to attenuate as it travels through a material is assessed, and the coefficient can be calculated using a variety of techniques, including direct measurement and the XCOM computer programme. The attenuation coefficient can be directly measured using proton-induced X-ray emission (PIXE)

(Abdullah *et al.* 2010), high energy gamma photon (Yusof *et al.* 2016, 2017b), X-ray fluorescent (XRF) techniques (Marashdeh *et al.* 2012; Alshipli *et al.* 2018).

X-ray fluorescence (XRF) spectroscopy is a non-destructive analytical technique that can be used to determine the elemental composition of a material. This technique makes use of fluorescent X-ray emissions from the sample that are detected after they are excited by a primary radiation source. By configuring the spectrometer to meet the requirements for the measurement and collection of counts at the detector for attenuation studies, this method can measure a material's linear attenuation coefficient (Shakhreet *et al.* 2009; Marashdeh *et al.* 2012; Hamid *et al.* 2017; Yusof *et al.* 2017b). Previous experiments have demonstrated the effectiveness of this design, and the materials employed include wood particles, Perspex®, and other phantom materials in radiation studies (Yusof *et al.* 2017b; Alshipli *et al.* 2018).

The employment of software and algorithms for the forecast or validation of any experimental investigation is crucial for researchers in the age of developing computer technology (Sharma *et al.* 2023). The Monte Carlo (MC) method in medical physics involves using statistical simulations to model and analyze complex systems, such as radiation transport in medical imaging. Since the 1930s, when the MC method was first introduced as a computing tool, it has been widely employed, making use of the simulating system to solve physics and mathematical issues. The paradigm change brought about by developments in statistics and physics sparked the creation of tactics and measurements utilizing MC, particularly to validate against diverse experimental findings.

Geant4 Application for Emission Tomography (GATE) is a well-known open-source MC simulation platform that enables straightforward and user-friendly dosimetry, imaging, and radiation simulation in the same environment (Jan *et al.* 2011, 2004). Nuclear medicine, radiation therapy, and dosimetry have all benefited from the development of the MC toolset, and the creation of GATE now makes it possible to do more broad simulation in a dosimetry setting (Ljungberg and Strand 1989; Harrison *et al.* 1993; Agostinelli *et al.* 2003). GATE application is a part of geant4 toolkit that simulates the interaction between same or different matters and able to provide high-level features to ease the simulation and design. GATE's unique scripting approach enables the smooth and easy development of geometry, resulting in accurate simulation in realistic setup (Agostinelli *et al.* 2003). Although GATE has been widely verified and utilized for many studies using single photon emission computed tomography (SPECT) and positron emission tomography (PET) imaging, there are only a limited number of articles that can demonstrate its application and dependability in dosimetry studies.

This work aims to determine the linear and mass attenuation coefficient of the soy-lignin bonded *Rhizophora* spp. particleboard for low energy photons using the Monte Carlo GATE simulation, and comparison was made with experimental data. The elemental fraction of particleboard used in the simulation was obtained from scanning electron microscopy with energy dispersive X-ray analysis (SEM-EDX).

EXPERIMENTAL

Preparation of Particleboard

Wood logs from *Rhizophora* species were acquired from a coal company in Kuala Sepetang. To create samples with various particle sizes, the logs underwent a number of processing steps, including washing, drying, debarking, grinding, and sieving. Slabs of particleboards bonded with different percentages of soy flour and lignin were then constructed at a target density of 1.0 g·cm^{-3}. *Rhizophora* spp. wood particles were prepared at 1.39 to 6.47% L moisture content at three different particle sizes (0 to 103 µm, 104 to 210 µm, and 211 to 500 µm). Soybean flour (type I) and lignin (alkali, low sulfonate content) (both in powder form), purchased from Sigma Aldrich, Germany, were prepared at two different percentage mixtures, 6% (4.5% soy flour and 1.5% lignin) and 12% (6% soy flour and 3% lignin). Hot pressing was used for the fabrication of particleboard at 200 °C and pressure of 20 MPa for 20 min. The samples were prepared accordingly at (5.0 × 5.0 × 0.5) cm^3 dimension.

Experimental Setup for Attenuation Coefficient Study

The experimental attenuation coefficient study was performed using the XRF configuration, with energy calibration carried out using (low energy Germanium) LEGe detector (Hamid *et al.* 2017). An annular Americium-241 (^{241}Am) source with a nominal activity of 100 mCi was used in conjunction with four metal plates – Niobium (Nb), Molybdenum (Mo), Palladium (Pd), and Tin (Sn) to determine the mass attenuation coefficient of the soy-lignin bonded *Rhizophora* particleboards at the energy ranges of 16.61 to 25.27 keV. Figure 1 visualizes the experimental setup for the attenuation study (Hamid *et al.* 2017). The LEGe detector (CANBERRA) was employed to collect the photons transmitted, and the output pulses were amplified by an amplifier (ORTEC 572). Multichannel analyzer (MCA-3 series) was used to collect the spectrum for 60 s. The experimental results were reported in a previous study (Zuber *et al.* 2021), and comparison with GATE simulation was made in this work.

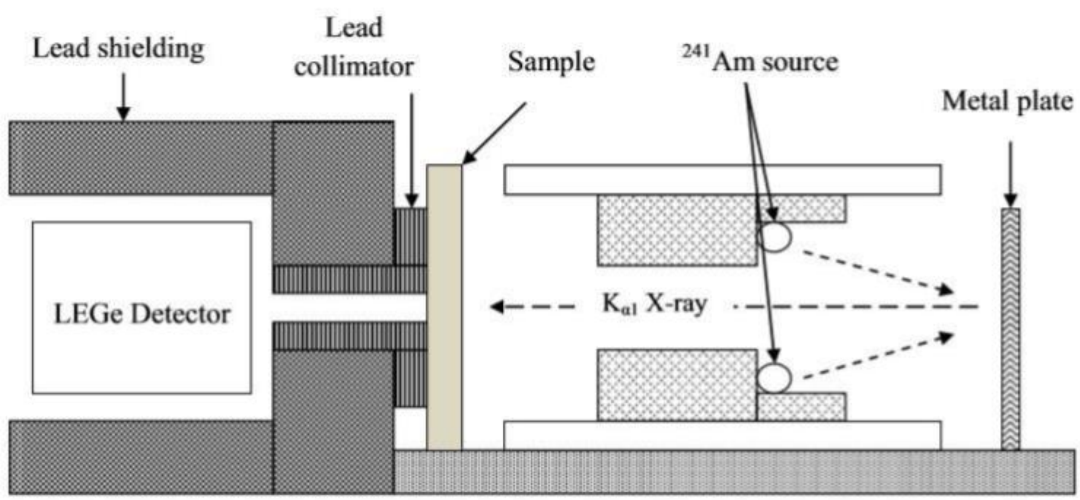

Fig. 1. Experimental setup for the attenuation study using ^{241}Am

Elemental Analysis Using Energy Dispersive X-Ray (EDX) Spectroscopy

For this analysis, *Rhizophora* spp. particleboards were prepared at 1.0 g·cm^{-3} target density with dimension (1.0 × 1.0 × 0.5) cm^3. Then, EDX (Field Emission Scanning Electron Microscope (FESEM) - FEI Nova NanoSEM 450 with EDX (FEI Company, Hillsboro, OR, USA) was performed to determine the elemental composition of the samples, where they were mounted onto specimen holders and examined under vacuum conditions using the scanning electron microscope, with weight percentage of elements recorded accordingly.

Monte Carlo Toolkit: GATE for the Simulation

The model of the computer employed in this study was a Lenovo H30-50 with Linux Mint 19 Tara 64-bit operating system (OS). GATE v8.2 with geant4 v10.05.p01 and Root v6.14/06 platform was used in the simulation. The SPECTHead example was modified for this work, and the input file created by GATE simulates the experimental configuration utilizing macro files with a variety of commands. The geometry setup for the simulation study is shown in Fig. 2.

Figure 3 provides a bird eye view of the setup with photon energy directed towards the sample in GATE simulation.

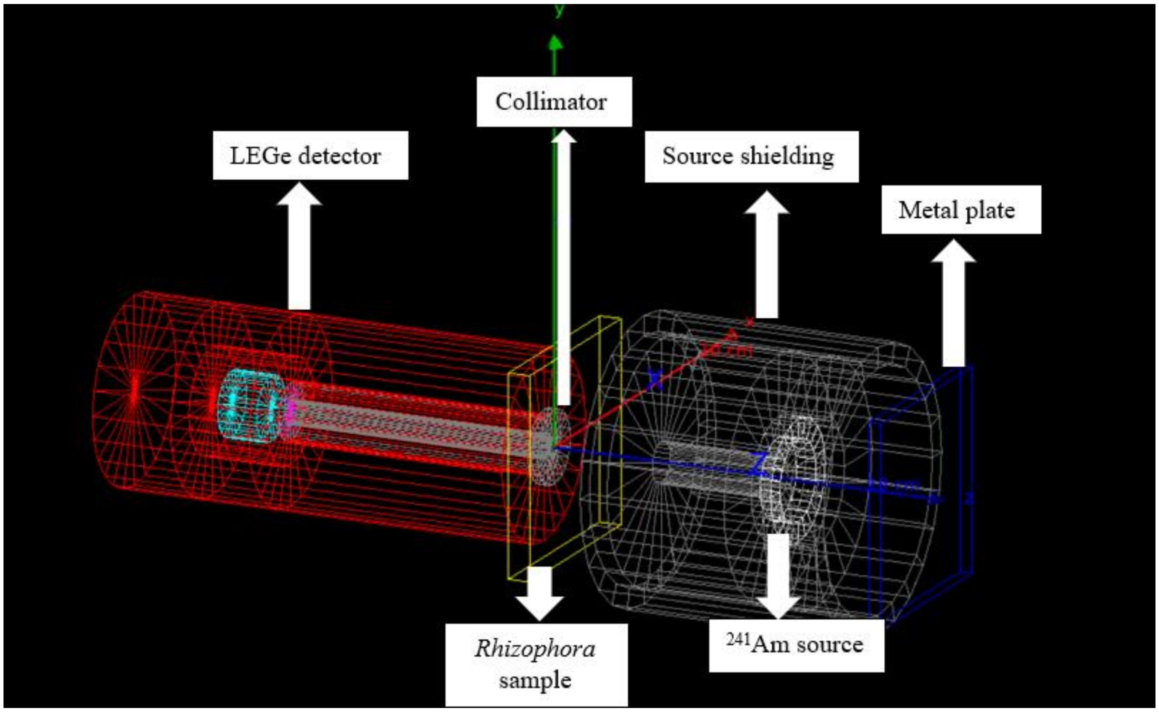

Fig. 2. Geometry setup for the simulation study

The challenge for Monte Carlo studies is to correctly quantify all the variables so that the internal and external influence of the geometry can be consistently detected. A 20-item checklist – RECORDS – Reporting of Monte Carlo Radiation Transport Studies – was included in this work, in an effort to improve the quality of MC study as proposed by AAPM Research Committee Task Group 268 (Sechopoulos *et al.* 2018). Table 1 reports the RECORDS checklist.

Command scripts were developed in various macro files, including actors, beam, geometry, physics, visualization, and main, which contains the entire ordered set of commands required to perform the simulation. The master macro was divided into three sections - data, mac, and output.

Output macro files made use of the ROOT graphical user interface TBrowser to analyse and visualize simulation results interactively. The geometry of the setup was developed based on the experimental setup, with detailed measurements prior to the pilot run to validate the energy peak with a predetermined energy window.

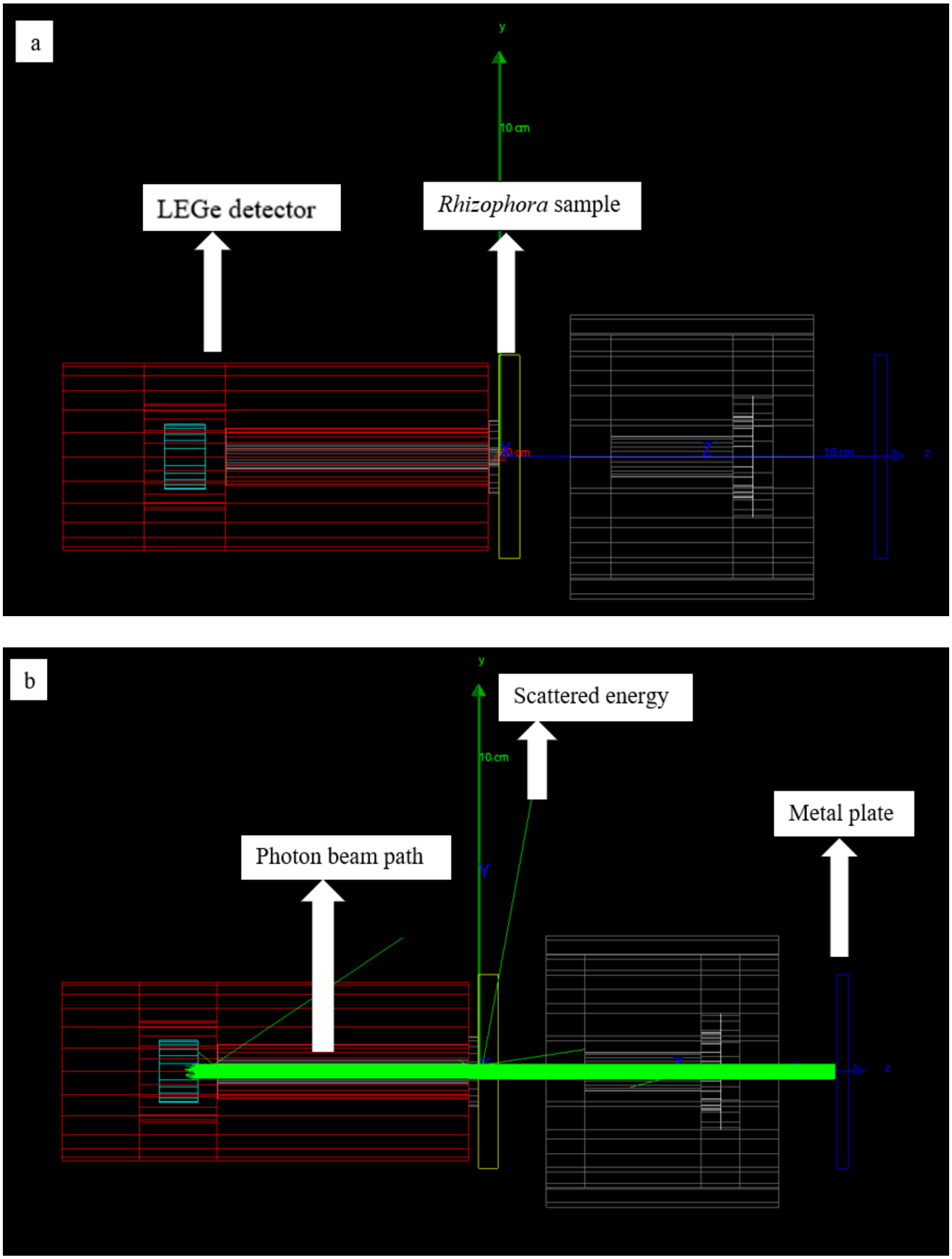

Fig. 3. (a) Bird's eye view (BEV) of the geometry setup for GATE simulation, and (b) BEV of the photon energy directed toward the sample

Table 1. RECORDS Items Checklist for Monte Carlo Study

Checklist Item #	Item Name	Description
2, 3	Code, version/release date	GATE v8.2 with geant4 v10.05.p01 and Root v6.14/06 platform Release Date: 15/02/2019
4, 17	Validation	XRF configuration to measure the linear and mass attenuation coefficient of phantom material
5	Timing	CPU based simulation: 4.0 GHz × 8 threads CPU 874 MHz GPU CPU/GPU model number: Intel i7-4790 NVIDIA GeForce GT 705
8	Source description	Mono energy X-ray based on photon energy from interaction ^{241}Am alpha with each metal plate Model to generate source: General Particle Source (geant4) Model parameter value: Nil
9	Cross-sections	Cross-section data: Nil
10	Transport parameters	EM Standard Option 4 (geant4)
11	VRT and/or AEIT	Nil
12	Scored quantities	GATE Actor - FluenceActor attached to detector
13, 18	Histories/statistical uncertainty	Histories used 1×10^7
14	Statistical methods	Standard Deviation
15, 16	Postprocessing	Nil

XRF = x-ray fluorescence; CPU = central processing unit; GPU = graphics processing unit; EM = electromagnetic; VRT = variance reduction technique; AEIT = approximate efficiency improving technique

In this work, soy-lignin bonded *Rhizophora* spp. samples were placed at 6.0 cm from the source, and 7.0 cm from the LEGe detector. A 3.8-mm collimator at the detector was used in this work. For the GATE simulation, mono-energy of X-ray was preset at the surface of the plate and directed to the detector based on the photon energy in Table 2, to allow for accurate representation of the metal plates. The setup was simulated *via* the GATE (version 1.2.3) MC package, with histories of 1×10^7. The simulation data revealed results in the form of entries for the predetermined energy window after the launch of ROOT for output, and the linear and mass attenuation coefficients were calculated.

Table 2. Photon Energy of Each Metal Plates Used in this Work

Metal Plate	Photon Energy (keV)
Nb	16.61
Mo	17.47
Pd	21.17
Sn	25.27

RESULTS AND DISCUSSION

Elemental Analysis for the Soy-Lignin Bonded Particleboard

Elemental analysis was performed for all soy-lignin bonded *Rhizophora* spp. wood particles. The fractional weight for each element was recorded in Table 3. The elemental composition of samples was documented to prepare for the command scripts in the GATE simulation.

Table 3. Weight Percentages of Elements for All Particleboards

Sample	Weight Percentage (%)			
	Carbon	Hydrogen	Oxygen	Nitrogen
A_0	47.19	-	48.74	4.08
A_6	47.12	-	48.10	4.78
A_{12}	47.11	-	49.32	3.57
B_0	47.94	-	49.02	3.03
B_6	48.22	-	49.38	2.40
B_{12}	47.67	-	48.39	3.95
C_0	48.42	-	48.43	3.15
C_6	47.35	-	48.59	4.06
C_{12}	47.74	-	49.17	3.09

A = Sample with particle size of 211 to 500 µm; B = Sample with particle size of 104 to 210 µm; C = Sample with particle size of 0 to 103 µm;
0 = 0% soy flour and lignin, 6 = 4.5% soy flour and 1.5% lignin, 12 = 9% soy flour and 3% lignin

Measurement of Linear and Mass Attenuation Coefficient in GATE Simulation

The linear and mass attenuation coefficient of the *Rhizophora* particleboards and the percentage differences in comparison to simulation data are shown in Tables 4 and 5. Table 6 recorded the percentage standard deviation calculated in GATE.

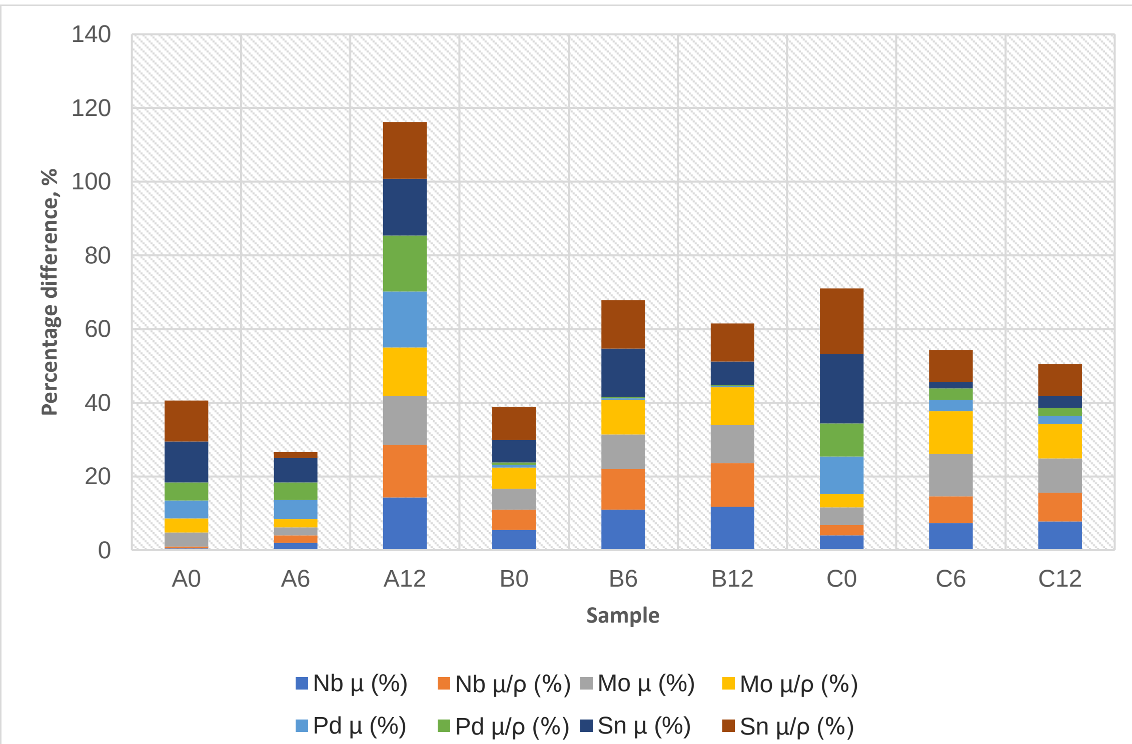

Fig. 4. Percentage differences between the experimental and simulated data for each *Rhizophora* sample (Each colored bar in the graph represents the percentage difference between the experimental and simulated data. The length of each color-coded bar indicates the magnitude of this difference)

Table 4. Linear and Mass Attenuation Coefficients of Particleboards in Experiment and GATE Simulation at 16.61 and 17.47 keV

Sample Type	Avg. Density ($g.cm^{-3}$)	Nb (16.61 keV)						Mo (17.47 keV)					
		μ (cm^{-1})	μ (GATE)	%	μ/ρ (cm^2g^{-1})	μ/ρ (GATE)	%	μ (cm^{-1})	μ (GATE)	%	μ/ρ (cm^2g^{-1})	μ/ρ (GATE)	%
A_0	0.95425	0.9637	0.9587	0.5	1.0099	1.00466	0.5	0.8803	0.8469	3.8	0.9225	0.88750	3.8
A_6	0.91175	0.9707	0.9903	2.0	1.0647	1.08615	2.0	0.8555	0.8743	2.2	0.9383	0.95893	2.2
A_{12}	1.00825	1.1037	0.9454	14.3	1.0947	0.93766	14.3	0.9617	0.8352	13.2	0.9538	0.82837	13.2
B_0	0.93200	0.9957	0.9412	5.5	1.0683	1.00987	5.5	0.8817	0.8317	5.7	0.9460	0.89238	5.7
B_6	0.93675	1.0640	0.9470	11.0	1.1358	1.01094	11.0	0.9230	0.8359	9.4	0.9853	0.89234	9.4
B_{12}	0.97900	1.1232	0.9902	11.8	1.1473	1.01144	11.8	0.9743	0.8741	10.3	0.9952	0.89285	10.3
C_0	0.99150	1.0227	0.9813	4.0	1.0315	1.00235	2.8	0.9095	0.8661	4.8	0.9173	0.88468	3.6
C_6	0.98050	1.0670	0.9894	7.3	1.0882	1.00908	7.3	0.9881	0.8740	11.5	1.0078	0.89138	11.6
C_{12}	0.94000	1.0283	0.9485	7.8	1.0939	1.00904	7.8	0.9235	0.8378	9.3	0.9824	0.89128	9.3
Perspex®	1.19000	0.9420			0.7920			0.8660			0.7280		
Water (XCOM)	1.00000	1.1930			1.1930			1.0950			1.0950		

A = 211 to 500 µm, B = 104 to 210 µm, C = 0 to 103 µm particle size ranges

0 = 0% soy flour and lignin, 6 = 4.5% soy flour and 1.5% lignin, 12 = 9% soy flour and 3% lignin

Table 5. Linear and Mass Attenuation Coefficients of Particleboards in Experiment and GATE Simulation at 21.17 and 25.27 keV

Sample Type	Average Density ($g \cdot cm^{-3}$)	Pd (21.17 keV)						Sn (25.27 keV)					
		μ (cm^{-1})	μ (GATE)	%	μ/ρ (cm^2g^{-1})	μ/ρ (GATE)	%	μ (cm^{-1})	μ (GATE)	%	μ/ρ (cm^2g^{-1})	μ/ρ (GATE)	%
A_0	0.95425	0.5767	0.5483	4.9	0.6043	0.57459	4.9	0.4397	0.3907	11.1	0.4608	0.40943	11.1
A_6	0.91175	0.5974	0.5661	5.2	0.5925	0.62090	4.8	0.3780	0.4031	6.6	0.4350	0.44212	1.6
A_{12}	1.00825	0.6377	0.5406	15.2	0.6325	0.53618	15.2	0.4555	0.3854	15.4	0.4518	0.38225	15.4
B_0	0.93200	0.5425	0.5385	0.7	0.5821	0.57779	0.7	0.4082	0.3833	6.1	0.4521	0.41127	9.0
B_6	0.93675	0.5391	0.5411	0.4	0.5755	0.57764	0.4	0.4437	0.3855	13.1	0.4737	0.41153	13.1
B_{12}	0.97900	0.5678	0.5660	0.3	0.5800	0.57814	0.3	0.4306	0.4030	6.4	0.4591	0.41165	10.3
C_0	0.99150	0.6243	0.5607	10.2	0.6297	0.57273	9.0	0.4914	0.3989	18.8	0.4956	0.40746	17.8
C_6	0.98050	0.5840	0.5659	3.1	0.5956	0.57716	3.1	0.4097	0.4028	1.7	0.4500	0.41081	8.7
C_{12}	0.94000	0.5543	0.5423	2.2	0.5897	0.57692	2.2	0.3991	0.3864	3.2	0.4500	0.41106	8.7
Perspex®	1.19000	0.5620			0.4720			0.4390			0.3690		
Water (XCOM)	1.00000	0.7550			0.7550			0.5060			0.5060		

See notes for Table 4.

Table 6. Summary of the Standard Deviation Calculated in GATE

Metal Plate	Sample	Standard Deviation (%)	Metal Plate	Sample	Standard Deviation (%)
Nb	A_0	0.004 to 0.037	**Pd**	A_0	0.006 to 0.036
	A_6	0.001 to 0.064		A_6	0.003 to 0.027
	A_{12}	0.008 to 0.059		A_{12}	0.002 to 0.033
	B_0	0.016 to 0.089		B_0	0.000 to 0.015
	B_6	0.001 to 0.065		B_6	0.016 to 0.042
	B_{12}	0.003 to 0.045		B_{12}	0.001 to 0.063
	C_0	0.000 to 0.085		C_0	0.007 to 0.020
	C_6	0.014 to 0.044		C_6	0.002 to 0.011
	C_{12}	0.005 to 0.097		C_{12}	0.005 to 0.053
Mo	A_0	0.007 to 0.049	**Sn**	A_0	0.007 to 0.024
	A_6	0.013 to 0.042		A_6	0.004 to 0.015
	A_{12}	0.012 to 0.031		A_{12}	0.005 to 0.028
	B_0	0.007 to 0.082		B_0	0.008 to 0.034
	B_6	0.020 to 0.024		B_6	0.014 to 0.047
	B_{12}	0.023 to 0.067		B_{12}	0.002 to 0.079
	C_0	0.004 to 0.049		C_0	0.009 to 0.042
	C_6	0.014 to 0.087		C_6	0.000 to 0.038
	C_{12}	0.029 to 0.050		C_{12}	0.024 to 0.040

A = 211 to 500 µm, B = 104 to 210 µm, C = 0 to 103 µm particle size ranges
0 = 0% soy flour and lignin, 6 = 4.5% soy flour and 1.5% lignin, 12 = 9% soy flour and 3% lignin

Based on the results, the percentage differences between experiment and simulation for the linear and mass attenuation coefficient of the soy-lignin bonded *Rhizophora* spp. particleboard were relatively varied; however the variation did not exceed 20 %, with B_{12} reported to be the smallest, at 0.3%. Figure 4 illustrates the overall percentage differences between the experimental and simulated data for each sample.

Based on the chart, A_6 presented the smallest overall percentage disparities, whereas A_{12} revealed higher percentage differences. At 16.61 keV, B_{12} presented 3.83% differences with XCOM value of water experimentally. Close proximity of attenuation coefficient with water indicates its close similarity to attenuation of human tissue, which is one of the key parameters (Samson *et al.* 2023) in determining its potential as phantom material for dosimetry and radiation study (Alshipli *et al.* 2018).

There is no evidence to support the assertion that the varied percentage differences (0.3 to 18.8%) are due to the low energy photons, as previous study utilizing GATE simulation at energy less than 50 keV reported that the level of GATE accuracy is adequate for dosimetry study (Thiam *et al.* 2008). The results may also be due to the boundary conditions and device limitation of the simulated model in GATE in corresponding to the experimental setup. Despite the intricate simulation setup, there may be a mismatch and discrepancy between actual performance and the assumed model's simulation. When compared to the simulated results, the experimental findings, which are derived from real-time systems, provide significantly more accurate outcomes. The experimental arrangement is, however, also prone to error because of both device limitations and its design. The resolution and accuracy limitations of the detector utilized in the work could also have an impact on the experimental results.

A smaller energy window with a greater number of histories can be used to lessen the inconsistency of the collected data (Zuber *et al.* 2022). It is recommended to leverage the continuous updates in GATE, as each new version enhances the accuracy and precision of simulations through refined models and improved features. Regularly updating to the latest GATE version can better align simulations with experimental setups by addressing boundary condition issues and incorporating advanced physics models. Additionally, upgrading experimental equipment to high-resolution detectors will complement these improvements, ensuring that both simulated and experimental data are as accurate and reliable as possible. It is also recommended to continue exploring the potential of GATE algorithm because it gives the user many options for carrying out adaptable experimental designs, all dependent on the accessibility of computer systems, without requiring expensive equipment setup. A more thorough study is recommended to evaluate the algorithm's applicability and accuracy in the validation of different energy ranges.

CONCLUSIONS

1. The findings highlight the promising potential of *Rhizophora*-based particleboard, bonded with soy flour and lignin, as phantom material.
2. The determination of linear and mass attenuation coefficient of the soy-lignin bonded *Rhizophora* spp. particleboard at low energy photons *via* GATE simulation has been shown to be in good agreement (smallest at 0.3%) with experimental data.
3. The outcome revealed GATE adequacy for validation of attenuation coefficient measurement in bioresources phantom material for medical physics application.

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