CHARACTERIZATIONS AND ATTENUATION PROPERTIES OF CORN STARCH BONDED *Rhizophora* SP. PARTICLEBOARDS AS WATER-EQUIVALENT PHANTOM MATERIAL FOR LOW ENERGY PHOTONS

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ABSTRACT

Rhizophora spp. had been identified as potential alternative phantom material to replace water. The physical properties, water-equivalent properties and mass attenuation coefficients of corn starch bonded Rhizophora spp. particleboards were studied. Rhizophora spp. particleboards were fabricated at ≤74 µm particles size ranges with 0%, 5% and 10% of corn starch treatment level. The particleboards were fabricated at target density 1.0 g/cm^3 similar to water as standard phantom material. The physical properties of particleboards were evaluated based on JIS A 5908. The effective atomic number and CT number were evaluated to determine their water equivalent properties. The mass attenuation coefficients of particleboards were measured at 16.59 to 25.26 keV photons and ^{99m}Tc gamma energy. Addition of corn starch had increased the physical properties of the particleboards shown by the IB strength, MOR, TS and WA values. Higher percentage of corn starch treatment level had further increased the physical properties of the particleboard. The calculated effective atomic number of corn starch bonded particleboard was found to be 7.59 which is in good agreement to water (7.42). Higher percentage of corn starch treatment level give nearer CT number to water at 120 kVp CT X-ray energy. The mass attenuation coefficients of the particleboards showed good agreement to calculated values of water (XCOM). The treatment level of corn starch influence the attenuation properties of particleboards. The overall results had indicated the potential of corn starch bonded Rhizophora spp. particleboards as phantom material at low energy photons.

Keywords: CT number, mass attenuation coefficient, phantoms, *Rhizophora* sp.

INTRODUCTION

The use of materials as phantom for quality assurance and dosimetry works in medical physics differs on the energy ranges of ionizing radiation and applications. Materials such as Perspex® and acrylic are preferred as phantom materials for low energy photons although their mass density and attenuation properties were significantly difference to water and human soft tissues [1]. Epoxy resin-based materials such as solid water and plastic water on the other hand are preferred as phantom materials for high and therapeutic range of photons due to their physical characteristics such as effective atomic number and electron density near to that in water and soft tissues. Earlier studies had indicated the suitability of *Rhizophora* spp. particleboards as s phantom material to substitute water and soft tissues in various dosimetry and imaging applications in medical physics [2-6]. Therefore, the use of *Rhizophora* spp. particleboards can be potentially used as a single phantom material that can accommodate various applications and photon energy ranges.

Rhizophora spp. is a type of mangroves tree that grow in tropical region and commonly used for charcoal, firewood and building materials. Previous researchers had found that *Rhizophora* spp. wood has potential to be used as phantom material due to its properties of mass density, attenuation coefficient, percentage depth dose and dose distribution in low and high energy photons and electron very similar to water [4, 7-11]. Unfortunately, the use of raw wood of *Rhizophora* spp. has some disadvantages regarding to phantom design for dosimetry purpose. The limited sizes of trunk maximum diameter trunk made the wood phantom unable to be designed to variety of applications in clinical use of ionizing radiations. In addition, the raw wood has tendency to curved and crack over period of time [12].

Shakhreet et al. [13, 14] suggested the *Rhizophora* spp. to be ground into small particles and compressed into particleboards using pressures and heat. Particleboards can be made into two types; binderless and with addition some adhesive. Marashdeh et al., [15] reported that binderless particleboards give the value of mass attenuation coefficients at low energy photons nearer to the calculated value of water and uniform density compared to raw wood. However, the fabrication of particleboards had reduced its physical properties to endure the rigid works as phantoms. Therefore, the uses of adhesives are required to improve the physical properties of particleboard. The commonly used adhesive in particleboard industry such as formaldehyde-based adhesive significantly lowered the density and attenuation properties of the particleboards besides the formaldehyde emission that can caused health concern [15]. Therefore, the search of new adhesive which is biodegradable, cost-effective, and readily available are required to improve the physical properties of the particleboards [2-6, 16-18]. Starch including corn starch had been widely used as alternative adhesives materials in particleboard industry [19, 20]. Starch is the carbohydrate-based source consists of composition that matches to *Rhizophora* spp. wood. This present study focused on the suitability of corn starch as bio-adhesive material for *Rhizophora* spp. particleboard phantoms.

METHODOLOGY

Particleboard preparation

The middle part *Rhizophora* spp. wood trunks were obtained based on the study by Shakhreet et al., [13]. The wood trunks were planed using surface planer before grounded into wood particles using grinder machine. The wood particles were screened using horizontal screening machine to obtain ≤ 74 µm particles size range. The corn starch purchased from Sigma-

Aldrich was used as bio-adhesive. The corn starch powder were added into the wood particle with 0%, 5% and 10% treatment level based on dried mass calculated according to target density, thickness and dimension of particleboards. The particleboards were fabricated at target density of is 1.0 g/cm^3 that is similar to water. The wood particles and corn starch powder were well mixed and distilled water was sprayed on the mixture. The addition of distilled water was made by ensuring that the overall moisture content of the mixture not exceeding 10%. The mixture was mixed well and distributed uniformly in a mould. The mixture was pre-pressed without temperature applied for 5 minutes to reduce air cavity within mixture. Then, the mixture was pressed at 190°C for 20 minutes with 20 MPa pressure load using hot press machine to required thickness.

Physical and Mechanical Properties

The strength test of particleboards in term of internal bonding (IB) and modulus of rupture (MOR) were conducted according to the Japanese Industrial Standard (JIS A 5908) [21]. The prepared test samples with dimension 5 cm × 5 cm were used to evaluate the IB. The test samples with approximately 5 cm × 20 cm were prepared for MOR test. The IB and MOR test were carried out using Universal Test Machine model Instron 5582. The IB strengths were calculated using the equation 1:

$$IB = \frac{P_{max}}{2wl} \qquad (1)$$

with P_{max} is maximum load (N), w is width of test sample (mm) and l is length of test sample (mm). The MOR of the particleboards were calculated using the equation 2:

$$MOR = \frac{3P_{max}L}{2wt^2} \qquad (2)$$

with P_{max} is maximum load (N), L is span length (mm), w is width of test sample (mm) and t is thickness of test sample (mm). The test samples *Rhizophora* spp. particleboards with 5 cm × 5 cm dimension were prepared for thickness swelling (TS) and water absorption (WA) tests to determine their dimensional stability based on JIS A 5908. The test samples were immersed in distilled water at room temperature for 24 hours. The WA of particleboards were calculated using the equation 3:

$$\text{WA}\ (\%) = \frac{M - M_0}{M_0} \times 100\%$$

(3) with mass (g) and M_0 and M is the mass (g) before and after the immersion respectively. The TS particleboards were calculated using the equation 4:

$$\text{TS}\ (\%) = \frac{T - T_0}{T_0} \times 100\% \qquad (4)$$

with T_0 and T is the thickness (mm) before and after the immersion respectively.

Elemental Composition and Effective Atomic Number

The elemental compositions of corn starch bonded *Rhizophora* spp. particleboard were determined using energy dispersive X-ray analysis (EDXA). The effective atomic number (Z_{eff}) of particleboard was calculated based on the study by Duvauchelle et al., [22] using the equation 5:

$$Z_{eff} = \sum_{i=1}^{N} (\alpha_i Z_i^m)^{\frac{1}{m}} \qquad (5)$$

with α_i and Z_i are the electronic fraction and atomic number of the i^{th} element in the compound respectively. The experimental coefficient (m) for biological material such as water, wood or human organs has been evaluated to be equal to 3.4 [22]. The electronic fraction of the i^{th} element was calculated using equation 6:

$$\alpha_i = \frac{w_i\left(\frac{Z_i}{A_i}\right)}{\sum w_i\left(\frac{Z_i}{A_i}\right)} \qquad (6)$$

where w_i and A_i are fractional weight and atomic mass of the i^{th} element respectively. The effective atomic number of sample was compared to the water. The paired-sample t-test was carried out to determine the significant difference between the mass attenuations of particleboards and those of water.

Computed Tomography Study

The density and attenuation properties of materials are related to the Computed Tomography (CT) images. CT images are often evaluated in CT numbers expressed in Hounsfield unit (HU) defines by equation 7:

$$CT\ number = \frac{\mu - \mu_w}{\mu_w} \times 1000 \qquad (7)$$

with µ is the linear attenuation coefficient of medium and μ_w is linear attenuation coefficient of water. The fabricated *Rhizophora* spp. particleboards were scanned using CT scanner model Siemens Somatom Definition AS at 120 kVp and 250 mAs exposure factor based on abdominal setting protocol. The CT numbers of *Rhizophora* spp. particleboards were obtained from the CT images and compared to the value of water.

Linear and Mass Attenuation Coefficients

The mass attenuation coefficients of *Rhizophora* spp. particleboards were determined at low energy photons and ^{99m}Tc gamma energy. X-ray fluorescence (XRF) configuration was used to evaluate the mass attenuation coefficient at low energy as shown as Figure 1(a). An annular ^{241}Am source was used in the XRF configuration in conjunction with niobium, molybdenum, palladium and tin plates that provided $K_{\alpha 1}$ photons energy of 16.56, 17.46, 21.21 and 25.26 keV respectively. The transmitted photons were detected by low-energy Germanium (LEGe) detector connected to a single channel analyzer (SCA). The ^{99m}Tc unsealed source was used in determination of mass attenuation coefficient at 140 keV of gamma energy using gamma camera configuration as shown in Figure 1(b). The linear attenuation coefficients of the particleboards were measured based on the attenuation of photons based on the Beer Lambert equation (8) of:

$$I = I_{\circ} e^{-\mu t} \quad (8)$$

with I_0 is the initial photons, I is transmitted photons, μ is linear attenuation coefficient and t is thickness of attenuator. Mass attenuation coefficients of *Rhizophora* spp. particleboards were calculated by dividing the linear attenuation coefficients with density of particleboards. The obtained values of mass attenuation coefficients of *Rhizophora* spp. particleboards were compared to the calculated values of water using photon cross-section database (XCOM) [15].

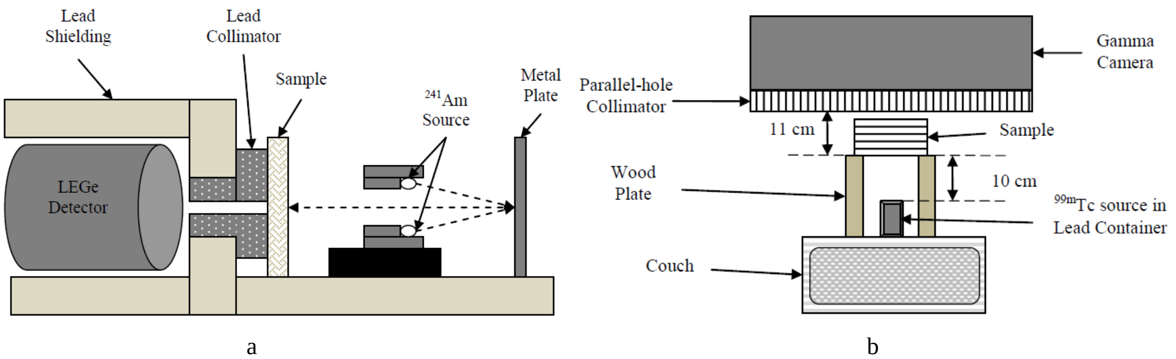

Figure 1: The experimental set-up of (a) XRF configuration and (b) gamma camera configuration for the measurements of the mass attenuation coefficients

RESULTS

Evaluation of Physical and Mechanical Properties

The results of IB strength and MOR values of *Rhizophora* spp. particleboards are shown in Figure 2(a) and 2(b) respectively. The results showed that the *Rhizophora* spp. particleboards with higher percentage of corn starch treatment level increased the IB strength and MOR values.

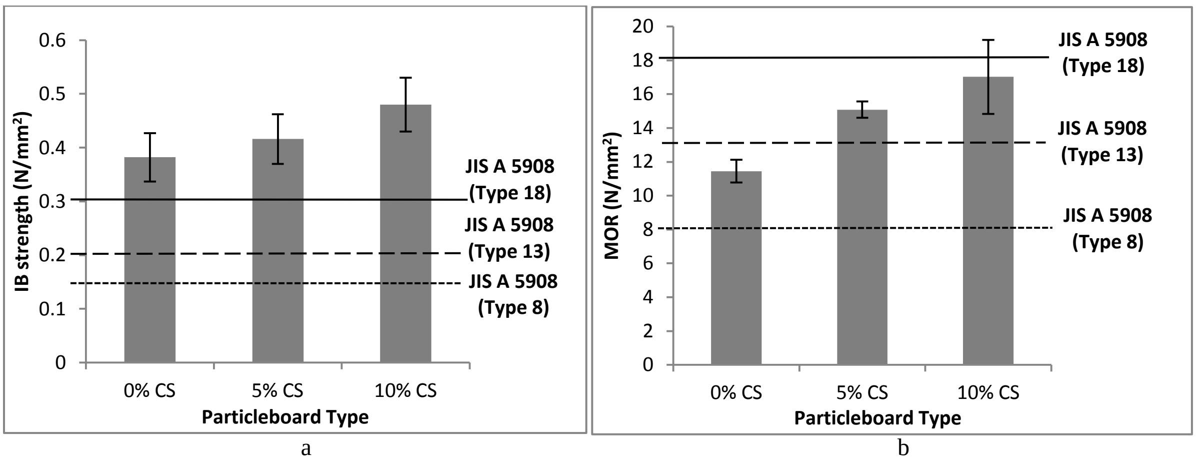

Figure 2: The average (a) IB strength and (b) MOR of *Rhizophora* spp. particleboards based on JIS A 5908

Figure 3 showed the WS and TS of *Rhizophora* spp. particleboards. The dimensional stability of *Rhizophora* spp. particleboards improved with higher percentage of corn starch treatment level.

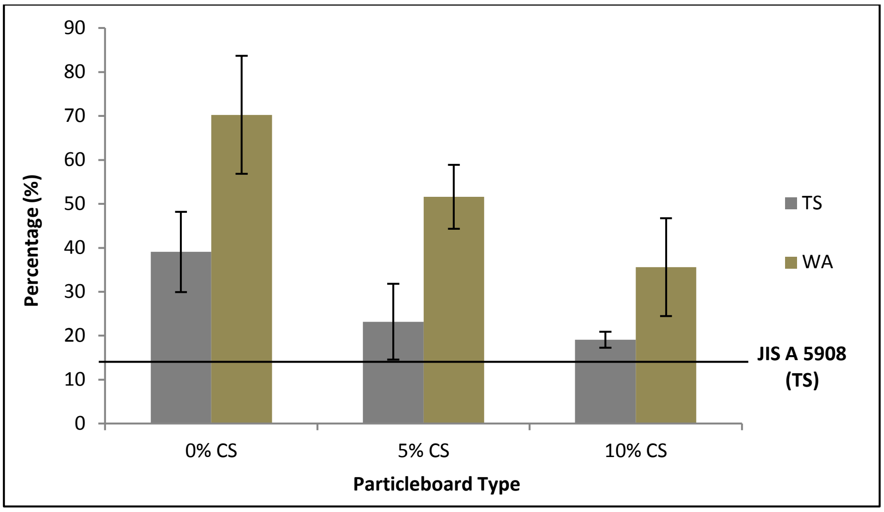

Figure 3: Average TS and WA of *Rhizophora* spp. particleboards based on JIS A 5908

Determination of Effective Atomic Number

The elemental compositions and effective atomic numbers of water, Perspex®, corn starch and *Rhizophora* spp. particleboards and raw wood are shown in Table 1. The calculated effective atomic number of corn starch bonded *Rhizophora* spp. particleboard in good agreement of water.

Table 1: The calculated effective number Z_{eff} of *Rhizophora* spp. particleboards in comparison to water and Perspex®

Sample	Percentage of elemental composition (%)				Z_{eff}
	Carbon (C)	Hydrogen (H)	Oxygen (O)	Nitrogen (N)	
Water [a]	-	11.11	88.89	-	7.42
Perspex[a]	59.98	31.97	8.05	-	5.21
Binderless *Rhizophora* spp.[c]	32.93	-	38.98	28.08	7.19
Corn Starch[b]	46.82	6.94	46.24	-	6.88
Corn starch bonded *Rhizophora* spp.[b]	27.20	-	72.55	0.25	7.59
Rhizophora spp. raw wood[d]	40.16	3.78	47.90	3.78	-

[a]AAPM-21 [23], [b]Current study, [c]Mohd Yusof et al., [5] and [d]Bradley et al., [8]

Evaluation of CT number

The average CT numbers of *Rhizophora* spp. particleboards measured at 120 kVp of CT X-ray energy in comparison to water are shown in Table 2. The result showed that the addition of corn starch had lowered the average CT numbers of the *Rhizophora* spp. particleboards. The use of higher percentage of corn starch treatment level also had further reduced the CT number of the particleboards. The *Rhizophora* spp. particleboards fabricated with 10% of corn starch treatment level was found to have the nearest CT number to the value of water.

Table 2: The CT numbers of water and corn starch bonded *Rhizophora* spp. particleboards

Type	CT number (HU)			Standard Deviation
	Minimum	Maximum	Average	
Water	-0.8	0.0	-0.34	0.24
0% corn starch- *Rhizophora* spp. particleboard	-16.3	27.4	7.43	14.04
5% corn starch- *Rhizophora* spp. particleboard	-11.9	14.1	6.67	11.69
10% corn starch- *Rhizophora* spp. particleboard	-19.3	9.6	-2.06	9.27
Solid Water	-22.95	-2.72	-11.60	6.68

Determination of Linear and Mass Attenuation Coefficient

The mass attenuation coefficients of *Rhizophora* spp. particleboards and water calculated by XCOM at low energy photons and ^{99m}Tc gamma energy are shown in Table 3. The values of mass attenuation coefficients of the *Rhizophora* spp. particleboards were found to be in good agreement to the XCOM value of water. The paired sample t-test were conducted to further determine the similarities of mass attenuation coefficients of the *Rhizophora* spp. particleboards to the values of water and presented in Table 4. The p-values from the paired sample t-test indicated the similarity of mass attenuation coefficients of particleboards to those of water. The results showed that the fabricated *Rhizophora* spp. particleboards did not give significant different to the values of water shown by the p values of ≥ 0.05.

Table 3: The linear and mass attenuation coefficients of *Rhizophora* spp. particleboards at 16.59-25.26 keV photons and ^{99m}Tc gamma energy

Energy		0% corn starch – *Rhizophora* spp. particleboard	5% corn starch – *Rhizophora* spp. particleboard	10% corn starch – *Rhizophora* spp. particleboard	Water (XCOM)
Nb (16.59 keV)	μ	1.164	1.286	1.228	1.193
	μ/ρ	**1.165**	**1.282**	**1.217**	**1.193**
	$\sigma_{(\mu/\rho)}$	0.034	0.054	0.136	-
Mo (17.46 keV)	μ	1.066	1.126	1.110	1.095
	μ/ρ	**1.067**	**1.123**	**1.100**	**1.095**
	$\sigma_{(\mu/\rho)}$	0.027	0.060	0.067	-
Pd (21.21 keV)	μ	0.655	0.720	0.741	0.755
	μ/ρ	**0.656**	**0.718**	**0.734**	**0.755**
	$\sigma_{(\mu/\rho)}$	0.012	0.079	0.120	-
Sn (25.26 keV)	μ	0.467	0.479	0.485	0.506
	μ/ρ	**0.467**	**0.478**	**0.481**	**0.506**
	$\sigma_{(\mu/\rho)}$	0.037	0.033	0.024	-
^{99m}Tc (140 keV)	μ	0.158	0.156	0.155	0.154
	μ/ρ	**0.157**	**0.156**	**0.155**	**0.154**
	$\sigma_{(\mu/\rho)}$	0.006	0.015	0.010	-

Table 4: The paired-sample *t*-test of mass attenuation coefficients of *Rhizophora* spp. particleboards to water (XCOM)

Pair	**Paired Differences**		**df**	**t**	***p*-value**
	Means	**St. Deviation**			**(2 tailed)**
Water – 0% corn starch-*Rhizophora* spp. particleboard	0.0381	0.0375	4	2.034	0.135
Water – 5% corn starch-*Rhizophora* spp. particleboard	-0.0107	0.0507	4	-0.423	0.701
Water – 10% corn starch-*Rhizophora* spp. particleboard	0.0033	0.0201	4	0.325	0.767

DISUSSION

Evaluation of Physical and Mechanical Properties

Higher the percentage of corn starch added had improved the IB strength and MOR of *Rhizophora* spp. particleboards. The IB strength of all the particleboards (0%, 5% and 10%) corn starch bonded *Rhizophora* spp. particleboards satisfied the minimum requirements of JIS (JIS A 5908) for particleboards Type 8 (0.15 N/mm^2), Type 13 (0.2 N/mm^2) and Type 18 (0.3 N/mm^2). The results of average MOR showed that all the types of *Rhizophora* spp. particleboards complied with minimum requirements of JIS standard (JIS A 5908) for particleboard type 8 (8 N/mm^2) and only binderless particleboard (0% corn starch added) do not satisfied Type 13 (13 N/mm^2) minimum requirement. The results were in good agreement to the previous studies on the fabrication of *Rhizophora* spp. particleboards as phantom materials [2, 3, 5, 16, 17, 18]. The analysis of dimensional stability showed that the TS and WA of the *Rhizophora* spp. particleboards were dramatically improved when higher percentage of corn starch treatment level added. The fabricated particleboards however did not satisfy the minimum requirement of JIS A 5908 for thickness swelling (12%). This is due to the hygroscopic properties of starch compared to other bio-adhesive materials.

Evaluation of Water-equivalent Properties

The addition of corn starch in particleboards had improved the Z_{eff} of *Rhizophora* spp. particleboard. The Z_{eff} of corn starch bonded *Rhizophora* spp. particleboard were close to those of water (7.42) compared to binderless *Rhizophora* spp. particleboard from the previous study by Mohd Yusof et al., [16]. Tursucu et al., [24] had suggested that the attenuation properties of a material are influenced by its atomic number. Duvauchelle et al., [22] suggested that a material are said to have similar attenuation properties towards ionizing radiation when the effective atomic number are similar. Therefore, it is postulated that the attenuation properties of corn starch added *Rhizophora* spp. having similar attenuation properties to water. The result was in good agreement to the bio-adhesive bonded *Rhizophora* spp. by previous studies [2-6, 16-18]. The CT number of corn starch (10%) bonded *Rhizophora* spp. particleboard having closest to the value of water indicated that the attenuation properties of particleboard were close to water. The CT imaging had been identified as the most suitable non-destructive method to determine the density and attenuation properties of a material [12]. Similarities in CT number therefore indicated similarities of density and attenuation properties between two materials. The CT number results were in good agreement with the studies of fabrication of *Rhizophora* spp. particleboards as phantoms by Ababneh et al., [2], Abuarra et al., [3], Mohd Yusof et al., [5] and Marashdeh et al., [15]. The standard deviation values of the CT numbers obtained from the particleboards however were significantly higher than that measured in water. This had indicated the sensitivity of the CT scan in determining the density uniformity of the fabricated particleboards. The standard deviation of water was significantly lower than the particleboards indicating better uniformity of density of water in comparison to solid water as standard material for quality assurance in CT imaging [5]. The previous works on the fabrication of *Rhizophora* spp. particleboards as phantom also showed relatively high standard deviation values on the CT numbers [2, 5, 15]. The results in the current study however showed significant reduction of standard deviation values when higher percentage of corn starch treatment level was used.

Determination of Mass Attenuation Coefficient

The fabricated *Rhizophora* spp. particleboards did not give significant different of mass attenuation coefficients to water indicated by the p-values of paired sample t-test. Therefore, a phantom material made of *Rhizophora* spp. can be fabricated at any percentage of corn starch treatment level. This is in good agreement to the study by Ababneh et al., [2] and Abuarra et al., [3]. The addition of corn starch however increased the physical properties and dimensional stability of *Rhizophora* spp. particleboards as phantoms. Therefore, the fabricated *Rhizophora* spp. particleboards with 10% corn starch treatment level was found to be the most suitable fabrication method for phantom material in applications of photons.

CONCLUSION

The addition of corn starch had improved the physical and mechanical properties of the particleboards shown by the higher values of IB strength, MOR, TS and WA. The effective atomic number also improved by addition of corn starch in *Rhizophora* spp. particleboard fabrication nearer to the value of water. The CT numbers of 10% corn starch bonded *Rhizophora* spp. particleboard having closest to water. These results indicated corn starch bonded *Rhizophora* spp. particleboard having water-equivalent properties. The evaluation of attenuation properties showed that all particleboards having mass attenuation coefficients near to value of water at low photons energies. The overall results showed the suitability of corn starch bonded *Rhizophora* spp. particleboards to be used as phantom material for low energy photons.

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