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The design and dosimetric evaluation of tannin-based *Rhizophora* spp. particleboards as phantoms for high energy photons and electrons

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Abstract. A set of phantom with an external dimension of 30 cm x 30 cm was constructed from tannin-based *Rhizophora* spp. particleboards similar to the solid water phantoms. The dosimetric characteristics of the particleboard phantoms were evaluated at high energy photons and electrons by measuring the beam output at 6 MV photons and 6 MeV electrons based on the IAEA TRS 398:2000 protocol. The tissue-phantom ratio ($TPR_{20,10}$) was measured at 6 and 10 MV photons. The beam output calibration of the particleboards was in good agreement to water and solid water phantoms at 6 MV photons with percentage difference of 1.7 and 6.2% respectively. The beam output calibration of the tannin-based *Rhizophora* spp. particleboards at 6 MeV electrons on the other hand were in excellent agreement to water with percentage difference of 0.3. The percentage depth dose of tannin-based *Rhizophora* spp. particleboards were in agreement to water and solid water within 4.5% when measured using ionization chamber and EBT2 film. The electron beam parameters of R_{50}, R_{80} and R_{90} at 6 MeV electrons also were in good agreement to water and solid water phantoms. The overall results had indicated the suitability of tannin-based *Rhizophora* spp. particleboards as water substitute phantom materials for high energy photons and electrons.

1. Introduction

Phantom materials are the most important tools in quality control (QC) and dosimetry works in radiotherapy. The phantom materials shall be made water equivalent so that the dosimetric evaluation made in the phantom can be directly related to the human soft tissues [1]. Solid water phantoms is the most commonly used water substitute phantom materials for dosimetry works and quality assurance in radiotherapy. The solid water phantoms are epoxy resin-based materials fabricated with mass density of 1.0 g/cm^3 to simulate the attenuation properties human soft tissue towards ionizing radiations.

Earlier studies suggested *Rhizophora* spp. as potential phantom material for dosimetry works and quality control for photons. *Rhizophora* spp. is the largest species of mangrove tree that grow in the saline coastal area of subtropical regions including Malaysia. Earlier study found that *Rhizophora* spp. wood had mass density and attenuation coefficient close to water [2]. *Rhizophora* spp. wood also showed similar absorption and scattering properties to water towards low energy photons [3]. A study on percentage depth dose at high energy photons and electrons also showed similarities within 4% to water and Perspex [4]. The use of *Rhizophora* spp. solid woods as phantom materials however has several limitations including limited size of the wood to construct full size phantoms. The *Rhizophora* spp. wood also have tendency to crack over period of times besides its density inhomogeneity across the trunk. The binderless particleboards made of *Rhizophora spp.* was introduced with advantages including better density uniformity and able to be fabricated at various size and shapes without compromising its attenuation properties [5,6]. The fabrication of binderless *Rhizophora* spp. particleboards however suffers significant reduction of physical and mechanical strength to endure the rigid and heavy workload as phantom.

The use of synthetic-based adhesives such as urea-formaldehyde (UF) commonly used in industrial particleboards manufacturing failed to retain the attenuation properties of *Rhizophora spp.* particleboards in comparison to water [7,8]. The use of biological-based adhesive materials was identified to be the suitable adhesive materials for *Rhizophora* spp. particleboards in compared to the commonly used synthetic-based adhesives. Several studies had indicated that the use of biological-based adhesives had increased the physical properties of *Rhizophora* spp. particleboards and retained their water equivalent and attenuation properties towards X-ray energies in the diagnostic imaging ranges [9-11].

Tannin has been used as alternative binder for particleboards and plywood to replace commonly used formaldehyde-based adhesives [12-14]. Tannin is a biological-based adhesive that can be extracted mainly from barks including *Rhizophora spp.* [15]. Previous study had suggested the suitability of tannin as biological-based adhesive for *Rhizophora spp.* particleboards as phantom at low energy photons [16]. The use of tannin-based particleboards at low treatment level of tannin (5%) however still failed to satisfy the industrial standards for physical and mechanical properties. Previous studies had suggested that the suitable percentage of biological-based adhesives for *Rhizophora spp.* is within 10% without changing their attenuation properties [9,10]. This study focused on the fabrication and characterisations of *Rhizophora spp* particleboards with 10% percentage of tannin adhesive as phantom materials in application of photon and electron beams.

2. Methodology

2.1. Fabrication of the Rhizophora spp. Particleboard Phantoms

The *Rhizophora* spp. particleboards were constructed based on the previous study by Mohd Yusof et al., [11]. The wood particles with particle size ranges of $\leq 104\ \mu$m were used to fabricate the particleboards. Amounts of 10% tannin based on the dry weight of wood particles were added in to the particleboards as binder to increase the physical and mechanical properties of the particleboard. The particleboards were fabricated with target density of 1.0 g/cm^3 based on the calculation of the amount of wood particles required to construct the particleboards at the desired size and density. The physical and mechanical properties of the particleboards were evaluated based on the internal bond (IB) strength and modulus of rupture (MOR) according to the Japanese Industrial Standards, JIS A 5908 [17]. A total of 32 particleboards with 30 cm x 30 cm size and thicknesses of 0.5 and 1.0 cm were constructed based on the external dimensions of typical solid water phantom as shown in figure 1. Two units of the particleboards were fabricated with insertion of plane-parallel ionization chamber inserts similar to that in solid water phantoms. The density of the particleboards were measured using gravimetric method based on the external dimension given by the equation

$$\rho = \frac{length \times width \times thickness}{mass} \quad (1)$$

Figure 1. The fabricated *Rhizophora* spp. particleboard phantoms

2.2. *Elemental Composition and Effective Atomic Number*

The attenuation properties of medium are related to the effective atomic number, therefore the effective atomic number value is used to determine the water equivalent and attenuation properties of the particleboard in comparison to water. The percentages of elemental composition of the particleboards were determined using energy dispersive x-ray analysis (EDXA). The effective atomic number, Z_{eff} was calculated based on the measured percentages of elemental composition of the particleboards. The effective atomic number is calculated according to the study by Duvauchelle et al., [18] using the equation:

$$Z_{eff} = \left[\sum_{i=1}^{n} (\alpha_i \, z_i^m)\right]^{\left(\frac{1}{m}\right)} \quad (2)$$

with a_i and z_i are electron fraction and atomic number of i^{th} element in the sample respectively. m is the experimental coefficient for biological materials and water with value of 3.4. The electron fraction of the i^{th} element can be calculated by the equation:

$$\alpha_i = \frac{wi\left(\frac{z_i}{A_i}\right)}{\Sigma w_i\left(\frac{z_i}{A_i}\right)} \quad (3)$$

with w_i and A_i are fractional weight and atomic mass of the i^{th} element respectively.

2.3. *Determination of Tissue-Phantom Ratio ($TPR_{20,10}$) and Output Calibration of the Particleboards*

The measurement of tissue-phantom ratio ($TPR_{20,10}$) is used to determine quality of the clinical photon beams in the medium. The $TPR_{20,10}$ of the tannin-based *Rhizophora* spp. particleboards were evaluated at 6 and 10 MV photons based shown the IAEA TRS 398:2000 protocol. The average charge at 10 and 20 cm depths were collected at respective photon energies and $TPR_{20,10}$ values were calculated using the equation:

$$\text{TPR}_{20,10} = \frac{charge\ collected\ at\ 20\ cm\ depth\ (nC)}{charge\ collected\ at\ 10\ cm\ depth\ (nC)} \quad (4)$$

The value of $TPR_{20,10}$ from the tannin-based *Rhizophora* spp. particleboards were compared to that in water and solid water phantoms.

The beam output calibration was performed on the tannin-based *Rhizophora* spp. particleboards at 6 MV photons and 6 MeV electrons based on the IAEA TRS 398:2000 protocol. The absorbed dose at the depth of maximum dose, d_{max} was measured and compared to that in water and solid water phantoms. The calibration of Gafchromic EBT2 film dosimeter on *Rhizophora* spp. particleboards were conducted at 6 MV photons and 6 MeV electrons. The EBT2 film was placed at the depth of maximum dose, D_{max} and exposed to 6 MV photons and 6 MeV electrons with dose between 50 and 600 cGy. The optical density of the exposed film is calculated using the equation:

$$OD = -Log_{10} \frac{PV}{65535} \tag{5}$$

with PV is the pixel value or the scanner value. The exposed films were scanned using a flatbed film dosimetry scanner and the calibration curve between the OD and radiation dose is plotted and compared to that in solid water phantoms.

2.4. Measurement of Percentage Depth Dose at High Energy Photons and Electrons
The percentage depth dose (PDD) of the tannin-based *Rhizophora* spp, particleboards at 6MV photons and 6 MeV electrons were measured using Markus plane-parallel ionization chamber and EBT2 film. The measurements using ionization chamber were conducted at calibration condition (10 cm x 10 cm field size, 100 cm source to surface distance and 100 monitor units). The PDD of the particleboards were measured using the equation

$$PDD = \frac{D}{D_{max}} \times 100\% \tag{6}$$

with D is the dose measured at any depth and D_{max} is the maximum dose across the central axis of the beam. The PDD curve of 6 MV photons and 6 MeV electrons were plotted and compared to that of water and solid water phantoms. The percentage of discrepancies of PDD between the tannin-based *Rhizophora* spp. particleboards to water and solid water phantoms were calculated at each measured depths. The depths of electron beam parameters including R_{50}, R_{80} and R_{90} were determined form the PDD curve of electrons and compared to that in water and solid water phantoms.

3. Results and Discussions

3.1. *Evaluation on Physical and Mechanical Properties of the Particleboards*
The average IB strength and of the particleboards is illustrated in figure 2 and 3 respectively. The results showed that the addition of tannin adhesive had significantly increased the average IB strength and MOR of the particleboards in comparison to the binderless *Rhizophora* spp. particleboards [6] and *Rhizophora* spp. particleboards with lower percentage of tannin (Safian, 2012). The average IB strength of the tannin-based *Rhizophora* spp. particleboards in this study satisfied the Type 18 (3.0 N/mm^2) for the JIS A 5908. Similar results were seen in the average MOR of the particleboards. The tannin-based *Rhizophora* spp. in this study satisfied the Type 8 for the JIS A 5908 with the increase of 18% from the binderless *Rhizophora* spp. particleboards.

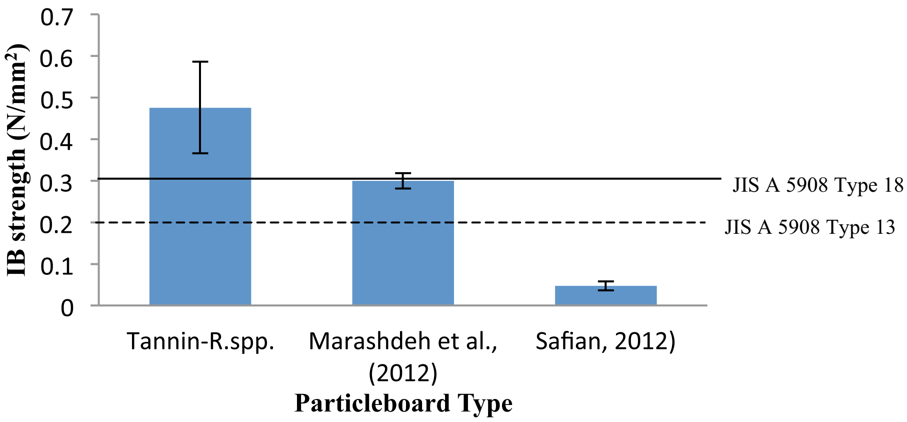

Figure 2. The average internal bond (IB) strength of the *Rhizophora* spp. particleboards

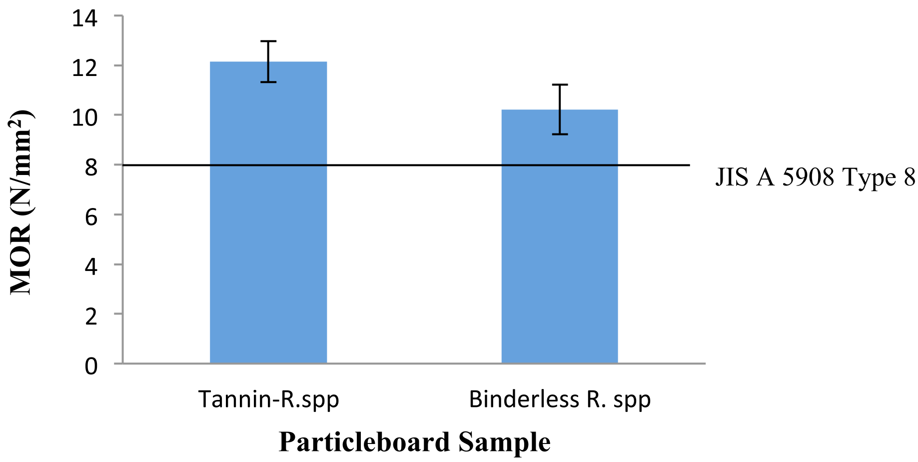

Figure 3. The average MOR of the *Rhizophora* spp. particleboards

The measured density, percentage of elemental compositions and calculated effective atomic number of the tannin-based *Rhizophora* spp. particleboards is presented in table 1. The average density of the particleboards was close to the value of water. The result is in good agreement to the study on the solid raw *Rhizophora* spp. wood by Bradley *et al.*, [2] and Banjade *et al.*, [4]. The results is also in good agreement to the study on the fabrication of *Rhizophora* spp. particleboards as phantom by Marashdeh et al., [6], Abuaraa *et al.*, [9] and Tousi *et al.*, [10]. The elemental composition of the tannin-based *Rhizophora* spp. particleboard was measured using the energy dispersive X-ray analysis (EDXA). The results showed high percentage of carbon and oxygen which is similar to the human soft tissue. It is postulated that the particleboards having similar attenuation properties to human soft tissue based on the similarity of elemental compositions. The effective atomic number of the particleboards was measured using the elemental compositions of the particleboards based on the study by Duvauchelle et al., [18]. The results showed that the effective atomic number of the tannin-based *Rhizophora* spp. particleboards was close to the value of water [19]. The attenuation properties of a material are proportional to the effective atomic number of the material [20]. Therefore, it is postulated that the attenuation properties of tannin-based *Rhizophora* spp. particleboards are similar to that of water. The average CT number of the particleboards was measured at 120 kVp CT X-ray energy and 250 mAs tube current setting based on the abdominal imaging protocol. The average CT number of tannin-based *Rhizophora* spp. particleboards was close to the value of water indicating close attenuation properties to water towards diagnostic X-ray energy. The results was in good agreement to the previous studies on the CT numbers of *Rhizophora* spp. particleboards by Marashdeh et al., [6], Abuarra *et al*., [9] and Tousi *et al*., [10].

Table 1. The physical properties of tannin-based *Rhizophora* spp. particleboard phantoms.

Physical property	Description
Average density ± standard deviation	1.003 ± 0.014
Elemental composition	Carbon (51.25%), Oxygen (43.11%), Fluorine (5.64%)
Effective atomic number, Z_{eff}	7.22 [a] (water = 7.42 [a])
Average CT number	-13.69 (water = -2.5, solid water = -11.61)

[a]AAPM-21, [19]

3.2. Evaluation of Tissue-Phantom Ratio ($TPR_{20,10}$) and Output Calibration of the Particleboards

The tissue-phantom ratio ($TPR_{20,10}$) of tannin-based *Rhizophora* spp. particleboards at 6 and 10 MV photons is presented in table 2. The value of $TPR_{20,10}$ in tannin-based *Rhizophora spp*. particleboards was compared to the value measured in water and solid water phantoms commonly used in the dosimetry works involving high energy photons and electrons. The results showed good agreement of tissue-phantom ratio of tannin-based *Rhizophora spp*. particleboards in comparison to water and solid water phantoms with percentage of variation within 2% and in agreement the study by Banjade *et al*., [4]. The value of $TPR_{20,10}$ remains as the most appropriate method to determine the beam quality of a clinical photon beams Therefore, a material with close value of $TPR_{20,10}$ to the water is postulated to have similar attenuation properties to water and soft tissues.

Table 2. The tissue-phantom ratio of tannin-based *Rhizophora* spp. particleboards in comparison to water and solid water at 6 and 10 MV photons.

Photon energy (MV)	$TPR_{20,10}$		
	Water (W)	**Solid water (S)**	**Tannin-based *Rhizophora* spp. (R)**
6	0.678	0.675	0.689
10	0.746	0.743	0.754

The beam output calibration of tannin-based *Rhizophora* spp. particleboards at 6 MV photons and 6 MeV electrons is presented in table 3. The absorbed dose at d_{max} in the particleboards showed an excellent agreement to the value in water at 6 MV photons with 1.69% percentage of discrepancy. The result was consistent with the earlier study by Banjade *et al*., (2001) that measured the absorbed dose at d_{max} in solid raw *Rhizophora* spp. wood (4%). A comparison to solid water phantoms at 6 MV photons also showed good agreement within 6% percentage of discrepancy and in agreement to the study by White and Constantinou [1] and Reft [21]. The output calibration of tannin-based *Rhizophora* spp. particleboards at 6 MeV electrons also showed good agreement within 0.3 and 2.4% percentage of discrepancy to that in water and solid water phantom respectively. The EBT2 film calibration curve of tannin-based *Rhizophora* spp. particleboards at 6 MV photons and 6 MeV electrons is shown in figure 4(a) and 4(b) respectively. The calibration curve showed good dose-dependence of EBT2 film on *Rhizophora* spp. particleboards at between 50 and 700 cGy. The results were also in good agreement to the solid water phantoms indicating similar attenuation properties of the particleboards to solid water phantoms at 6 MV photons and 6 MeV electrons.

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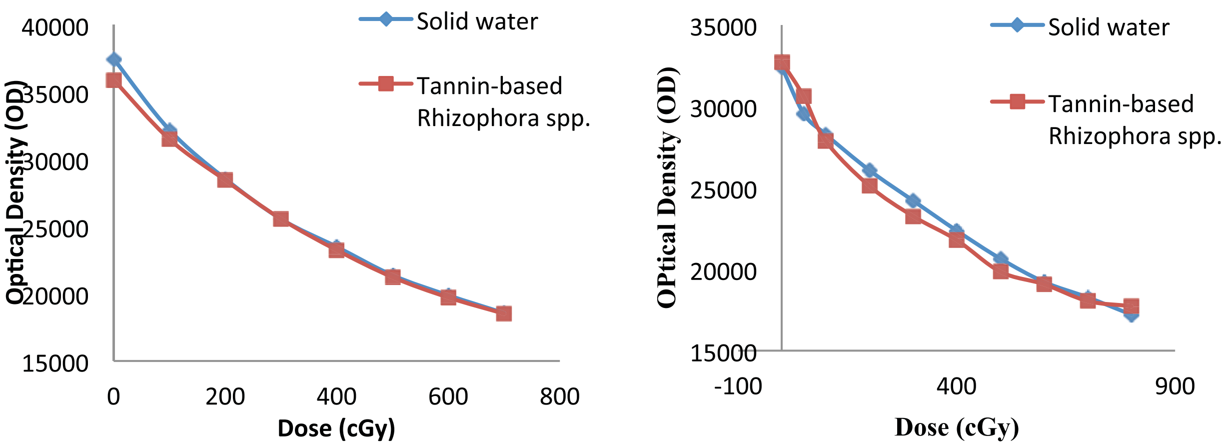
Table 3. The beam output calibration of tannin-based *Rhizophora* spp. particleboards at 6 MV photons and 6 MeV electrons based on IAEA TRS 398:2000.

Energy	Output (cGy/MU)		
	Water	Solid water	Tannin-based *Rhizophora spp.* particleboards
6 MV	1.001	1.083	1.018
6 MeV	1.004	0.977	1.001



(a) (b)

Figure 4. The EBT2 film calibration curve at (a) 6 MV photons and (b) 6 MeV electrons.

3.3. Evaluation on Percentage Depth Dose in High Energy Photons and Electrons

The PDD curve of tannin-based *Rhizophora* spp. particleboards at 6 MV photons measured using ionization chamber and EBT2 film is illustrated in figure 5(a) and 5(b) respectively. The PDD curve of the particleboards was in good agreement to water within 4.39% percentage of discrepancies at all measured depths when measured using ionization chamber. The PDD curve of the particleboards was also in good agreement with solid water phantoms within 4.05% percentage of discrepancies at all measured depths. The results are in good agreement to the study on the PDD curve of solid raw *Rhizophora* spp. wood by Banjade at al., [4]. The PDD measurement using EBT2 film showed that the PDD curve of tannin-based *Rhizophora* spp. particleboards was in good agreement to solid water phantoms within 4% at all measured depths. The results had indicated the similarity of attenuation properties of tannin-based *Rhizophora* spp. to that in water and solid water phantoms and can be potentially used as phantom for high energy photons.

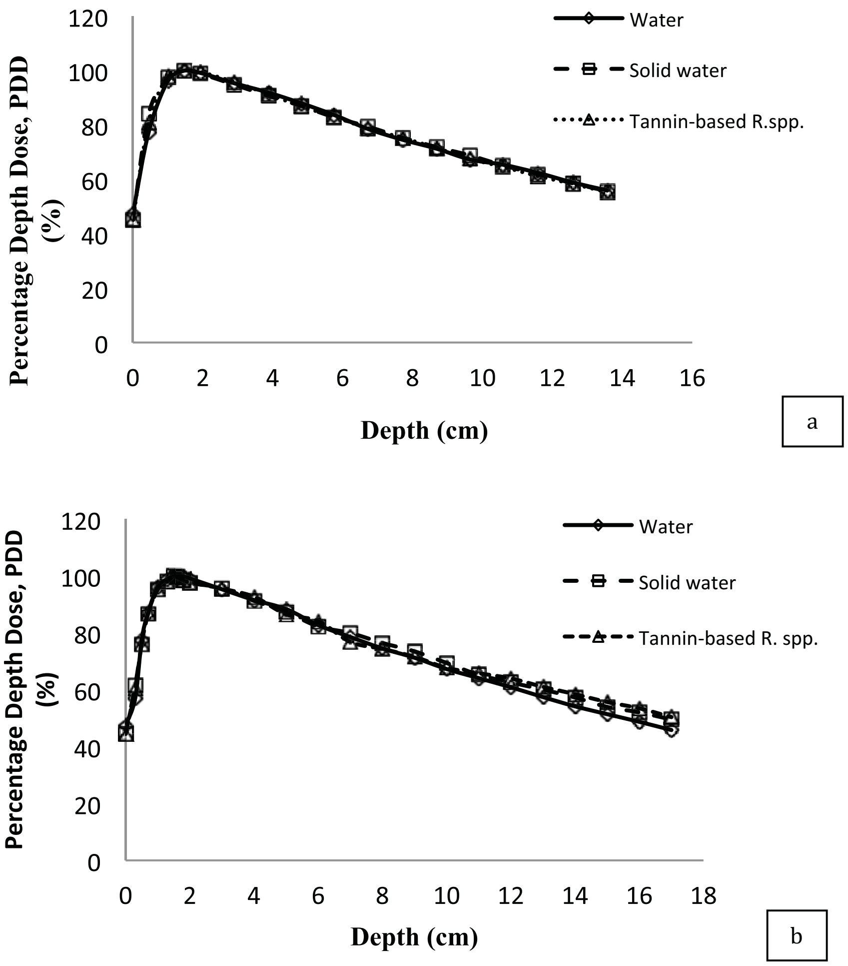


Figure 5. The percentage depth dose (PDD) curve of tannin-based *Rhizophora* spp. particleboards in comparison to water and solid water phantoms at 6 MV photons measured using (a) ionization chamber and (b) EBT2 film.

The PDD curve of tannin-based *Rhizophora* spp. particleboards at 6 MeV electrons measured using ionization chamber and EBT2 film is illustrated in figure 6(a) and 6(b) respectively. The PDD curve of the particleboards was in good agreement within 5.12% to solid water phantoms at all measured depths. A comparison to water also showed good agreement within 5.24% at all measured depths. The results were in good agreement to the study by Banjade et al., [4]. The measurement of PDD using EBT2 film showed an excellent agreement to solid water phantoms within 2% percentage of discrepancies at all measured depths.

The electron beam parameters of *Rhizophora* spp. particleboards at 6 MeV electrons in comparison to water and solid water phantom are presented in Table 4. The results showed that all electron beam parameters of R_{50}, R_{80} and R_{90} of the particleboards were close to that in water and solid water phantoms. The R_{80} and R_{90} has been used to determine the effectiveness of phantom material as it indicated the therapeutic range of electrons where the target volume received 80 and 90% of the prescribed dose respectively [22]. The overall results showed that the attenuation properties and dosimetric profiles of tannin-based *Rhizophora* spp. particleboards was similar to water and solid water phantoms as standard phantom materials for dosimetry works and quality assurance in high energy photons and electrons. The results also showed the compatibility of the particleboards when measured using ionization chamber and EBT2 film as the most common dosimeters used in dosimetry works and quality assurance of high energy photons and electrons.

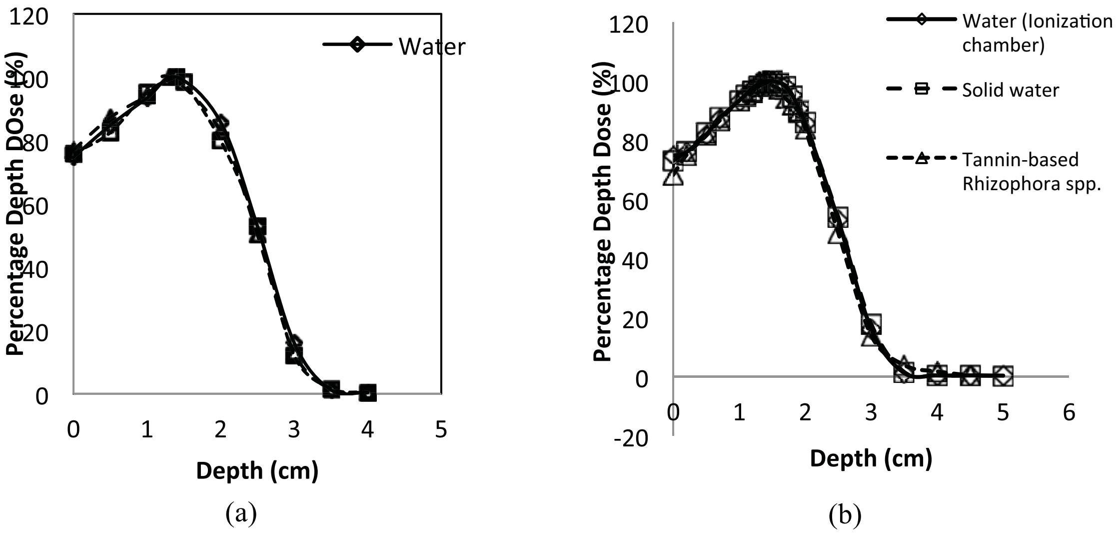


Figure 6. The percentage depth dose (PDD) curve of tannin-based *Rhizophora* spp. particleboards in comparison to water and solid water phantoms at 6 MeV electrons measured using (a) ionization chamber and (b) EBT2 film.

Table 4. The electron beam parameters of 6 MeV electrons in tannin-based *Rhizophora* spp. particleboards in comparison to water and solid water phantoms.

Parameter	**Depth (cm)**		
	Water	**Solid water**	**Tannin-based *Rhizophora* spp.**
R_{50}	2.36	2.32	2.18
R_{80}	1.86	1.86	1.85
R_{100}	1.50	1.40	1.50

4. Conclusions

The addition of tannin had increased the physical and mechanical properties of the *Rhizophora* spp. particleboards shown by the average IB strength and MOR. The fabricated tannin-based *Rhizophora* spp. particleboards showed similar physical properties to water indicated by the mass density, effective atomic number and average CT number. The $TPR_{20,10}$ values of the tannin-based *Rhizophora* spp. particleboards was close to the value of water and solid water phantoms measured at 6 and 10 MV photons. The beam output calibration at 6 MV photons and 6 MeV electrons showed that the absorbed dose in the tannin-based *Rhizophora* spp. particleboards was close to that in water and solid water phantoms. The calibration curve of tannin-based *Rhizophora* spp. particleboards showed good linearity between 50 and 700 cGy radiation doses of 6 MV photons and 6 MeV electrons. The PDD curves of tannin-based *Rhizophora* spp. particleboards showed an excellent agreement within 5% percentage of discrepancies when measured using ionization chamber and EBT2 film at 6 MV photons and 6 MeV electrons. The overall results had indicated the potential use of tannin-based *Rhizophora* spp. particleboards as phantom for high energy photons and electrons.

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