

Compton Scattering Study using Ludlum Configuration for Tissue-Equivalent Phantom Material Made from Soy-Lignin Bonded *Rhizophora* spp. Particleboard (Kajian Penyebaran Compton menggunakan Konfigurasi Ludlum untuk Bahan Fantom Setaraf Tisu yang Diperbuat daripada Lignin Soya Terikat *Rhizophora* spp. Papan Partikel)

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ABSTRACT

Rhizophora spp. particleboards were prepared at approximately $(20.0 \times 20.0 \times 1.0)$ cm³ and at $1.0 \text{ g}\cdot\text{cm}^{-3}$ target density. The mass attenuation coefficient of the soy-lignin bonded *Rhizophora* spp. particleboard was measured by Compton scattering using Ludlum configuration utilizing the Cesium-137 (¹³⁷Cs). Monte Carlo (MC) GATE code was employed to simulate the scattering by using the same set-up. Compton scattering results from both experimental and simulation methods were compared with XCOM value of water. Half value layer (HVL) and mean free path (MFP) were calculated and analyzed. For Compton scattering method in comparison to XCOM value of water, both non-coated and coated samples showed a statistically non-significant value with p-value more than 0.05. The overall results suggested that the mass attenuation coefficient, HVL and MFP of soy-lignin bonded *Rhizophora* spp. particleboard based on Compton scattering study is within close agreement with XCOM value for water, exhibiting its potential as phantom materials.

Keywords: Compton scattering; Monte Carlo simulation; *Rhizophora* spp.; soy-lignin bonded; tissue-equivalent phantom

ABSTRAK

Rhizophora spp. papan partikel disediakan pada ukuran $(20.0 \times 20.0 \times 1.0)$ cm³ dan pada ketumpatan sasaran $1.0 \text{ g}\cdot\text{cm}^{-3}$. Pekali pelemahan jisim papan partikel yang diperbuat daripada *Rhizophora* spp. terikat soya-lignin diukur dengan penyebaran Compton menggunakan konfigurasi Ludlum Cesium-137 (¹³⁷Cs). Kod GATE Monte Carlo (MC) digunakan untuk simulasi penyerakan dengan menggunakan susunan uji kaji yang sama. Hasil penyerakan Compton daripada kedua kaedah uji kaji dan simulasi dibandingkan dengan nilai air XCOM. Lapisan nilai separuh (HVL) dan jalur bebas min (MFP) dihitung dan dianalisis. Untuk kaedah penyebaran Compton dibandingkan dengan nilai air XCOM, kedua-dua sampel yang tidak bersalut dan bersalut menunjukkan nilai yang tidak signifikan secara statistik dengan nilai p lebih daripada 0.05. Hasil keseluruhan menunjukkan bahawa pekali pelemahan jisim, HVL dan MFP daripada papan partikel yang dibuat daripada *Rhizophora* spp. terikat soya-lignin berdasarkan kajian hamburan Compton adalah sangat dekat dengan nilai XCOM untuk air, menunjukkan potensinya sebagai bahan fantom.

Kata kunci: Fantom setara tisu; ikatan lignin soya; penyebaran Compton; *Rhizophora* spp.; simulasi Monte Carlo

INTRODUCTION

Compton scattering study was often recognized as one of the methods to measure linear and mass attenuation

coefficient of a material towards ionizing radiation (Çevik & Baltaş 2007; Hamid et al. 2017; Kucuk et al. 2013). Photon interactions with human tissues, tissue

substitutes such as phantom and dosimeters can be defined by mass attenuation coefficients (μ/ρ). The values of mass attenuation coefficients are dependent upon the absorption and scattering of the incident radiation caused by several different mechanisms such as coherent scattering and Compton scattering. This parameter is vital especially in the evaluation of a material for use in radiation dosimetry studies. Mass attenuation coefficient can be obtained by the methods of transmission using mono-energetic photons, and scattering using gamma source such as Cesium-137, (^{137}Cs).

Material used for radiation and dosimetric studies need to be assessed in terms of its physical properties, mechanical properties, and attenuation properties in comparison to water (Samson et al. 2020a; Zuber et al. 2020a, 2020b). Water has been recommended as standard phantom material in many international dosimetric protocols due to its specific characteristics including mass density and effective atomic number, (Z_{eff}) that are close to human soft tissues (Khan & Stathakis 2010). Various materials had been studied to replace water as phantom in radiation study due to the liquidity form of water, that limits its usage in conjunction of several types of dosimeters such as film, optically stimulated luminescent dosimeter (OSLD) and thermoluminescent dosimeter (TLD). Acrylic Perspex® and solid water phantom are the common solid water-equivalent phantom materials that simulated close attenuation values to water (Johnston & Fauber 2015).

Rhizophora spp. particleboards had been studied by many previous researchers for its potential as water-equivalent phantom material (Azahari et al. 2020; Hamid et al. 2018; Rabaiee et al. 2015; Yusof et al. 2016; Zuber et al. 2020a). Most notable characteristics of *Rhizophora* spp. that was ideal as phantom material is its attenuation coefficient that was similar to water (Bradley et al. 1991). This is mainly due to its mass density close to the value of water. However, raw *Rhizophora* spp. presented with several limitations which can be overcome by the incorporation of adhesive to further strengthen and stabilize the material. The raw wood was made into particleboard for density homogeneity and bonded with various natural adhesives such as tannin (Yusof et al. 2017), soy flour (Zuber et al. 2020a), corn starch (Hamid et al. 2017), lignin (Zuber et al. 2020a) and gum Arabic (Abuarra et al. 2014).

The breakthrough of Monte Carlo method in medical physics applications allows various improvement in terms of reconstruction images, design of detector prototypes, qualitative and quantitative analysis, and correction methods. Beginning with the

application alongside positron emission tomography (PET) and single photon emission computed tomography (SPECT), more improvements had been made based on the models and geometry, thus allowing more set-up to be easily constructed. This became possible with GEANT4 Application for Tomographic Emission (GATE), which contains all the GEANT4 features such as variety of physics models, basic event timing information, geometry modelling, and visualization tools. GATE provides easy scripting language without the needs of C++ programming (Jan et al. 2011, 2004; Strulab et al. 2003).

In this study, Compton scattering study was used to measure the attenuation coefficient by using Ludlum configuration utilizing ^{137}Cs source and comparison was made with XCOM of water and GATE simulation study. The GATE simulation study was performed by using GATE MC package based on the same set-up. Half value layer and mean free path were also calculated for all coated and non-coated *Rhizophora* spp. samples and analysis was performed.

METHODS AND MATERIALS

FABRICATION OF PARTICLEBOARD AND DETERMINATION OF ELEMENTAL COMPOSITION OF SAMPLES

Samples for this study were prepared by using *Rhizophora* spp. wood trunk from Kuala Sepetang, Perak. The samples were shredded using a grinder, sieved into 0 - 103 μm particle size and compressed using a hot press machine at approximately 200 °C, at the pressure of 20 MPa for 20 min (Zuber et al. 2020a). In this study, 12% adhesives bonded with *Rhizophora* spp. wood particle was chosen for the fabrication of particleboard based on previous result that showed its potential as the best formulation for phantom material (Zuber et al. 2020a, 2020b). The particleboards were made at approximately (20.0×20.0×1.0) cm^3 at a target density of 1.0 $\text{g}\cdot\text{cm}^{-3}$. The fabricated particleboard samples were prepared with and without gloss finish coating (Zuber et al. 2020b). Elemental composition of samples was obtained from spectroscopy study using Energy-dispersive x-ray (EDX) spectroscopy, with fractions of element used for simulation study.

MEASUREMENT OF MASS ATTENUATION COEFFICIENTS BY USING COMPTON SCATTERING METHOD

A Ludlum configuration was used to determine the linear and mass attenuation coefficients of the samples as shown in Figure 1 (Mohd Yusof et al. 2019; Yusof et

al. 2018). ^{137}Cs gamma sealed source with effective peak energy of 0.662 MeV was used in this study. The source was placed in full lead housing and was collimated with a hole of diameter 0.5 cm and radioactive source activity of 36.9 MBq. An aluminum (Al) plate with approximate thickness of 1.0 mm was used as an attenuator to provide scattered photons of various energies. The radioactive source initial activity used is 36.9 MBq, the diameters of source and detector are 2.5 and 6.5 cm, respectively. The collimator diameter and thickness are 0.5 and 2.0 cm, respectively. Al attenuator dimensions used is (7.0×7.0×0.1) cm. The *Rhizophora* spp. particleboard was placed between the attenuator and detector. The Ludlum detector with collimator was used to measure the transmitted photons from the particleboards at different angles of 0 and 30 °C from the Al attenuator. The peak of Compton scattered photon energy widths (keV) had been measured at the two scattering angles with uncertainty less than 1%. The distance between the Ludlum and phantom material was at approximately 9.1 cm. The distance between the source and attenuator was 30 cm, similar to the distance between attenuator and detector. The photons collected at the detector were recorded in count per min and from the reading, appropriate value was taken and attenuation coefficient was calculated. Filtering was performed to remove any deviated data. The energies of inelastic scattered gamma can be calculated based on the relationship between the incident and

scattered gamma energy in Equation (1) (Knoll 2000; Tsoulfanidis 1983).

$$E_{\gamma'} = \frac{E_{\gamma}}{1+(1-\cos\theta)E_{\gamma}/mc^2} \quad (1)$$

where E_{γ} and $E_{\gamma'}$ is the incident and scattered gamma energy, respectively; θ is the angle of scattered gamma and m is the electron rest mass. This equation is easily derived by assuming a relativistic collision between gamma ray and an electron initially at rest. Attenuation coefficient can be calculated using Beer-Lambert law given in Equation (2).

$$I = I_0 e^{-\mu x} \quad (2)$$

where I_0 and I are the initial photon and photon intensity; μ (cm^{-1}) is the linear attenuation coefficient of the material; and x is the thickness of the samples. Equation 3 showed the linear attenuation coefficient μ (cm^{-1}) formulation.

$$\mu = \frac{1}{x} \ln \left(\frac{I_0}{I} \right) \quad (3)$$

The measured mass attenuation coefficient of the samples was compared with the theoretical value calculated using the photon cross-section database (XCOM) and GATE simulation.

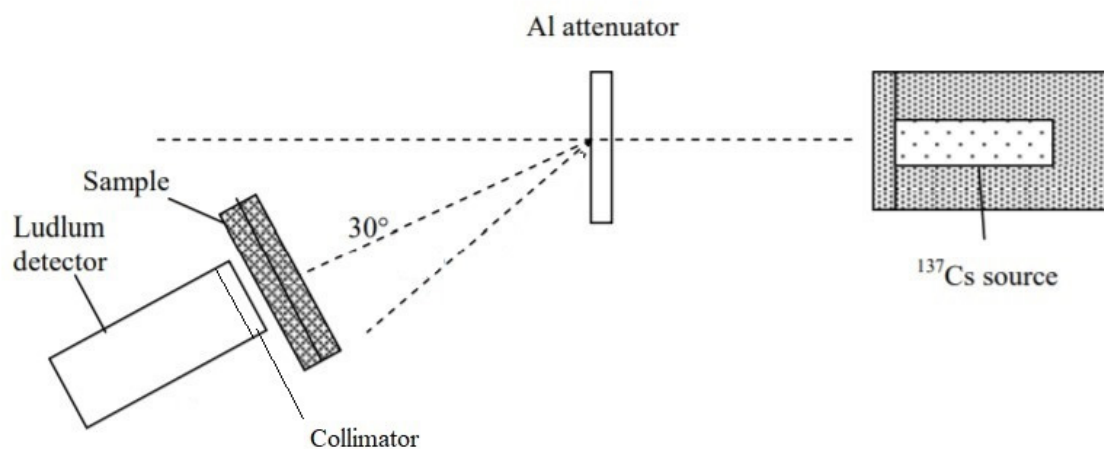


FIGURE 1. The experimental set up for scattering study (Mohd Yusof et al. 2019; Yusof et al. 2018)

CALCULATION OF MASS ATTENUATION COEFFICIENTS BY USING MC GATE CODE

For GATE simulation, the model was generated using Lenovo H30-50 in Linux Mint 19 Tara 64-bit operating

system (OS). MC toolkit: GATE v8.2 with geant4 v10.05.p01 and Root v6.14/06 platform were employed in this study. Table 1 displays the RECORDS checklist to improve the reporting for MC studies (Sechopoulos et al.

2018). The geometry setup and beam path for Compton scattering study is shown in Figure 2. For the simulation study, the same primary source of ^{137}Cs was used and simulated against three different scattering angle, 0, 30 and 45 °. To simulate the scattering angle, cosine triangle calculation was employed to adhere to the axis of the

geometry for the whole set-up. The MC GATE package was employed with histories between 1×10^7 and 1×10^8 . The results were obtained in preset energy window of ^{137}Cs , in form of entries and the values were recorded with increment of sample thickness. Deviated data and incorrect response were filtered and mass attenuation coefficients were calculated.

TABLE 1. Records items checklist for MC study using Gate

Item name	Description
Code, version/release date	GATE v8.2 with geant4 v10.05.p01 and Root v6.14/06 platform Release Date: 15/02/2019
Validation	Code was being validated against experimental measurements (Ludlum configuration to measure the mass attenuation coefficient of phantom material using Compton scattering study)
Timing	CPU based simulation: 4.0 GHz × 8 threads CPU 874 MHz GPU CPU/GPU model number: Intel i7-4790 NVIDIA GeForce GT 705
Source description	Energy spectrum generated from radioactive decay of ^{137}Cs and Aluminium plate as scattering medium Model to generate source: RadioactiveDecay (geant4) Model parameter value: Nil
Cross-sections	Cross-section data: Nil
Transport parameters	EM Standard Option 4 (geant4)
VRT and/or AEIT	Nil
Scored quantities	Number count in energy windows range using Digitizer (GATE)
# histories/statistical uncertainty	Range of histories used between 1×10^7 to 1×10^8
Statistical methods	Standard Deviation
Postprocessing	Nil

EVALUATION OF HALF VALUE LAYER AND MEAN FREE PATH OF THE SAMPLES

The calculation of half value layer represents the thickness of the materials that will reduce the radiation penetration into half. It constitutes the penetrating ability of the ^{137}Cs through the materials. For half value layer, the equation for the calculation is shown in Equation (4).

$$HVL = \frac{\ln 2}{\mu} \quad (4)$$

For mean free path, it is the average distance of photon travel between collision with atoms of the target material and the equation is shown in Equation (5).

$$MFP = \frac{1}{\mu} \quad (5)$$

where μ represents the linear attenuation coefficient of the samples.

RESULTS AND DISCUSSION

ELEMENTAL COMPOSITION OF THE SAMPLES

Table 2 shows the elemental composition of the samples. For simulation geometries in GATE, material composition needs to be described in the form of

elemental fraction or chemical formula. The input from elemental composition was used in the geometry macro files in GATE simulation set up to define the *Rhizophora*

spp. samples used, along with other materials employed in the study, such as Al plate, Ludlum detector and the primary source.

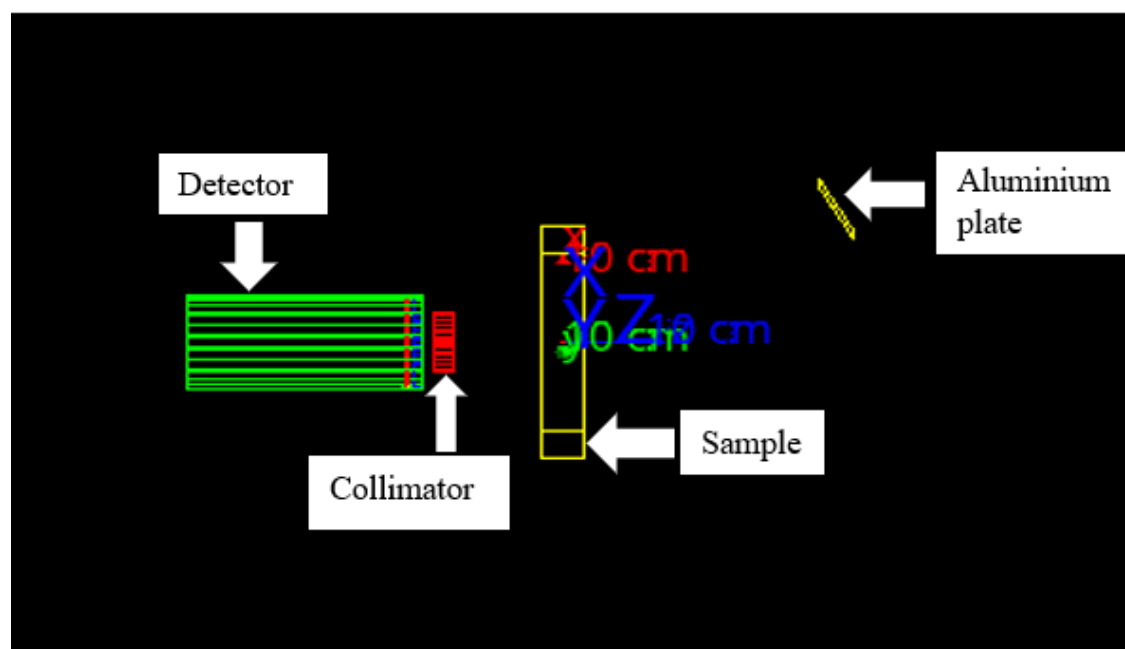


FIGURE 2. A bird's eye view (BEV) geometry set up for 30° scattering angle

SCATTERED GAMMA ENERGIES AND MEASUREMENT OF MASS ATTENUATION COEFFICIENT BY EXPERIMENTAL SET-UP

The calculated scattered gamma energies of ^{137}Cs at 0, 30 and 45 ° scattering angles were 662, 564, and 480 keV, respectively. Table 3 describes the mass attenuation of *Rhizophora* spp. particleboard at scattered ^{137}Cs gamma energies and comparison with XCOM and previous studies (Mohd Yusof et al. 2019; Yusof et al. 2018). Table 4 shows the paired sample t-test for both non-coated and coated samples. The result shows that mass attenuation coefficients increased with the decreased in gamma ray energies (Limkitjaroenporn et al. 2013). Based on Table 3, the percentage difference for A_0 (*Rhizophora* spp. particleboard bonded with 12% soy-lignin adhesives with no coating) and XCOM of water is 6.2% whereas for A_{gloss} (*Rhizophora* spp. particleboard bonded with 12% soy-lignin adhesives with gloss finish coating), the percentage discrepancy is 1.03% for 30° scattering angle. For 0° scattering angle, the percentage difference for A_0 (*Rhizophora* spp. particleboard bonded with 12% soy-lignin adhesives with no coating) and A_{gloss} (*Rhizophora* spp. particleboard bonded with 12% soy-lignin adhesives

with gloss finish coating) is the same with 5.8% discrepancy. The coating of particleboard with gloss finish might reflect the attenuation coefficients with the values increasing gradually, attributed by the increasing in the scattering angle with diminishing gamma energies. This result hence proposed a higher value-added use of *Rhizophora* spp. bonded with natural-based soy flour and lignin with the addition of gloss coating as possible phantom material with attenuation value in close agreement with XCOM of water.

The paired sample t-test for both non-coated and coated sample showed the p-value of 0.058 and 0.626, respectively, which disclose that the mass attenuation coefficient measured by Compton scattering method did not statistically give significant difference in comparison to XCOM value of water. Based on the result, the mass attenuation coefficient calculated by Compton scattering method deemed suitable to determine the attenuation properties of the phantom material for its role in radiation study, and closely in agreement with previous studies (Mohd Yusof et al. 2019; Yusof et al. 2018). Filtering process was carried out during the data collection. Uncertainty due to device error and human

error need to be taken into consideration during the experiment. Full lead block coverage may allow photon to scatter accordingly during the count collection.

Regardless, the experimental values of mass attenuation coefficient based on Compton scattering using Ludlum configuration is within good agreement with theoretical value based on XCOM of water.

TABLE 2. Elemental composition of *Rhizophora* spp. particleboard for MC study

Sample	Weight percentage (%)		
	Carbon (C)	Oxygen (O)	Nitrogen (N)
A ₀	47.74	49.17	3.09
A _{gloss}	62.66	33.77	3.57

A₀ = *Rhizophora* spp. particleboard bonded with 12 % soy-lignin adhesives without coating

A_{gloss} = *Rhizophora* spp. particleboard bonded with 12 % soy-lignin adhesives with gloss finish coating

TABLE 3. Mass attenuation coefficient of sample at scattered ¹³⁷Cs gamma energies

Scattering angle, °	Energy (keV)	Mass attenuation coefficient, μ/ρ (cm ² g ⁻¹)						Percentage discrepancy (%)	
		Water (XCOM)	^a A ₀	^a A _{gloss}	^b A	^c Solid water	^c Perspex ®	A ₀ x XCOM	A _{gloss} x XCOM
0	662	^b 0.086	0.081	0.081	0.080	-	-	5.8	5.8
30	564	^c 0.097	0.091	0.098	0.090	0.085	0.085	6.2	1.03
45	480	^b 0.105	-	-	0.095	0.096	0.091	-	-

A₀ = *Rhizophora* spp. particleboard bonded with 12 % soy-lignin adhesives without coating

A_{gloss} = *Rhizophora* spp. particleboard bonded with 12 % soy-lignin adhesives with gloss finish coating

^aCurrent study, ^b(Mohd Yusof et al. 2019), ^c(Yusof et al. 2018)

TABLE 4. Paired sample t-test for non-coated and coated samples in comparison with XCOM value of water

Pair	A ₀ – XCOM of water	A _{gloss} – XCOM of water
Mean difference	0.0055	0.003
Standard Deviation of difference	0.00071	0.02828
Standard Error of difference	0.0005	0.02
T alpha half 95% confidence level (CI)	12.7062	12.7062
Lower confidence level	-0.00088	-0.25109
Upper confidence level	0.01188	0.25709
p-value	0.058	0.626
Degree of freedom (df)	1	1

A₀ = *Rhizophora* spp. particleboard bonded with 12 % soy-lignin adhesives without coating

A_{gloss} = *Rhizophora* spp. particleboard bonded with 12 % soy-lignin adhesives with gloss finish coating

TABLE 5. Mass attenuation coefficient of samples with and without coating by experimental and simulation study

Angle, °	Energy (keV)	XCOM for water, μ/ρ (cm^2g^{-1})	Mass attenuation coefficient, μ/ρ (cm^2g^{-1}) – Experimental study		Mass attenuation coefficient, μ/ρ (cm^2g^{-1}) – Simulation study	
			A_0	A_{gloss}	A_0	A_{gloss}
0	662	0.086	0.081	0.081	0.099	0.088
30	564	0.097	0.091	0.098	0.117	0.149
45	480	0.105	-	-	0.125	0.154

A_0 = *Rhizophora* spp. particleboard bonded with 12 % soy-lignin adhesives without coating

A_{gloss} = *Rhizophora* spp. particleboard bonded with 12 % soy-lignin adhesives with gloss finish coating

CALCULATION OF MASS ATTENUATION COEFFICIENT BY USING GATE SIMULATION

Table 5 illustrates the comparison of experimental and GATE simulation between the attenuation coefficients of the sample with and without the coating. In experiment set-up, scattering angle of 0 and 30° were employed and compared with the result from simulation study using GATE code. For A_0 (*Rhizophora* spp. particleboard bonded with 12% soy-lignin adhesives with no coating), the disparity between the result when compared with simulation study showed percentages of 22.22 and 28.57% for 0 and 30° scattering angle. For A_{gloss} (*Rhizophora* spp. particleboard bonded with 12% soy-lignin adhesives with gloss finish coating), the percentage discrepancy is smaller which is 8.64% for 0° scattering angle, whereas for 30° scattering angle, result showed a larger percentage difference. The mass attenuation coefficient of the simulated A_{gloss} is close to the calculated value of water, which may contribute to its added value as potential phantom material in radiation and dosimetric study. The percentage differences of the mass attenuation coefficient between the experimental

and GATE simulation may be due to several factors. The geometry for each set-up was designed to mimic the experimental set-up, however, uncertainties may occur due to the cosine triangle calculation from 0° to 45° angles, among other indicators (Chin et al. 2003). Other than that, there is higher probability of photons scattered and dispersed as they passed through the Al plate in higher degree of scattering angle. Shielding block is required to limit the scattering photons within the detection area. Due to the limitation in controlling the condition of experiment set-up, many scattering photons were expected to escape without reaching the detector. Number of histories employed in the simulation study might also reflect the output recorded. In order to reduce the inaccuracy of recorded data, a smaller energy window and higher number of histories is recommended to counter for the backscattered peak of ^{137}Cs .

EVALUATION OF HALF VALUE LAYER AND MEAN FREE PATH OF THE SAMPLES

Figures 3 and 4 illustrate the variation of half value layer (HVL) and mean free path (MFP) of the coated

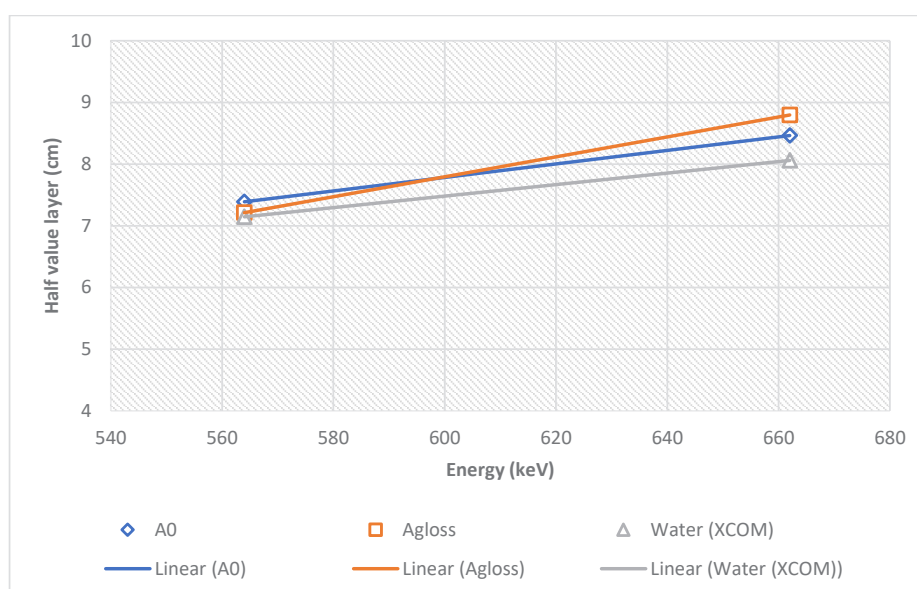


FIGURE 3. The half value layer calculated for the samples and XCOM of water against gamma energies

(A_{gloss}) and non-coated (A_0) adhesive-bonded *Rhizophora* spp. particleboards and XCOM of water against the gamma energies. The performance of all the samples in terms of HVL and MFP analysis showed that the HVL and MFP increased as energy increased. The highest HVL and MFP were observed in sample A_{gloss} (*Rhizophora* spp. bonded with 12% adhesives, coated with gloss finish)

at the energy of 662 keV. The study demonstrates that the curves for all samples were consistent across the energies and with good agreement with the computed theoretical value of water (XCOM). These findings are also congruous with the earlier attenuation studies on the fabrication of *Rhizophora* spp. particleboards utilizing bio-adhesive materials (Abuarra et al. 2014; Samson et al. 2020b).

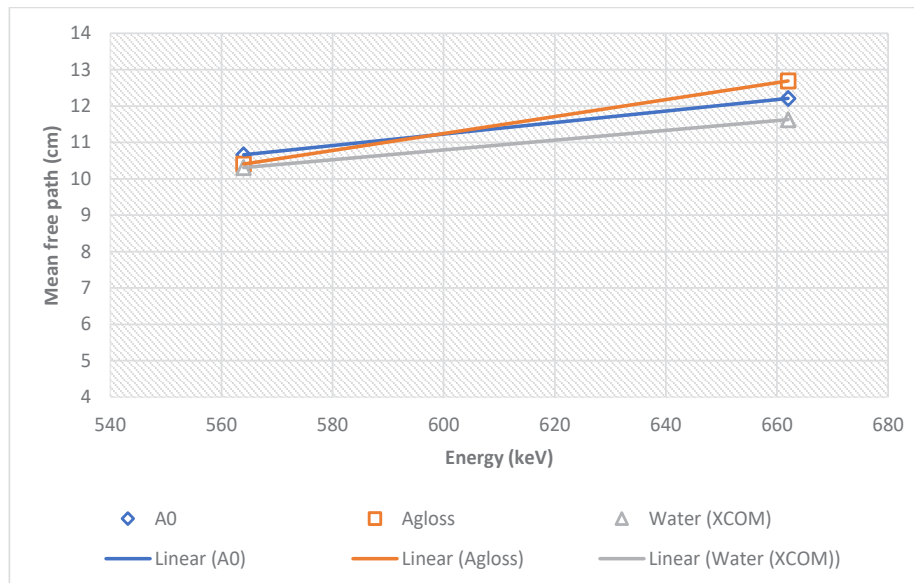


FIGURE 4. The mean free path calculated for the samples and XCOM of water against gamma energies

CONCLUSION

Mass attenuation coefficient, HVL, and MFP of soy-lignin bonded *Rhizophora* spp. particleboard based on experimental results of Compton scattering study are within close agreement with XCOM value for water, exhibiting its potential as phantom materials. Large incongruity between simulation and experimental results may be due to the limitation in the set-up environment and further attention to the set-up protocol is required in scattering study. It is important to address the importance of scattering study in the evaluation of phantom material for medical physics applications as this study point to noteworthy scattering radiation effects on the attenuation outcomes.

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