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Effect of reinforcement phase loading on the dosimetry response of a Polycarbonate/Bismuth Oxide nanocomposite for beta particles

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HIGHLIGHTS

- PC/Bi₂O₃ nanocomposites at various Bi₂O₃ weight fractions up to 50 wt% are prepared via the solution method.
- The samples are exposed to beta rays of Sr-90 at various dose rates ranging from 30 to 102 mSv.h⁻¹.
- Variation of electric current during the irradiation is measured as the dosimetry response of the samples.
- Increasing the Bi₂O₃ wt% leads to improvement in the sensitivity and dosimetry response linearly at various dose rates.

ABSTRACT

In this experimental work, Polycarbonate/Bismuth Oxide (PC-Bi₂O₃) nanocomposites were prepared in various concentrations of 0, 10, 30, and 50 wt% with thicknesses of 1 mm and irradiated by a pure beta-emitter source of Sr-90. To fabricate the electrodes, copper sheets with thickness of 100 μm were attached to the top and bottom surfaces of the samples using the silver paste. Then, electric current as the dosimetry response, was measured at various dose rates ranging from 30 to 102 mSv.h⁻¹ at a fixed voltage of 400 V using an electrometer. Results showed that increasing the Bi₂O₃ wt% led to improvement in the dosimetry response linearly at various dose rates. Also, the amounts of sensitivities for the samples of 0, 10, 30, and 50 wt% were measured as 20.3, 19.8, 28.6, and 36.7 nC.mSv⁻¹.cm⁻³, respectively. Regarding the mechanism of beta interaction with a polymer-heavy metal oxide nanocomposite, the Bremsstrahlung radiation can be considered as a dominant effect.

KEYWORDS

Beta-ray Dosimeter
PC-Bi₂O₃ nanocomposite
Dose Rate
Sr-90
Sensitivity

HISTORY

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1 Introduction

Polymer-nanocomposites have attracted considerable interest to be used as radiation sensors, detectors, dosimeters, and shields (Saavedra, 2005; Korostynska et al., 2007; Intaniwet et al., 2012; Malekie et al., 2016a,b,c; Malekie and Hajiloo, 2017; Malekie and Ziaie, 2017; Mosayebi et al., 2017; Kazemi et al., 2019; Mosayebi et al., 2019; Rahimi et al., 2020; Hosseini et al., 2021; Mehrara et al., 2021; Hosseini et al., 2022; Safdari et al., 2022). The interaction mechanisms of the beta particles with matter are classified into two sections, electron excitation and ionization. Electrons via the Coulomb electric field interact with the particles traversing the material (Attix, 2008; Yanagida, 2018; Kang et al., 2020). Besides, light-weight materials including polymers are excellent absorbers of charged particles which will exhibit high sensitivity in the charged particle detectors.

The linear stopping power for charged particles in a particular absorber is defined as the energy loss for that particle within the material divided by the corresponding path length via the Bethe-Bloch formula (Knoll, 2010):

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} N Z \left[\ln \frac{2m_0 v^2}{I} - \ln \left(1 - \frac{v^2}{c^2} \right) - \frac{v^2}{c^2} \right] \quad (1)$$

in which v and z are the velocity and charge (in multiples of the electron charge) of the particles, N and Z are the number density and the atomic number of the absorber atoms, m_0 is the electron rest mass, e is the electronic charge, and I indicates to average ionization potential of the absorber material (Knoll, 2010).

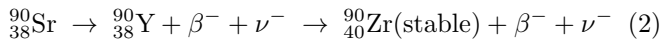
In a polymer-heavy metal oxide nanocomposite, the amount of sensitivity for detecting the beta-rays can be arranged through the weight fractions of the reinforcement phase. Commonly, different factors affect the dosimeter

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response of this material, including polymer crystallinity, weight fraction of the nanoparticles or reinforcement phase loading, uniformity of the material, thickness of the nanocomposite, and so on. Continuous slowing-down approximation or CSDA is used to determine energy loss of electrons (Borg, 1996; Miramonti, 2002; L'annunziata, 2016). The collisions of electrons with the particles involve inelastic scattering with orbital electrons, whereby produces excitation or ionization, inelastic scattering with nuclei in which leads to create Bremsstrahlung, and finally elastic scattering, by which electrons lose a small fraction of their energies (Kang et al., 2020).

Usually scintillators are applied to be used as detectors for beta-rays. A disadvantage of some scintillators is due to limitations in their hygroscopicity and scalability (Torrise, 1997; Miramonti, 2002; Quaranta et al., 2002; Ghergherehchi et al., 2010; Tam et al., 2018). Several pure beta-emitters are H-3 (18.6 keV), C-14 (156 keV), P-32 (1.71 MeV), P-33 (248 keV), S-35 (167 keV), Cl-36 (714 keV), Ca-345 (252 keV), Ni-63 (67 keV), Sr-90/Y-90 (546 keV/2.27 MeV), Pm-147 (224 keV), and Tl-204 (766 keV) (Knoll, 2010).

In this experimental work, Strontium-90 (Sr-90) was considered as a pure beta-emitter source. The decay mechanism of Sr-90 is as follows (L'Annunziata, 2012):



in which Sr-90 decays to Y-90 with a half-life of 28.78 years, with beta particle energy of 546.2 keV; the Y-90, which emits beta and gamma, converts to Zr-90 with a half-life of 64 hours, with beta particle energy of 2.28 MeV (L'Annunziata, 2012).

In this research, Polycarbonate/Bismuth oxide (PC-Bi₂O₃) nanocomposite was considered, for dosimetry purpose of beta particles. The dosimeter response was regarded as a variation of electric current during the irradiation, in which the photocurrent was measured by an electrometer at a certain voltage. So, this research aims to investigate the response linearity of a novel real-time beta-ray dosimeter based on PC-Bi₂O₃ nanocomposite.

2 Materials and methods

2.1 Sample preparation

Pure PC, 10, 30, and 50 wt% PC-Bi₂O₃ nanocomposites were prepared with thicknesses of 1 mm using the solution casting method, in which the details of synthesis have been described in our previous works (Mehrra et al., 2021; Safdari et al., 2022). Polycarbonate as a polymer matrix and Bi₂O₃ nanoparticles as the reinforcement phase with the average size of 90-210 nm as nano-fillers were utilized with densities of 1.2 g.cm⁻³ and 8.9 g.cm⁻³, respectively. Also, Sr-90 as a pure beta-emitter source was applied. Also, Copper sheets with thickness of 100 μm were attached to the top and bottom surfaces of the nanocomposites using the silver paste.

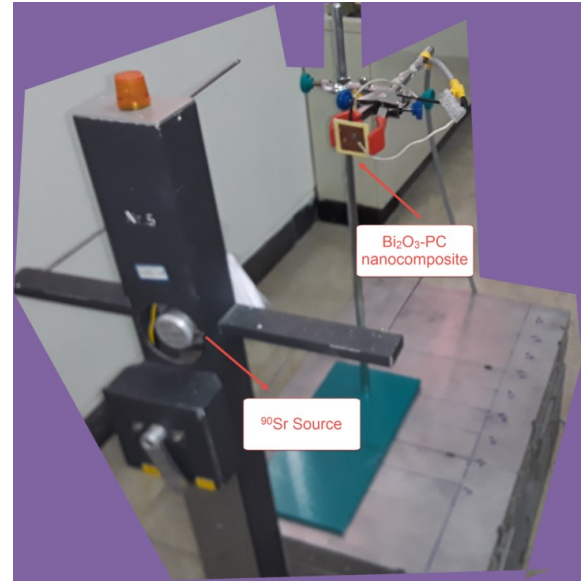


Figure 1: Experimental setup to measure the dosimetry response of the PC-Bi₂O₃ nanocomposite.

Table 1: The amounts of SSDs for Sr-90 and corresponding dose rates.

SSD (cm)	Dose Rate (mSv.h ⁻¹)
30	102.436
35	75.259
40	57.620
45	45.527
50	36.877
55	30.477

2.2 Setup of the measurement

In this experimental work, to irradiate the PC-Bi₂O₃ nanocomposite with beta-rays, a beta irradiation system model Buchler BSS-BA containing Sr-90 reference source with an initial activity of 50 mCi (production date 1978) which is located in Secondary Standard Dosimetry Laboratory (SSDL) Karaj-Iran was applied at different source-surface distances (SSDs) according to Table 1. The setup of the measurement is depicted in Fig. 1. To measure the electric charge during irradiation at fixed time steps of 15 s, the Supermax Standard Imaging electrometer was used.

To verify the calibration of this system, an extrapolation chamber, a sensitive current measuring system and a sophisticated evaluation procedure have to be used according to the Safety Series No. 16 and other standards (Böhm, 1976; Ehrlich et al., 1985; Dozik, 2001; ISO-6980-2, 2004).

2.3 FESEM analysis

The Field Emission Scanning Electron Microscopy (FESEM) of the 50 wt% PC-Bi₂O₃ nanocomposite is depicted in Fig. 2. FESEM device model MIRA3TESCAN-XMU was used. The FESEM analysis was conducted at the Razi Metallurgy Research Centre in Iran. Results showed an appropriate dispersion state of the inclusions into the polymer matrix.

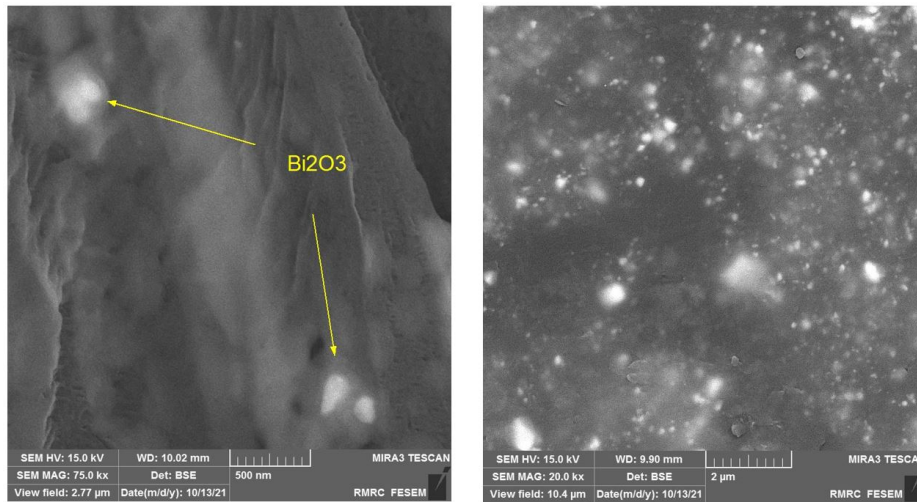


Figure 2: Exhibition of FESEM for the 50 wt% PC-Bi₂O₃ nanocomposite.

3 Results and discussion

In Fig. 3, the I-V plot of the dosimeter based on the 50 wt% PC-Bi₂O₃ nanocomposite in the presence of beta radiation field of Sr-90 source at fixed SSD=30 cm and dose rate of 102.436 mSv.h⁻¹ is exhibited. The I-V plot demonstrates that there is no saturation in the dosimeter response at voltages ranging from 100 to 1000 V. Also, the I-V plot showed that the bias polarity exhibits 15.2% discrepancy on the dosimetry response of the nanocomposite material.

Generally ionization chambers and Geiger Muller counters operate within a specific region of the applied voltage, between 300 to 400 V. Therefore, in this experimental work a fixed voltage of 400 V was selected to carry out other dosimetry characteristics of the samples. However, as shown in Fig. 3, up to 1000 V, no saturation was observed in the dosimeter response.

As shown in Fig. 4, for various nanocomposites, the photocurrent was measured at each dose rate using an electrometer at a fixed voltage of 400 V. Results show that increasing the reinforcement phase loading leads to increasing the dosimetry response linearly at various dose rates ranging from 30 to 102 mSv.h⁻¹.

The sensitivities of the samples were evaluated by dividing the slope of the I-Dose rate plots in Fig. 4 by the active volume of the dosimeter material (4 cm × 4 cm × 0.1 cm). The values of sensitivities for different reinforcement phase loadings, namely 0, 10, 30, and 50 wt% were measured as 20.3, 19.8, 28.6, and 36.7 nC.mSv⁻¹.cm⁻³, respectively.

To justify this effect, it can be mentioned that at higher Bi₂O₃ wt%, due to increasing the probability of occurring Bremsstrahlung secondary radiation and increasing the amount of total stopping power of the electrons, the dosimetry response will be increased subsequently. Regarding the mechanism of beta interaction with the PC-Bi₂O₃ nanocomposite material, the Bremsstrahlung radiation can be considered as the dominant effect due to the presence of the heavy metal oxide nanoparticles in the polymer matrix.

It should be mentioned that each measurement was repeated four times, thus the uncertainty was obtained regarding the random and systematic errors related to precision of the electrometer system during the measurement.

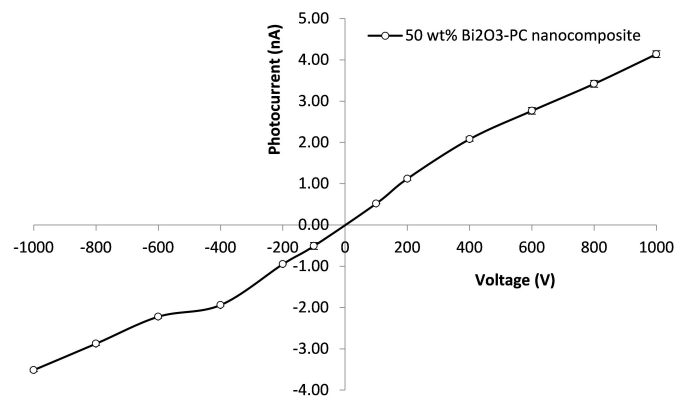


Figure 3: I-V plot of the 50 wt% sample irradiated by Sr-90 at fixed SSD=30 cm and dose rate of 102.436 mSv.h⁻¹, with maximum standard deviation (1 σ) of 3.8%.

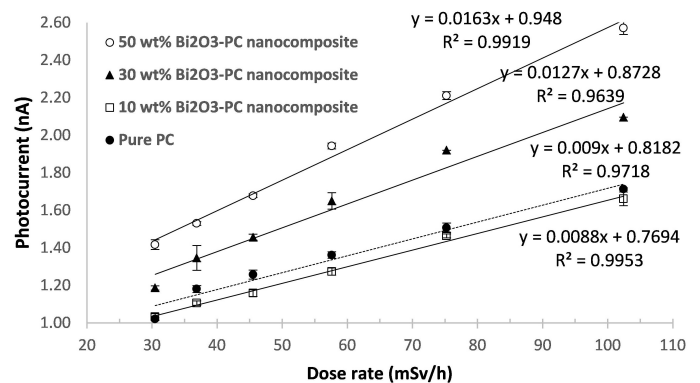


Figure 4: Dosimetry response of 0, 10, 30, and 50 wt% samples irradiated with Sr-90 exhibiting a maximum 1.9% standard deviation (1 σ).

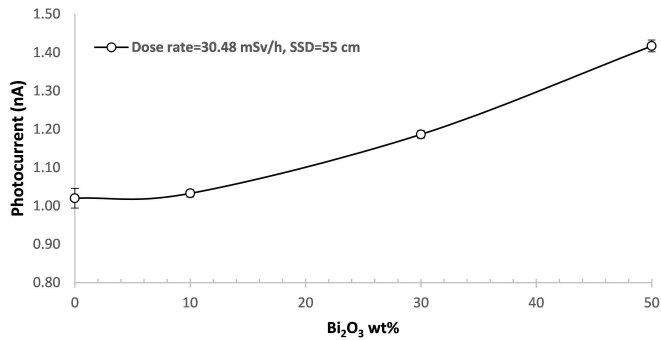


Figure 5: Photocurrent vs. heavy metal oxide nanoparticles wt% irradiated by Sr-90.

Also, as can be seen from Fig. 5, the photocurrent vs. Bi₂O₃ wt% is exhibited. It seems that the dosimeter response until 10 wt% is constant and after that the dosimetry response will be increased significantly.

4 Conclusions

This experimental research studied the effect of reinforcement phase loading on the dosimetry response of a Polycarbonate/Bismuth Oxide nanocomposite. Thus, four loadings of the Bi₂O₃ nanoparticles, namely 0, 10, 30, and 50 wt% were subjected to beta-irradiation using a Sr-90 source. Results showed that increasing the reinforcement phase loading led to increasing the dosimetry response linearly at various dose rates. The I-V plot revealed that there was no saturation in the dosimeter response at voltages ranging from ± 1000 V. Also, the I-V plot showed that the bias polarity exhibits 15.2% discrepancy on the dosimetry response of the nanocomposite material.

This exploration demonstrated that the cost-benefit Polycarbonate/Bismuth Oxide nanocomposite could be considered as a novel real-time beta-ray dosimeter to be used in the radioactive monitoring systems for medical and industrial applications.

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