Results in Physics 5 (2015) 228–234

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.journals.elsevier.com/results-in-physics

Determining the mass attenuation coefficient, effective atomic number, and electron density of raw wood and binderless particleboards of *Rhizophora* spp. by using Monte Carlo simulation

Mohammad W. Marashdeh [a,b,*], Ibrahim F. Al-Hamarneh [a,c], Eid M. Abdel Munem [b], A.A. Tajuddin [b], Alawiah Ariffin [b], Saleh Al-Omari [d]

[a] Department of Physics, College of Sciences, Al Imam Mohammad Ibn Saud Islamic University (IMSIU), P.O. Box 90950, Riyadh 11623, Saudi Arabia
[b] School of Physics, Universiti Sains Malaysia, Minden, 11800 Penang, Malaysia
[c] Department of Physics, Faculty of Science, Al-Balqa Applied University, Salt 19117, Jordan
[d] Department of Physics, Faculty of Science, The Hashemite University, Zarqa 13115, Jordan

ARTICLE INFO

Article history:
Received 16 July 2015
Accepted 24 August 2015
Available online 31 August 2015

Keywords:
Effective atomic number
Effective electron density
Rhizophora spp. wood
MCNP5
XCOM

ABSTRACT

Rhizophora spp. wood has the potential to serve as a solid water or tissue equivalent phantom for photon and electron beam dosimetry. In this study, the effective atomic number (Z_{eff}) and effective electron density (N_{eff}) of raw wood and binderless *Rhizophora* spp. particleboards in four different particle sizes were determined in the 10–60 keV energy region. The mass attenuation coefficients used in the calculations were obtained using the Monte Carlo N-Particle (MCNP5) simulation code. The MCNP5 calculations of the attenuation parameters for the *Rhizophora* spp. samples were plotted graphically against photon energy and discussed in terms of their relative differences compared with those of water and breast tissue. Moreover, the validity of the MCNP5 code was examined by comparing the calculated attenuation parameters with the theoretical values obtained by the XCOM program based on the mixture rule. The results indicated that the MCNP5 process can be followed to determine the attenuation of gamma rays with several photon energies in other materials.

Introduction

Materials used as solid water and tissue equivalent phantoms have to exhibit radiological characteristics similar to those of water. Hence, the tissue-equivalence for photon beams can be ensured by checking the total mass attenuation coefficient (μ_m), effective atomic number (Z_{eff}), and effective electron density (N_{eff}) [1,2]. Numerous experimental and theoretical investigations have been conducted to determine the interaction parameters of X-rays and γ-rays with elements, compounds, and mixtures. These studies aimed to determine the values of μ_m and Z_{eff} [3–5] to represent the attenuation of radiation in compounds and mixtures, as well as in dose calculations in radiation therapy [6]. The accurate values of radiation interaction parameters in several materials are invaluable in many applied fields of science, such as nuclear and radiation physics, radiation protection and dosimetry, nuclear diagnostics and nuclear medicine, as well as agricultural, environmental, and industrial studies. Hubbell and Seltzer [7] tabulated the μ_m in a wide energy range (1–20 MeV) for all elements ($Z = 1$ to 92) and 48 additional substances of dosimetric interest. As an alternative technique, Berger and Hubbell [8] developed a computer program named XCOM for calculating the attenuation coefficients of elements, compounds, and mixtures in a wide range of photon energies. Gerward et al. [9] converted this program to the Windows platform and named it WinXcom. This program is based on the mixture rule for calculating the partial and total mass attenuation coefficients for all standard elements and mixtures and selected energies.

Rhizophora spp. is a type of mangrove wood that exhibits the characteristics of ionizing radiation interaction similar to those of water, as well as similarities in radiometric properties with other standard phantom materials in radiation dosimetry [10–13]. However, the natural wood of *Rhizophora* spp. suffers from a number of drawbacks, such as inhomogeneity of density and propensity to grow mold, and it becomes slimy, warped, and cracked with time, which limit its use as a tissue-equivalent phantom material. Hence,

* Corresponding author at: Department of Physics, College of Sciences, Al Imam Mohammad Ibn Saud Islamic University (IMSIU), P.O. Box 90950, Riyadh 11623, Saudi Arabia.
E-mail addresses: mwmarashdeh@gmail.com, mwmarashdeh@imamu.edu.sa (M.W. Marashdeh).

http://dx.doi.org/10.1016/j.rinp.2015.08.009
2211-3797/

binderless *Rhizophora* spp. particleboard is preferable than raw wood because of its accessibility to be fabricated easily into homogenous slabs without cracks [11,14]. In the current study, the photon interaction for *Rhizophora* spp. wood is evaluated. The effective atomic number (Z_{eff}) and effective electron density (N_{eff}) of raw *Rhizophora* spp. wood and *Rhizophora* spp. binderless particleboard in four different particle sizes, as well as that of pure liquid water and young-age breast tissue, are calculated in the energy range from 10 keV to 60 keV. The mass attenuation coefficients used in these calculations are obtained using the Monte Carlo N-Particle (MCNP5) simulation code. The obtained data are compared with the theoretical values calculated using the XCOM program based on the mixture rule. The dependencies of these parameters among the investigated samples over the photon energy considered, as well as the relative differences, are examined and discussed accordingly.

The values of Z_{eff} and N_{eff} in the 10–60 keV energy region of *Rhizophora* spp. wood classified as a tissue equivalent material have not been reported. Banjade et al. [10] reported an estimated average value of 7.09 for Z_{eff} of *Rhizophora* spp. wood, but did not consider the variation over energy. Thus, we conducted this study as a sequel to the work conducted by Marashdeh et al. [12]. The present calculations are performed on the same composite materials of the previous study, but in a wider range of energy (10–60 keV). The present work is important because accurate values of attenuation parameters are necessary to establish the regions of validity of theory-based parameterization, in addition to providing essential data in such diverse fields as tomography, X-ray and γ-ray fluorescence studies, and radiation biophysics.

Theory

The interaction of radiation with matter is important in radiation, nuclear, medical, biophysics, and other applied sciences. The probability of photon interaction by one physical process or another per unit distance traveled is called the linear attenuation coefficient or macroscopic cross section and is denoted by μ_ℓ. The mass attenuation coefficient μ_m is a density independent coefficient, which is a measure of the degree of absorption or scattering of radiation by a chemical species or substance at a given wavelength per unit mass. The coefficient μ_m (in $cm^2\,g^{-1}$) is obtained by dividing μ_ℓ by the density ρ of the absorber material. A collimated beam of radiation penetrating a material with mass-per-unit-area x is attenuated according to the exponential absorption law, Eq. (1) [15]:

$$\frac{I}{I_o} = e^{-(\mu_\ell/\rho)x} = e^{-\mu_m x} \tag{1}$$

where I_o and I are, respectively, the intensity of un-attenuated and attenuated radiation in the absorber medium. Then Eq. (1) can be rewritten as:

$$\ln\left(\frac{I_o}{I}\right) = \mu_m x \tag{2}$$

Eq. (2) is a linear equation for the mass-per-unit-area x of the target, and the mass attenuation coefficient μ_m is thus directly obtained as the slope of this straight line. According to Nordfors criteria [16], the optimum range of attenuation coefficients should match to satisfy the condition ($0.5 < \mu_\ell x < 5.0$).

Attenuation of X-rays and γ-rays in matter is related to density and atomic number. The effective atomic number (Z_{eff}) of compounds and composite materials plays a crucial role in representing the attenuation of X-rays and γ-rays [5], particularly for dose calculations in radiation therapy [4]. This parameter has gained considerable interest in terms of radiation interaction with composite materials. Z_{eff} can be calculated based on knowledge of the total atomic cross-section σ_a for materials that can be obtained from the measured values of μ_m using the following relation, Eq. (3) [17]:

$$\sigma_a = \frac{\mu_m A_r}{N_A} \tag{3}$$

where N_A is the Avogadro's number ($6.022045 \times 10^{23}\ mol^{-1}$), and A_r is the relative atomic mass of the compound and is given by $A_r = \frac{\sum_i n_i A_i}{\sum_i n_i}$. The total electronic cross-section σ_e for the element is expressed by the following Eq. (4) [18]:

$$\sigma_e = \frac{1}{N_A}\sum_i \frac{f_i N_i}{Z_i}(\mu_m)_i = \frac{\sigma_a}{Z_{eff}} \tag{4}$$

where f_i denotes the fractional abundance of the element i with respect to the number of atoms, Z_i is the atomic number of the element i. Then, the effective atomic number Z_{eff} of the material can be defined as the ratio by Eq. (5):

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \tag{5}$$

Effective electron number or electron density N_{eff}, i.e., the number of electrons per unit mass, can be calculated through the Eq. (6):

$$N_{eff} = \frac{N_A}{N} Z_{eff} \sum n_i = \frac{\mu_m}{\sigma_e} \tag{6}$$

Methods and materials

The values of the attenuation parameters were calculated in the energy range 10–60 keV for the investigated samples of natural raw and binderless *Rhizophora* spp. particleboards in four different particle sizes. The chemical composition and detailed information of the investigated samples are given elsewhere [12]. The binderless *Rhizophora* spp. particleboards were fabricated to obtain four different-sized particles with a target density of 1 g/cm^3. The particle sizes of the *Rhizophora* spp. samples are as follows: A (>147 μm), B (147–74 μm), C (74–50 μm), and D (<50 μm). Detailed information on the samples are shown elsewhere [11]. In addition, sample E is the *Rhizophora* spp. raw wood. The weight fractions of hydrogen, carbon, oxygen, and nitrogen in samples A, B, C, and D are 0%, 48.32%, 47.9%, and 3.78%, respectively. The weight fractions of the same elements in Sample E are 5.41%, 40.16%, 54.4%, and 0.03%, respectively. Finally, the maximum errors in the attenuation coefficients were calculated from the errors with different physical parameters associated with the present calculations; the estimated error of less than 4% was achieved.

MCNP5 is a general Monte Carlo code that can be used for neutron, photon, and electron or coupled neutron/photon/electron transport [19]. The MCNP5 input file simulates the experimental setup by using cell and surface cards in the input file. The MCNP5 output of the experimental setup is shown in Fig. 1. The photon mode is also considered in this simulation. The source (SDF) card was simulated to have a disk-shaped surface with 3 mm diameter and located 7 cm away from the end of the sample.

The elemental composition of the samples in the experimental setup was defined in the input file under the data cards. The detector shielding was designed in the form of a cylindrical lead collimator housing the detector with a diameter of 3 mm. The distances between (source–sample) and between (sample–detector) were 70 and 89 mm, respectively, as obtained experimentally by Marashdeh et al. [12]. The diameter of the samples was 1.34 cm. The transmitted beam of the photons was estimated for different

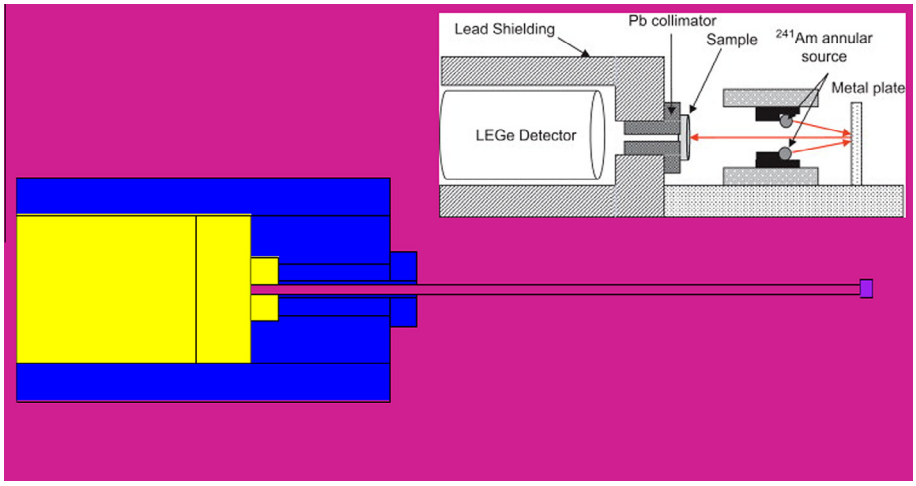

Fig. 1. The MCNP5 output of the experimental setup.

thicknesses of each sample (0.2–0.7 cm); then, the average value was calculated over these thicknesses. The linear attenuation for the samples at specified photon energy was determined using the output file value of the sample and an output file value without a sample to represent transmitted and incident gamma photon intensities respectively. The values were substituted into Eq. (1) to evaluate the linear attenuation coefficient of the sample. The code was repeated for different samples, and the simulation results were compared with the experimental results [12], and with the mass attenuation coefficient values determined by the XCOM program [20].

Results and discussion

Mass attenuation coefficient

The MCNP5 simulation code was employed to calculate the values of the mass attenuation coefficients (μ_m) for pure liquid water (Water 1), young-age breast tissue (Breast 1), and Aluminum (Al) over the photon energy range of 10–60 keV. The MCNP5 and the XCOM calculated values are plotted in Fig. 2. Relative differences of less than ±0.7% were observed in the μ_m values generated by the two calculation methods, which validates the MCNP5 simulation method applied in this study. Similar findings were obtained by other workers (Medhat et al. [21] and Singh et al. [22]) validated the use of MCNP as an alternative method for XCOM to determine the mass attenuation coefficients for different composite materials at various energy ranges.

The MCNP5 code was then used to calculate the μ_m values for the raw *Rhizophora* spp. wood (sample E) and the binderless *Rhizophora* spp. particleboards with different particle sizes (samples A, B, C, D) in the 10–60 keV energy regions. The MCNP5 calculations of the μ_m values for *Rhizophora* spp. samples A to E are shown in Fig. 3. The values of μ_m decreased sharply with energy, while the attenuation of photons also decreased with the increase in incident energy. This trend was observed for all curves regardless of particle size. Photoelectric absorption is the dominant interaction process for photon energy of less than 30 keV because of the importance of atomic binding. In this energy region, the μ_m curves did not show absorption-edge discontinuities because the materials used have no high-Z constituents [23]. The contribution of the photoelectric absorption becomes negligible and the Compton scattering process dominates in the energy range of 30 keV and

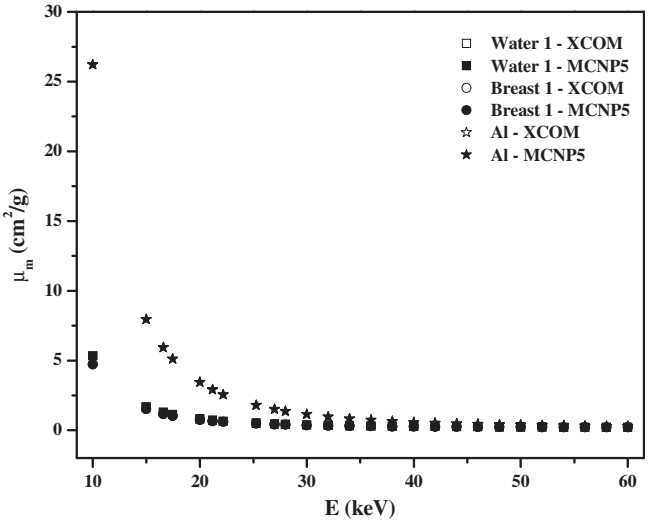

Fig. 2. A comparison of MCNP5 and XCOM calculated values of mass attenuation coefficients versus photon energy for water, breast and Al samples.

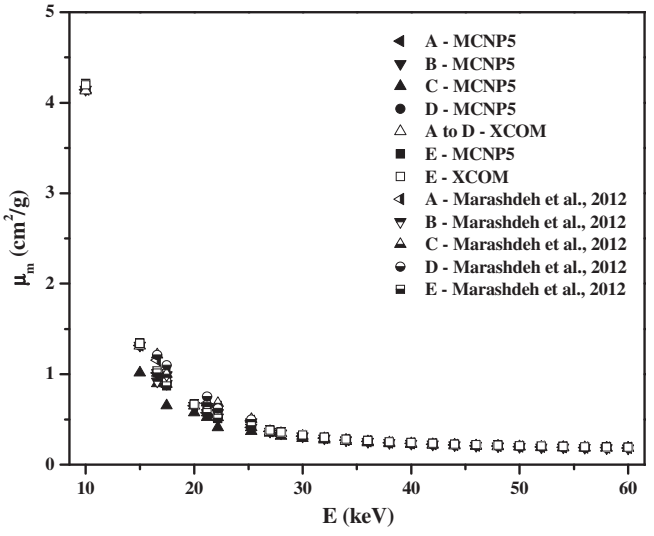

Fig. 3. A comparison of MCNP5 and XCOM calculated values as well as measured values of mass attenuation coefficients versus photon energy for *Rhizophora* spp. samples A to E.

above because the effective cross section is inversely proportional to the incident photon energy.

The μ_m results for the *Rhizophora* spp. samples generated by the XCOM program in Fig. 3 shows that the MCNP5 generated values are in agreement with the corresponding XCOM calculated values. The relative differences in the μ_m values between the two calculation methods are less than 0.6%, whereas no noticeable variations have been observed in the μ_m values among the different binderless *Rhizophora* spp. particleboard samples. These results support the validity of the MCNP5 simulation code for the prescribed calculations and indicate that particle size has no effect on the attenuation of *Rhizophora* spp. wood for photon radiation. However, the figure reveals a slight difference in the attenuation of photons for the binderless *Rhizophora* spp. particleboards compared with that for raw wood, with relative differences in the μ_m values of less than −4%. This discrepancy can be attributed to the differences in elemental composition between the two types of wood. Fig. 3 also shows the μ_m coefficients for same samples (A, B, C, and E), as obtained experimentally by Marashdeh et al. [12] at energies between 16.59 and 25.26 keV. The MCNP5 calculations of the μ_m values agree well with the measured values; thus, these findings unambiguously support the earlier conclusions [12].

The values of μ_m for *Rhizophora* spp. samples were compared with those for water and breast samples by calculating their relative differences. The results are graphically depicted in Fig. 4. Noticeable variations in μ_m values for the *Rhizophora* spp. samples are observed compared with those for Water 1 and Breast 1 samples, with average relative difference values of up to −15% and −11%, respectively. Fig. 4 also shows that the maximum relative difference in μ_m values for the *Rhizophora* spp. samples compared with the Water 1 and Breast 1 samples is observed at 10 keV where the photoelectric absorption is dominant. This behavior can be attributed to the strong dependence of photoelectric absorption on atomic number [23] and the presence of higher atomic number components (carbon and nitrogen) in *Rhizophora* spp. wood that do not exist in water. At 60 keV, where the Compton scattering is important, the relative differences in μ_m values for the *Rhizophora* spp. samples compared with the Water 1 and Breast 1 samples is minimal because of the similar values of the electron density of the samples in this energy region, as presented below in the next section. Notably, the μ_m values for the *Rhizophora* spp. samples are closer to those quoted for breast tissue than water as indicated in Fig. 4. This result agrees with the earlier findings obtained by Abuarra et al. [13]. Nevertheless, the noticeable discrepancies in μ_m values compared with those of water and breast, strongly suggest that the elemental composition of *Rhizophora* spp. particleboard samples should be modified to obtain similar attenuation coefficients to water and breast tissue.

Effective atomic number and effective electron density

The total atomic cross-sections (σ_a) for the investigated samples were calculated from the values of μ_m, as previously described. The calculated σ_a values were compared against the theoretical σ_a values, as estimated using the XCOM program. A typical behavior of σ_a with photon energy for samples D and E is shown in Fig. 5. The σ_a values for Water 1 and Breast 1 samples are also included in the figure for validation and comparison. The values of σ_a calculated based on the MCNP5 code are in a very good agreement with those obtained theoretically. Meanwhile, the σ_a values for sample D are greater than those obtained for sample E, with relative differences of up to 60%, which is also attributed to the differences in elemental composition of samples. Afterward, the σ_e values were calculated to obtain the values of Z_{eff} and N_{eff} for all samples.

The calculated values of Z_{eff} for the investigated samples reveal the dependence of Z_{eff} on the elemental composition and relative proportions of the constituent elements. Thus, remarkable discrepancies were observed regarding the behavior of Z_{eff} values

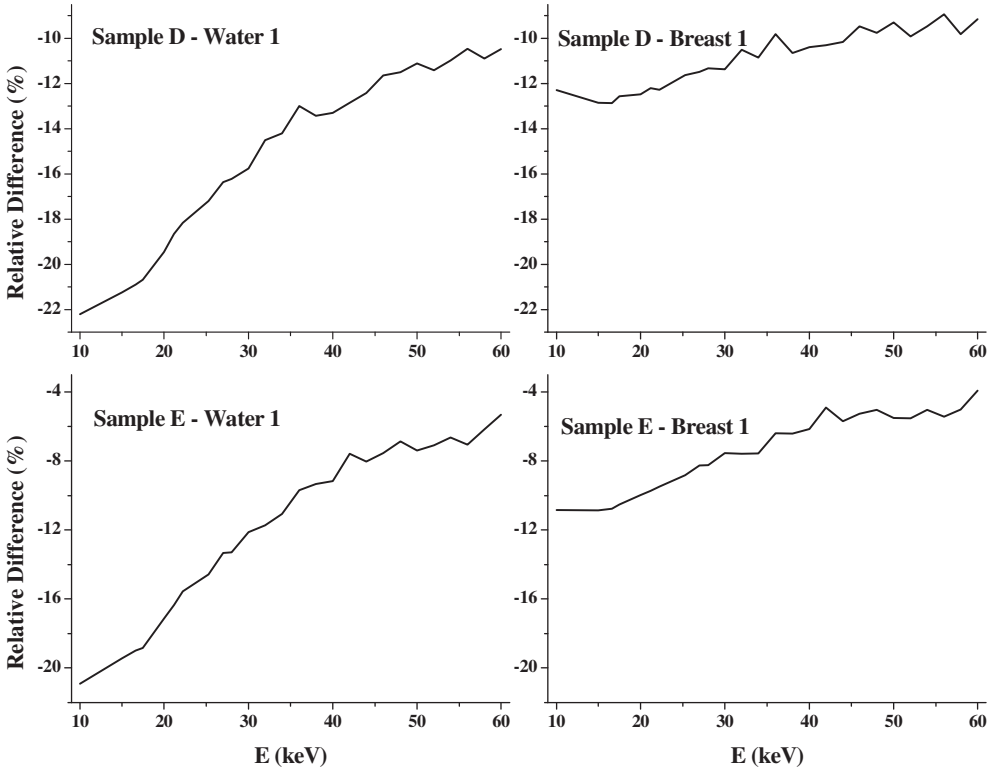

Fig. 4. Relative differences (%) in mass attenuation coefficients versus photon energy between water and breast samples, and *Rhizophora* spp. samples D and E.

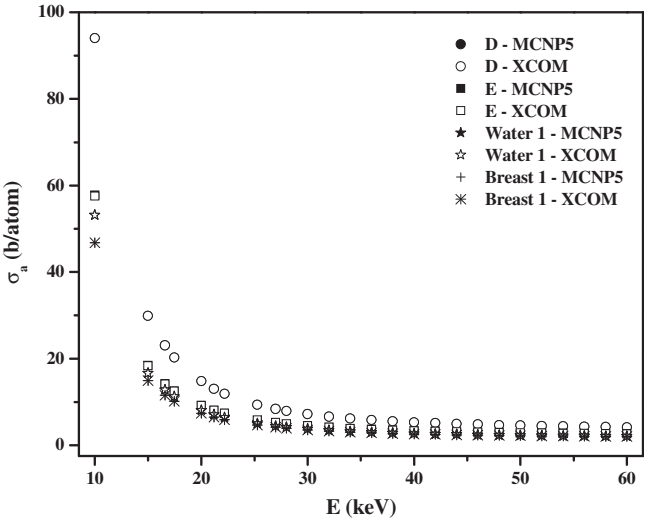

Fig. 5. Variation of total atomic cross section of samples D, E, Water 1 and Breast 1 with photon energy as obtained based on the MCNP5 and XCOM methods.

for each *Rhizophora* spp. sample with photon energy compared with those for water and breast samples. A typical variation of the Z_{eff} values for *Rhizophora* spp. samples D and E with photon energy is shown in Fig. 6, whereas the corresponding behavior of N_{eff} values is shown in the inset. In the case of variation of the μ_m values, the variation of Z_{eff} and N_{eff} can be explained by the predominance of different processes of photon interaction in different energy regions. The main interaction in the low photon energy is photoelectric absorption; thus, maximum values of Z_{eff} and N_{eff} are obtained. Compton scattering is the main photon interaction when the photon energy increases; thus, the Z_{eff} and N_{eff} values are almost constant for the given samples. Moreover, Fig. 6 also shows that the Z_{eff} values for almost all of the samples lie within the range of 3.5–7.5. Worth to mention that Banjade et al. [10], have reported a value of Z_{eff} for *Rhizophora* spp. raw wood is 7.09, which matches our present result.

The effective atomic number is the most vital parameter in investigating the water and tissue equivalency of *Rhizophora* spp. [10,12,24]. In this regard, Fig. 6 clearly reveals that the variation trend of the Z_{eff} values for raw wood is much closer to that of water and breast tissue than the binderless *Rhizophora* spp. particleboard samples. The four different particle sizes of binderless *Rhizophora* spp. particleboard (samples A, B, C, and D) show a slight variation in the Z_{eff} values over the photon energy used in this study, with minimum and maximum values of 7.3 and 6.9, respectively. However, this narrow range of variation in the Z_{eff} values for binderless *Rhizophora* spp. particleboards is expected and common among composites consisting of elements with close atomic numbers [24]. In the current case, the elements are C, N, and O. Therefore, the variation dependence of Z_{eff} for the binderless *Rhizophora* spp. particleboards significantly differs from those of water and breast tissue. This result implies that the equivalency parameters of binderless *Rhizophora* spp. particleboards with this particular composition do not match adequately with those of water or breast tissues. Meanwhile, Fig. 6 and its inset reveal that the variations of Z_{eff} and N_{eff} with the photon energy for all samples are similar because the two quantities are related by Eq. (5). Therefore, the relationship between Z_{eff} and N_{eff} is linear, as indicated in Fig. 7.

The mean atomic number of each compound investigated in this study was calculated from the chemical formula of the molecule $\langle Z\rangle = \frac{1}{n}\sum_i n_i Z_i$. The values of $\langle Z\rangle$ for Water 1, Breast 1, samples A to D, and sample E were 3.33, 3.25, 6.85, and 4.33, respectively. A satisfactory agreement was found between the MCNP5 calculations of Z_{eff} and the $\langle Z\rangle$ values in the upper energy region (60 keV) wherein the Compton scattering dominates. Therefore, in the energy region where the Compton scattering process is predominant, particularly for low Z compounds, the effective atomic number can be estimated by the mean atomic number, which is an average single-valued, composition-dependent but energy-independent number. This result is consistent with Sidhu et al. [25], who concluded that low Z composite materials can be represented by the energy independent and composite dependent mean atomic number $\langle Z\rangle$. However, the effective atomic number for the use of dosimetric or substitute materials should be evaluated for the energy range of interest and should not be assumed to be a constant. Such conclusions can also be verified using the XCOM software. Therefore, the values obtained by MCNP5, as well as the theoretical values of the Z_{eff} and N_{eff} for Water 1 and Breast 1 samples, are plotted against photon energy in Figs. 8a and 8b, respectively. Good agreement was achieved between the values of both calculation methods because the relative differences

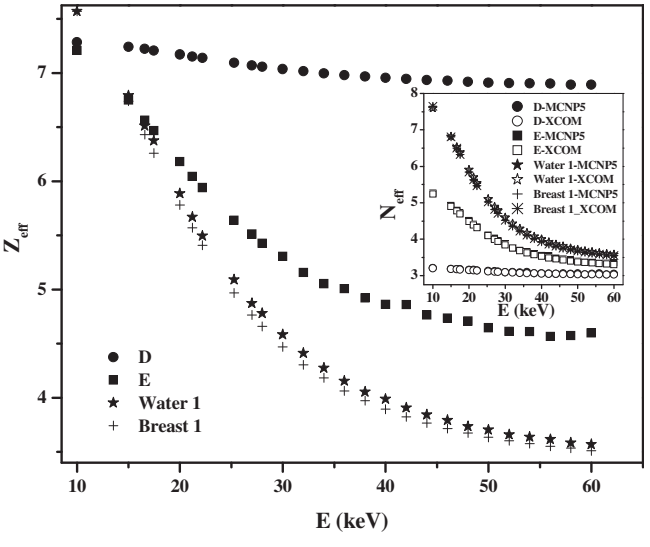

Fig. 6. Variation of effective atomic numbers of samples D, E, Water 1 and Breast 1 with photon energy as obtained based on the MCNP5 method. The inset shows the variation of effective electron density with photon energy for the same samples.

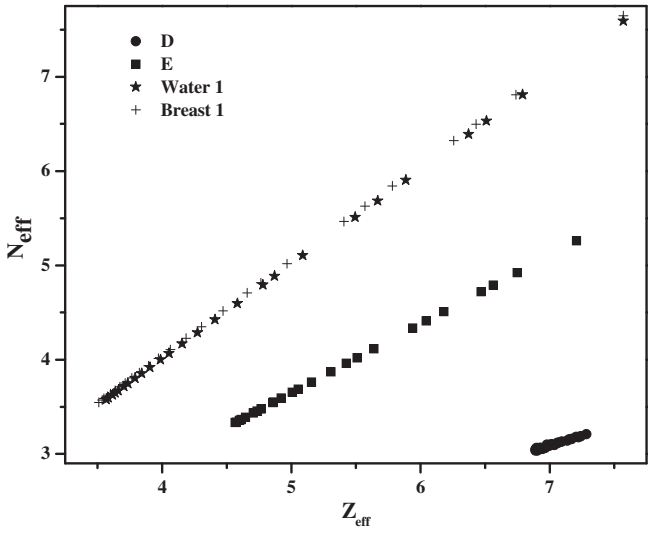

Fig. 7. Effective atomic numbers of samples D, E, Water 1 and Breast 1 versus effective electron density as obtained based on the MCNP5 method.

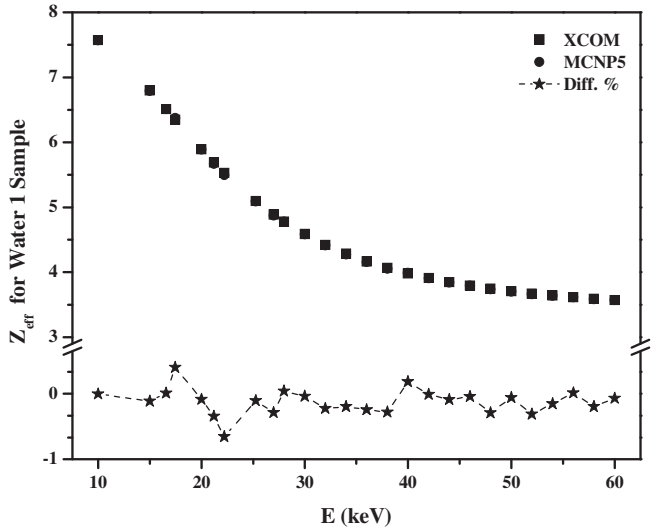

Fig. 8a. Variation of the effective atomic numbers for water with photon energy as obtained based on the MCNP5 and XCOM methods with the corresponding relative differences (%).

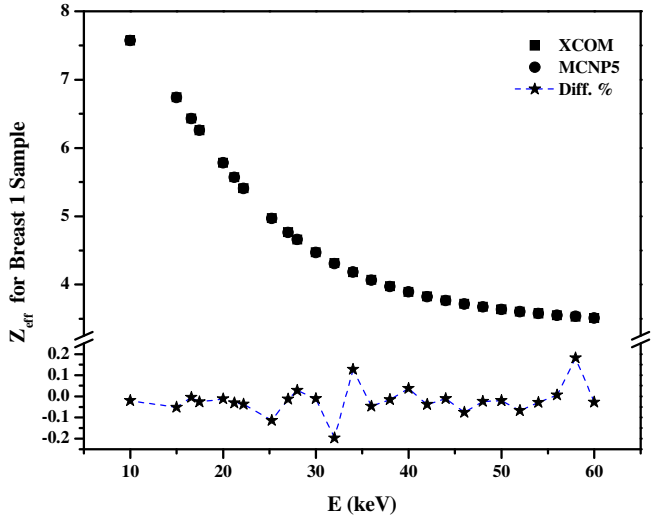

Fig. 8b. Variation of the effective atomic numbers for breast sample with photon energy as obtained based on the MCNP5 and XCOM methods with the corresponding relative differences (%).

between them were smaller than ±1%. This consistency of the MCNP5 calculated values of Z_{eff} with the theoretically XCOM calculated values establishes the validity of the MCNP5 simulation for finding the Z_{eff} of such materials. Notably, the discrepancy is large in the low energy region where photoelectric effect is the predominant process, indicating that photoelectric absorption is strongly dependent on individual atomic numbers.

Conclusion

In this study, the MCNP5 simulation code was applied to calculate the values of the mass attenuation coefficients (μ_m), total atomic cross section (σ_a), effective atomic numbers (Z_{eff}), and effective electron density (N_{eff}) of *Rhizophora* spp. wood samples, as well as water and young-age breast tissue, over the energy range of 10 keV of 60 keV. The applicability of the MCNP5 code was satisfactory and in good agreement with the results generated by the XCOM program based on the mixture rule.

Therefore, all of these parameters are dependent on the incident photon energy, particularly in the low incident photon energies (1–30 keV) because of the predominant photoelectric absorption process. These parameters are nearly constant because of the predominance of the Compton scattering at $\geqslant$30 keV. In addition, the energy dependence of photon interaction cross section is identical to the total mass attenuation coefficient; the same can be concluded for the electron density and effective atomic number.

The binderless *Rhizophora* spp. particleboard samples exhibited attenuation parameters that significantly differ from those of Water 1 and Breast 1 samples, and thus do not match the water and tissue equivalency requirements. However, the raw wood of *Rhizophora* spp. is much closer to the breast tissue in terms of radiation interaction data. A satisfactory agreement between the calculated values of Z_{eff} and mean atomic number $\langle Z \rangle$ of *Rhizophora* spp. wood is found in the 30–60 keV energy region. Therefore, this energy-independent and composition-dependent parameter of low-Z composite materials can be a good estimate of the effective atomic number in the energy region wherein Compton scattering is predominant.

Acknowledgements

The authors would like to appreciate the technical support received by the staff members of the department of Physics, Al Imam Mohammad Ibn Saud Islamic University (IMSIU).

References

[1] Khan FM. The physics of radiation therapy. Lippincott Williams & Wilkins; 2010, ISBN 0781788560.
[2] Baldock C, De Deene Y, Doran S, Ibbott G, Jirasek A, Lepage M, McAuley K, Oldham M, Schreiner L. Polymer gel dosimetry. Phys Med Biol 2010;55(5):R1.
[3] Jayachandran C. Calculated effective atomic number and kerma values for tissue-equivalent and dosimetry materials. Phys Med Biol 1971;16(4):617.
[4] Kirov A, Shrinivas S, Hurlbut C, Dempsey J, Binns W, Poblete J. New water equivalent liquid scintillation solutions for 3D dosimetry. Med Phys 2000;27 (5):1156–64.
[5] Taylor M, Franich R, Trapp J, Johnston P. Electron interaction with gel dosimeters: effective atomic numbers for collisional, radiative and total interaction processes. Radiat Res 2009;171(1):123–6.
[6] Jackson DF, Hawkes DJ. X-ray attenuation coefficients of elements and mixtures. Phys Rep 1981;70(3):169–233.
[7] Hubbell JH, Seltzer SM. Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements Z = 1 to 92 and 48 additional substances of dosimetric interest. National Inst. of Standards and Technology-PL, Gaithersburg, MD (United States). Ionizing Radiation Div., 1995.
[8] Berger M, Hubbell J. XCOM: photon cross sections database, Web Version 1.2. National Institute of Standards and Technology, Gaithersburg, MD, 20899, 1999.
[9] Gerward L, Guilbert N, Jensen KB, Levring H. X-ray absorption in matter. Reengineering XCOM. Radiat Phys Chem 2001;60(1):23–4.
[10] Banjade D, Tajuddin AA, Shukri A. A study of *Rhizophora* spp. wood phantom for dosimetric purposes using high-energy photon and electron beams. Appl Radiat Isot 2001;55(3):297–302.
[11] Marashdeh MW, Hashim R, Tajuddin AA, Bauk S, Sulaiman O. Effect of particle size on the characterization of binderless particleboard made from *Rhizophora* spp. Mangrove wood for use as phantom material. BioResources 2011;6 (4):4028–44.
[12] Marashdeh M, Bauk S, Tajuddin AA, Hashim R. Measurement of mass attenuation coefficients of *Rhizophora* spp. binderless particleboards in the 16.59–25.26 keV photon energy range and their density profile using X-ray computed tomography. Appl Radiat Isot 2012;70(4):656–62.
[13] Abuarra A, Bauk S, Hashim R, Kandaiya S, Tousi ET, Aldroobi K. Microstructure examination, elemental composition analysis of gum arabic bonded *Rhizophora* spp. Particleboards and their potential as tissue equivalent material. Int J Chem, Environ Biol Sci (IJCEBS) 2014;2(1):2320–4087.
[14] Shakhreet B, Bauk S, Tajuddin AA, Shukri A. Mass attenuation coefficients of natural *Rhizophora* spp. wood for X-rays in the 15.77–25.27 keV range. Radiat Prot Dosim 2009;135(1):47–53.
[15] Hubbell J. Photon mass attenuation and energy-absorption coefficients. Int J Appl Radiat Isot 1982;33(11):1269–90.
[16] Creagh D, Hubbell J. Problems associated with the measurement of X-ray attenuation coefficients. II. Carbon. Report on the international union of crystallography X-ray attenuation project. Acta Crystallogr Sect A: Found Crystallogr 1990;46(5):402–8.

[17] Perumallu A, Rao AN, Rao GK. Photon interaction measurements of certain compounds in the energy range 30–660 keV. Can J Phys 1984;62(5):454–9.
[18] El-Kateb A, Abdul-Hamid A. Photon attenuation coefficient study of some materials containing hydrogen, carbon and oxygen. Int J Radiat Appl Instrum. Part A: Appl Radiat Isot 1991;42(3):303–7.
[19] Briesmeister JF. MCNPTM-A general Monte Carlo N-particle transport code. Version 4C, LA-13709-M, Los Alamos National Laboratory, 2000.
[20] Hubbel J, Berger M. X-COM: photon cross section on a personal computer. (NBSIR), 1987.
[21] Medhat ME, Shirmardi SP, Singh VP. Comparison of geant 4, MCNP simulation codes of studying attenuation of gamma rays through biological materials with XCOM and experimental data. Appl Comput Math 2014;3(6):2168–9679.
[22] Singh VP, Shirmardi SP, Medhat ME. Determination of mass attenuation coefficient for some polymers using Monte Carlo simulation. Vacuum 2015;19:1–5.
[23] Jayaraman S, Lanzl LH, Lanzl EF. Clinical radiotherapy physics. 2nd ed. Springer Science & Business Media; 2004. p. 75–76.
[24] El-Kateb A, Rizk R, Abdul-Kader A. Determination of atomic cross-sections and effective atomic numbers for some alloys. Ann Nucl Energy 2000;27 (14):1333–43.
[25] Sidhu BS, Dhaliwal A, Mann K, Kahlon K. Study of mass attenuation coefficients, effective atomic numbers and electron densities for some low Z compounds of dosimetry interest at 59.54 keV incident photon energy. Ann Nucl Energy 2012;42:153–7.