Comparative X-ray shielding properties of bismuth oxide/natural rubber composites using a Monte Carlo code of PHITS

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Abstract. Natural rubber (NR) is a material for potential development as a flexible X-ray shielding material, subject to improvement in its attenuation ability as one of the necessary measures to ensure safety for radiation-related workers and the general public. Consequently, this work used Monte Carlo coding and the Particle and Heavy Ion Transport System (PHITS) to simulate the X-ray shielding properties of NR composites that were added with Bi2O3 particles at different Bi2O3 contents (0–50 wt% in 10-wt% increments) and different material thicknesses (2, 4, and 6 cm). The X-ray source used for the simulation was a point source with energy ranges of 0.05, 0.1, 0.5, 5.0, and 15.0 MeV, respectively, and the detector was assumed to have 100% detection efficiency. The simulated results showed that at lower energies of X-rays (0.05 and 0.1 MeV), the values of X-ray transmission substantially decreased with increasing filler contents and material thicknesses. However, at higher energies of X-rays (0.5, 5.0, and 15.0 MeV), changes in the X-ray transmission ratios for different filler contents and material thicknesses were not as pronounced as for the lower-energy X-rays due to the high penetration ability of the high-energy X-rays. In particular, the highest attenuation ability of the materials obtained in this work was in the NR composites with 50 wt% Bi2O3, which had the values of half value layer (HVL; the thickness required to attenuate the incoming X-ray intensity by 50%) of 0.002, 0.004, 0.324, 0.990 and 1.540 m for X-ray energies of 0.05, 0.1, 0.5, 5.0, and 15.0 MeV, respectively. Other parameters including the linear attenuation coefficients (μ) and HVL of all filler contents were also reported and thoroughly discussed in this work.

1. Introduction
X-ray technology has many uses such as in agriculture, in food preservation, in industry, and especially in medical fields for diagnosis and therapy [1]. Although X-ray radiation is used in many useful applications, researchers, technicians, and the general public are at risk of receiving excessive doses of X-rays that are harmful to human health, cause symptoms such as skin burn and vomiting within hours, and can also result in long-term health effects such as memory loss, cancer, and cardiovascular disease [2]. Consequently, it has become necessary to evaluate the risks and to reduce the hazards from excessive X-ray radiation exposure. In principle, X-ray attenuation requires their energy transfer into matter.
encountered through two main interactions: the photoelectric effect and Compton scattering by interacting with heavy elements such as lead or lead compounds [3]. Examples of such materials are lead/polyethylene composites or lead/glass composites [4]. However, while lead is useful and effective in X-ray radiation reduction, it is considered a hazardous chemical, particularly for the manufacturer, especially when it is accidentally inhaled or ingested [5]. In this work, we aimed to develop flexible, lead-free, X-ray-shielding materials that are safe and environmentally friendly based on natural rubber (NR) composites that could provide flexibility, resistance to abrasion, and highly efficient X-ray attenuation, with the addition of bismuth (III) oxide (Bi$_2$O$_3$). The selection of Bi$_2$O$_3$ used in this work was based on the fact that bismuth has a high atomic number ($Z$) of 83 (greater than lead, which has $Z$ = 82), high density, a high melting point, and also is highly effective in X-ray attenuation.

This work aimed to simulate the shielding properties of NR composites having different Bi$_2$O$_3$ contents, different material thicknesses, and different X-ray energies (0.05, 0.1, 0.5, 5.0, and 15.0 MeV) by using Monte Carlo coding of a particle and heavy ion transport code system (PHITS) to simulate and to measure important properties, including the X-ray transmission ratio ($\frac{l}{l_0}$), the linear attenuation coefficient ($\mu$), and the half-value-layer ($HVL$) to assess the capabilities of X-ray attenuation of the NR composites and to design X-ray shielding materials for use in actual experiments.

2. Experimental

PHITS is a general-purpose Monte Carlo particle transport simulation code using several nuclear reaction models and nuclear data, of which the program has been used in various research fields, including in accelerator technology, in medical physics, in geosciences, in facility design, and in radiation protection. In this work, PHITS was used to simulate X-ray shielding properties of Bi$_2$O$_3$/NR composites that were added with different Bi$_2$O$_3$ contents (0–50%wt) in air. The sizes of all samples used in the simulation were 20 cm × 20 cm with thicknesses varied from 2, 4, to 6 cm, respectively. X-ray point source had a 0.005-cm diameter and its emitted energies varied from 0.05 MeV to 0.1, 0.5, 5.0, and 15.0 MeV, respectively. The X-ray source was located 5 cm away from the surface of NR composites. In order to correctly estimate the X-ray shielding properties of the samples, the detector was set to have 100% detection efficiency and located 20 cm away from the surface of NR composites in the opposite side of the X-ray source. The setup of the simulation is shown in Figure 1.

![Figure 1. Setup of the simulation of Bi$_2$O$_3$ composites by using PHITS.](image)

From the simulation, the X-ray shielding properties ($\frac{l}{l_0}$, $\mu$, and $HVL$) could be calculated using Eq. 1 and Eq. 2:
\[ I = I_0 e^{-\mu x} \]  
\[ HVL = \frac{\ln(2)}{\mu} \]

where \( I_0 \) is the initial intensity of the X-ray beam, \( I \) is the intensity of the X-ray after passing through the NR composites, \( \mu \) is the linear attenuation coefficient of shielding calculated from the material thicknesses of 0.5, 1.0 and 1.5 cm in order to reduce the effect of build-up factors, and \( x \) is the thickness of the NR composites.

3. Results and discussion
The results from the simulation are shown in Fig. 2 and Table 1, which showed that, at 0.05 and 0.1 MeV, the values of X-ray transmission substantially decreased with increasing filler contents and material thicknesses due to the greater ability of X-ray interaction and the impact of the photoelectric effect or Compton scattering with bismuth atoms in the material to attenuate and to reduce X-ray energies and intensities. However, at higher X-ray energies (0.5, 5.0, and 15.0 MeV), the changes in the X-ray transmission ratios for different filler contents and material thicknesses were not as pronounced as for the lower X-ray energies. This behaviour was observed because of the much increases in penetrating ability of the high-energy X-rays [6].

![Figure 2](image_url)

**Figure 2.** X-ray transmission factors of 0-50wt% Bi2O3/NR composites in different material thicknesses (2, 4 and 6 cm) and (a) 0.05-MeV, (b) 0.1-MeV, (c) 0.5-MeV, (d) 5-MeV, and (E) 15-MeV incoming X-rays.
The ability of the X-rays to penetrate the Bi$_2$O$_3$ composites being dependent on their energy, at the lower energies (0.05, 0.1 MeV) of X-rays had a greater probability of being absorbed by Bi$_2$O$_3$ when the values of $\mu$ clearly increased with increasing Bi$_2$O$_3$ content (0-50 wt%). However, at higher X-ray energies (0.5, 5.0, and 15.0 MeV) had a greater probability of penetrating the composites and the differences in values of $\mu$ and HVL for different energies were not as pronounced as in the case of lower energies. This could be because the probability of X-ray interaction with an orbital electron of Bi atoms is the largest when the X-ray energy equals the binding energy of bismuth atom and the probability tends to decrease when the X-ray energy becomes larger than the binding energy [7].

4. Conclusions
In this study, Bi$_2$O$_3$/NR composites provided effective shielding against low energy X-rays (energy less than 0.1 MeV). Furthermore, it was found that the X-ray attenuation property improved with increasing Bi$_2$O$_3$ content and material thickness.

5. References
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