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Comparative Study of Chloroform and Dichloromethane Synthesized PMMA-Bismuth Nanocomposites for Enhanced X-Ray Attenuation

(Kajian Perbandingan Nanokomposit PMMA-Bismut yang Disintesis Kloroform dan Diklorometana untuk Atenuasi Sinar-X Dipertingkat)

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ABSTRACT

Radiation shielding is a critical component of safety protocols for protection against ionizing radiation. This study investigates the potential of Polymethyl Methacrylate (PMMA) doped with bismuth nanoparticles as a non-toxic, lead-free alternative for radiation shielding in medical diagnostics. PMMA-bismuth nanocomposites were synthesized and evaluated for their attenuation efficacy at diagnostic X-ray energies of 80 and 100 kVp. The influence of synthesis parameters specifically solvent type (chloroform and dichloromethane), solvent mass (2.5 g and 3.0 g), and bismuth nanoparticles (BiNP) loading (1%-5% wt) on shielding performance was systematically examined. Key shielding parameters, including the linear attenuation coefficient (LAC), mass attenuation coefficient (MAC), half-value layer (HVL), and tenth-value layer (TVL) were determined. Results indicate that LAC and MAC values for all samples increased proportionally with bismuth loading, while HVL and TVL values conversely decreased. The optimal shielding performance was observed in samples prepared using 2.5 g of chloroform with 5% BiNP loading at 80 kVp with the peak attenuation reached approximately 4.85 in comparison to 3.88 at 100 kVp for the same samples. These findings demonstrate that PMMA-bismuth nanocomposites are effective for diagnostic X-ray shielding and that synthesis parameters significantly influence their final attenuation properties.

Keywords: Bismuth nanoparticles; poly(methyl methacrylate); radiation shielding

ABSTRAK

Perisai sinaran merupakan komponen penting dalam protokol keselamatan bagi melindungi daripada sinaran pengion. Penyelidikan ini mengkaji potensi Polimetil Metakrilat (PMMA) yang didop dengan nanozarah bismut sebagai alternatif tidak toksik dan bebas plumbum untuk aplikasi perisai sinaran dalam diagnostik perubatan. Nanokomposit PMMA-bismut telah disintesis dan dinilai dari segi keberkesanan pelemahan sinaran pada tenaga sinar-X diagnostik iaitu 80 dan 100 kVp. Pengaruh parameter sintesis khususnya jenis pelarut (kloroform dan diklorometana), jisim pelarut (2.5 g dan 3.0 g) serta kandungan nanozarah bismut (BiNP) (1%-5% berat) terhadap prestasi perisai sinaran telah dikaji secara sistematik. Parameter utama perisai sinaran termasuk pekali pelemahan linear (LAC), pekali pelemahan jisim (MAC), lapisan separuh nilai (HVL) dan lapisan sepersepuluh nilai (TVL) telah ditentukan. Keputusan menunjukkan bahawa nilai LAC dan MAC bagi semua sampel meningkat secara berkadar dengan peningkatan kandungan bismut, manakala nilai HVL dan TVL menurun secara songsang. Prestasi perisai sinaran optimum diperoleh bagi sampel yang disediakan menggunakan 2.5 g kloroform bersama pemuatan BiNP 5% pada tenaga sinar-X 80 kVp dengan puncak pelemahan mencecah 4.85 berbanding 3.88 pada tenaga sinar-X 100 kVp untuk sampel yang sama. Keputusan ini

menunjukkan bahawa nanokomposit PMMA-bismut berkesan untuk perisai sinar-X diagnostik dan parameter sintesis memainkan peranan penting dalam menentukan sifat pelemahan akhir bahan tersebut.

Kata kunci: Nanozarah bismut; perisai sinaran; poli(metil metakrilat)

INTRODUCTION

Ionizing radiation is utilized globally across diverse sectors, including medical diagnostics, nuclear energy, agriculture, and border security (Klein et al. 2009; Mazrani, McHugh & Marsden 2007). While advanced imaging technologies such as accelerator-based scanners enhance national security, they also increase radiological risks for personnel and the public. Inadequate shielding or safety protocols can result in severe health complications, including DNA damage, reduced bone mineral density, and developmental growth retardation (Alsaab & Zeghib 2023a; Charkiewicz & Backstrand 2020). Consequently, adhering to the ALARA (As Low as Reasonably Achievable) principle through effective structural and source shielding is paramount (Johnson & Cember 2017).

Traditionally, lead (Pb) and concrete have been the primary materials for radiation attenuation. Concrete is favored for its cost-effectiveness and mechanical strength, yet its susceptibility to cracking and its immobility limit its versatility (Adlienė, Gilys & Griškonis 2020; Alabsy et al. 2024). Lead offers superior shielding performance but is significantly constrained by its high toxicity and environmental impact. These drawbacks have catalyzed the search for lightweight, non-toxic, and flexible alternatives, particularly within medical environments (AbuAlRoos, Baharul Amin & Zainon 2019).

Polymer composites have emerged as promising candidates for radiation shielding due to their chemical stability, low density, and tunable properties (Sayyed et al. 2022). Polymethyl Methacrylate (PMMA) is particularly noteworthy for its optical transparency, high resistance to corrosion and biocompatibility, making it an ideal matrix for inorganic fillers (Almutery et al. 2026, 2025b; Hazim, Abduljalil & Hashim 2020). To enhance the attenuation capabilities of PMMA, high-atomic number (Z) elements such as Bismuth (Bi, Z=83) are incorporated (Almutery et al. 2025a). Bismuth is a non-toxic alternative to lead that exhibits comparable shielding efficiency across a wide range of photon energies (AbuAlRoos, Baharul Amin & Zainon 2019). The integration of nanoparticles into polymer matrices has improvised radiation protection strategies.

Research indicates that increasing the density of high-Z fillers, specifically bismuth oxide nanoparticles, significantly enhances the absorption coefficient at low-to-medium photon energies (Almutery et al. 2025a). For instance, low density polyethylene (LDPE)/bismuth oxide (Bi_2O_3) composites with a 15% filler loading have been shown to obstruct 80% of X-rays at an effective energy of 47.9 keV (Alshahri et al. 2021). The efficacy of these composites is largely attributed to the nanometric scale of the fillers; their small size and uniform spatial distribution increase the effective electron density and the probability of photon-matter interactions, thereby optimizing shielding performance (Ortaç et al. 2025). Comparative studies between micro and nano-sized fillers consistently demonstrate the superior attenuation properties of nanocomposites (Muthamma et al. 2021). In particular, styrene-butadiene (SR)/Bismuth oxide (Bi_2O_3) nanocomposites have been found to outperform their micro-scale counterparts across various energy spectra, highlighting the critical role of particle size and dispersion in maximizing protection efficiency (Almuqrin et al. 2022). Furthermore, Bi_2O_3 has emerged as a premier non-toxic alternative to lead. Investigations into various hosting matrices, including epoxy and silicone resins, confirm that bismuth-based nanocomposites provide robust absorption of both gamma and X-ray radiation across the energy ranges typically encountered in diagnostic and industrial applications (Alsaab & Zeghib 2023b; Hedaya et al. 2024).

Despite the advantages of PMMA-Bismuth composites, research regarding the optimization of their synthesis parameters remains limited. Existing studies have utilized various fabrication methods, such as UV curing and melt mixing, yet the specific impact of solvent selection and precise filler concentrations on diagnostic X-ray attenuation requires further investigation (Alsaab & Zeghib 2023b). Previously we have investigated the impact of Bi_2O_3 and Magnesium oxide (MgO) nanoparticles on PMMA for the enhancement of gamma radiation (Almutery et al. 2025a). The results suggest that the PMMA doped with Bi_2O_3 are excellent in reducing gamma ray attenuation (Almutery et al. 2025a).

In this study, the performance of PMMA-Bismuth nanoparticles (BiNP) synthesized using two different solvents which is chloroform and dichloromethane (DCM) were evaluated. The research systematically investigates the effects of solvent mass and BiNP loading (1% - 5% wt) on key shielding parameters, including linear attenuation coefficient (LAC), mass attenuation coefficient (MAC), half value layer (HVL) and tenth value layer (TVL) measured using 80 kVp and 100 kVp x-rays energy.

MATERIALS AND METHODS

SYNTHESIS OF PMMA-BISMUTH NANOCOMPOSITES

The main ingredients used are Polymethyl Methacrylate (PMMA) and Bismuth Nanoparticles (BiNP). The PMMA

material was procured from Sigma Aldrich Co., Germany and bismuth nanoparticles were synthesized based on hydrothermal methods according to the previously publish reports (Zulkifli, Razak & Rahman 2017; Zulkifli et al. 2018). The PMMA was transformed into fine powder using an ultra-high-speed electrical grinder. The PMMA was mixed with BiNP at weight percentages or loadings of 1%, 2%, 3%, 4%, and 5%. The PMMA-Bismuth nanocomposites radiation shields were synthesized using two solvents with different weight: chloroform (2.5 g and 3 g) and DCM (2.5 g and 3 g). A very sensitive balance was utilized to weigh both powders accurately. Prior to oven heating the samples, the two powders were thoroughly mixed. The PMMA-Bismuth nanocomposites were synthesized using the melt-mixing method. The melted composite was gently mixed and then heated again to prevent the formation pores. Afterwards, the composites were cold pressed immediately into cylinder molds to form the thin film samples, as shown in Figure 1. The molds were then left to cool to ambient conditions. The thickness of the samples produced approximately about 0.1 mm. Characterization of the samples have been reported in our previous publication (Almutery et al. 2025a).

MEASUREMENT OF X-RAY ATTENUATION

The radiography system (Toshiba, Tokyo, Japan) was utilized in this study to investigate the attenuation properties of the PMMA-Bismuth nanocomposite thin film. The X-ray tube voltages were set at 80 kVp and 100 kVp with 50 mAs. A Cobia Smart R/F type X-ray meter was used to directly obtain the dose readings for all nanocomposites samples. The distance between the X-ray source, the samples and the dosimeter were set at 100 cm, as shown in Figure 1. The exposure dose was taken 5 times for each sample. The average exposure was calculated and then using the exposure value, the attenuation percentage and attenuation parameters were calculated.

X-RAY ATTENUATION PARAMETER AND CALCULATION

The percentage attenuation ratio is calculated using the following equation:

$$Attenuation\ (\%) = \frac{Dose\ without\ shield - Dose\ with\ shield}{Dose\ without\ shield} = \times 100 \quad (1)$$

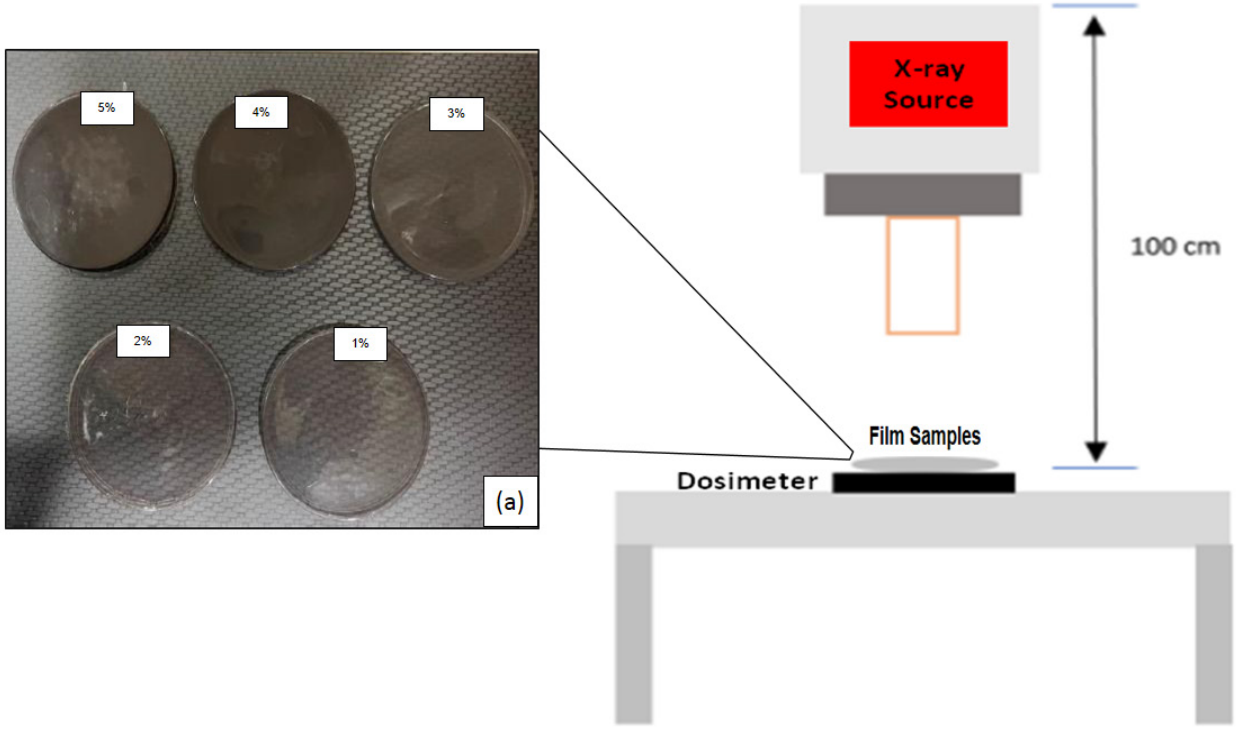


FIGURE 1. The PMMA-Bismuth nanocomposites samples positioned for X-ray attenuation measurement

The linear attenuation coefficient (LAC), mass attenuation coefficient (MAC), half-value layer (HVL) and tenth value layer (TVL) is calculated based on the Equations (2) to (5). The LAC describes the fraction of attenuated incident photons in a monoenergetic beam per unit thickness of a material. LAC is defined as:

$$\mu = -\frac{\ln\left(\frac{I_x}{I_0}\right)}{x}(cm^{-1}) \quad (2)$$

where μ symbolizes linear attenuation coefficient; (x) represents dose measured with nanocomposite shielding; $I(0)$ denotes average delivery dose without nanocomposite shielding; and x is sample thickness.

The MAC measure of how a material attenuates or reduces the intensity of a radiation beam as it passes through it. The formula for MAC is presented in Equation (3).

$$\mu_m = \frac{\mu}{\rho}(cm^2/g) \quad (3)$$

where μ_m denotes mass attenuation coefficient; μ represents linear attenuation coefficient; and ρ symbolizes sample density.

The HVL is the nanocomposite shielding thickness required to reduce the radiation intensity to one half.

$$\text{HVL} = \frac{ln2}{\mu}(cm) \quad (4)$$

The TVL is the nanocomposite shielding thickness required to reduce the radiation intensity to one-tenth of the initial reading.

$$\text{HVL} = \frac{ln10}{\mu}(cm) \quad (5)$$

RESULTS AND DISCUSSION

The densities of samples containing 1% to 5% wt BiNP, synthesized in either chloroform or DCM are summarized in Table 1. While the mass of the samples remained consistent across the different bismuth nanoparticle loadings, the density exhibited slight variations. Specifically, PMMA-bismuth nanocomposites synthesized with chloroform displayed marginally higher density values compared to those prepared with DCM. The density difference between chloroform and DCM are between 1.6% - 24.8% where the largest difference occurred at 5% bismuth loading.

The percentage attenuation of the PMMA-bismuth nanocomposites as a function of bismuth nanoparticle (BiNP) loading for 80 kVp and 100 kVp X-ray energies is illustrated in Figure 2. A clear positive correlation is observed between BiNP loading (0% to 5% wt) and the attenuation percentage across all samples. This enhancement is attributed to the high atomic number (Z = 83) of bismuth, which increases the probability of photoelectric interactions within the composite matrix. As the concentration of BiNPs increases, the effective atomic number (Z) and the density of the material rise, resulting in more frequent photon matter interactions and superior shielding efficiency.

The results also show that the choice of solvent and its corresponding mass significantly influenced the shielding performance. Samples synthesized with chloroform consistently exhibited higher attenuation percentages compared to those prepared with DCM. The 2.5 g chloroform samples showed the highest attenuation values at both 80 kVp and 100 kVp. The mass discrepancy also can likely be linked to the differences in

TABLE 1. Density values of solvents used for synthesis of PMMA-Bismuth nanocomposites

Bismuth loading (%)	Solvent type			
	Chloroform		Dichloromethane	
	2.5	3.0	2.5	3.0
	Density (g/cm^3)			
0	1.18 ±0.06	1.20 ±0.04	1.14 ±0.08	1.02 ±0.12
1	1.32 ±0.06	1.22 ±0.04	1.18 ±0.08	1.34 ±0.12
2	1.28 ±0.06	1.26 ±0.04	1.16 ±0.08	1.20 ±0.12
3	1.30 ±0.06	1.24 ±0.04	1.06 ±0.08	1.02 ±0.12
4	1.26 ±0.06	1.32 ±0.04	1.24 ±0.08	1.18 ±0.12
5	1.36 ±0.06	1.26 ±0.04	1.06 ±0.08	1.20 ±0.12

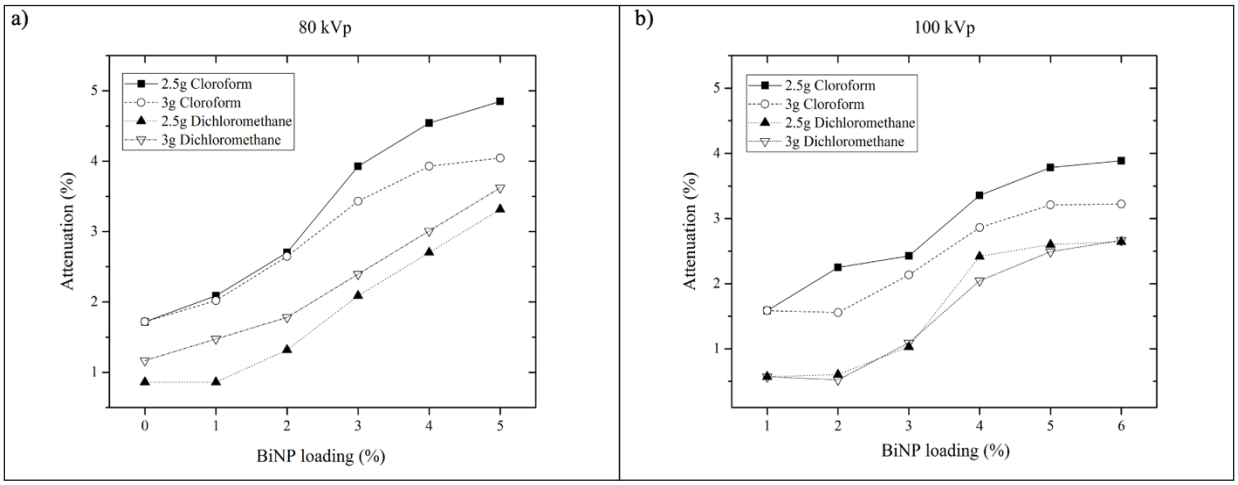


FIGURE 2. The percentage attenuation of PMMA-Bismuth nanocomposite of different BiNP loading percentage for a) 80 kVp and b) 100 kVp energies

solvent evaporation rates and their impact on the polymer chain arrangement. The slightly higher density observed in chloroform based samples suggests a more compact and uniform distribution of BiNPs within the PMMA matrix, which minimizes void spaces and maximizes X-ray interception. The results primarily indicate that the 2.5 g chloroform solvent casting method provides the most favorable conditions for creating high-performance shielding films. At 5% BiNP loading and 80 kVp, this configuration reached a peak attenuation of nearly 5%, outperforming the DCM based counterparts. These findings underscore that while filler concentration is the primary driver of attenuation, synthesis parameters specifically solvent type play a critical role in optimizing the physical microstructure for radiation protection.

Another important parameter is the impact of X-ray energy (kVp). A comparison between the 80 kVp and 100 kVp datasets shows a decrease in overall attenuation percentage as the X-ray energy increases. This trend is consistent with the physical principles of X-ray attenuation, where the mass attenuation coefficient typically decreases with increasing photon energy in the diagnostic range, away from the absorption edge. At higher energies (100 kVp), photons possess greater penetrating power, requiring a higher density or thickness of bismuth to achieve the same shielding effect observed at 80 kVp. This is in agreement with previous reported results that demonstrates the effectiveness of bismuth doped PMMA increasing attenuation ratio particularly at energy range of 20 to 40 kVp (Bawazeer et al. 2025). The effectiveness of PMMA-Bismuth nanocomposites as radiation shielding is evaluated by analyzing the x-ray attenuation values. The obtained results of LAC, MAC, HVL and TVL for 80 kVp x-ray have been presented in Figure 3.

The experimental data shows a strong positive correlation between the LAC and MAC. Both LAC and MAC increase linearly as the BiNP loading increases from 1% to 5% wt. This trend directly mirrors Figure 2 where higher filler concentrations resulted in greater X-ray obstruction. Consistent with the attenuation percentage results, samples synthesized with 2.5 g chloroform consistently show the highest LAC and MAC values. This confirms that chloroform promotes a more effective distribution of BiNPs, leading to a higher probability of photon interaction per unit path length.

Meanwhile, the HVL and TVL value represent the thickness of the material required to reduce the X-ray intensity to 50% and 10%, respectively, show inverse relationship. As the BiNP loading increases, both HVL and TVL values decrease significantly. This inverse relationship is the mathematical consequence of the rising LAC values. The sharp decline in TVL, particularly for the Chloroform based samples, indicates that adding small amounts of bismuth significantly reduces the material thickness needed for effective protection. This correlates with the attenuation percentage spikes seen at 80 kVp, proving that the nanocomposite becomes a much denser radiation barrier as loading increases. Studies also have highlighted the effectiveness of Bi_2O_3 as a high-Z additive, with higher nanoparticle concentrations significantly enhanced photon shielding capabilities (Alsaab & Zeghib 2023b; Marshall et al. 2025).

Similar trend was also observed for 100 kVp measurement as shown in Figure 4. Comparative analysis of shielding performance between 80 kVp and 100 kVp show the LAC and MAC exhibit a clear dependence on both the bismuth loading and the incident X-ray energy. As X-ray energy increases from

80 kVp to 100 kVp, a general decrease in both LAC and MAC values is observed for all samples. For example, the maximum LAC for the 2.5 g chloroform sample drops from approximately 4.97 at 80 kVp to roughly 3.97 at 100 kVp. At both energy levels, LAC and MAC increase linearly with BiNP loading. This confirms that the addition of high-Z bismuth nanoparticles consistently enhances the interaction probability via the photoelectric effect, though the efficiency is slightly lower at higher energies (100 kVp) due to increase photon penetration.

The HVL and TVL data reflect the physical thickness required to achieve specific protection levels. The HVL and TVL values are significantly higher at 100 kVp than at 80 kVp. At 80 kVp, the TVL for 3.0 DCM at 1% is roughly 1.55 and at 100 kVp, this value increases to nearly 4.39. Despite the higher penetration at 100 kVp, increasing the bismuth loading remains highly effective. The decline in TVL and HVL is more pronounced at 100 kVp, suggesting that higher bismuth concentrations are even more critical for maintaining protection as the X-ray energy increases. The results on percentage attenuation directly support these attenuation coefficient findings. At 80 kVp, the peak attenuation reached approximately 4.85, whereas at 100 kVp, it peaked at roughly 3.88 for the same 5% BiNP loading (2.5 g chloroform). Chloroform (2.5 g) remains the superior solvent across both energy ranges. The gap between chloroform and DCM performance is slightly narrower at 100 kVp than at 80 kVp, indicating that the synthesis dependent density variations have a more significant impact on lower energy X-ray interactions.

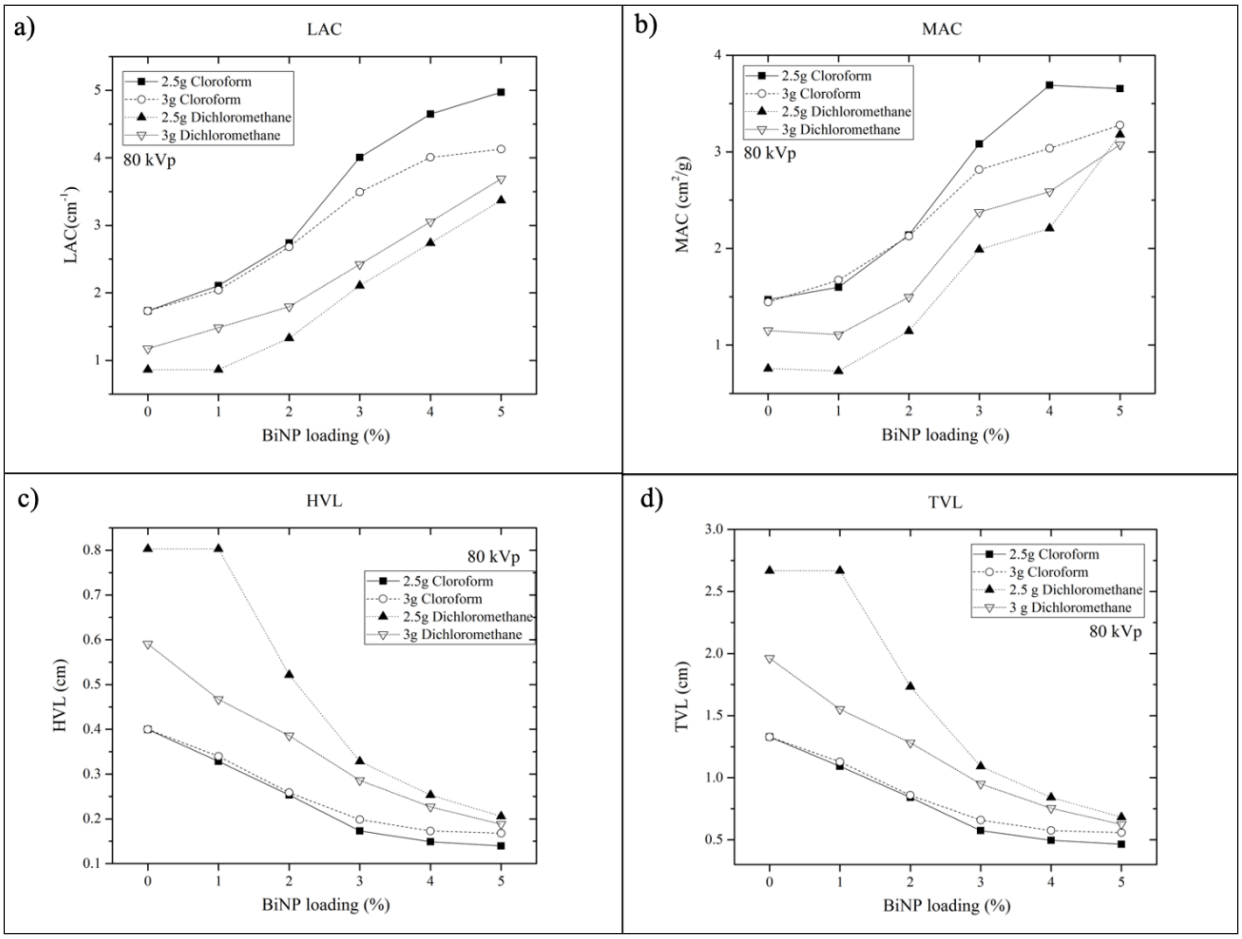


FIGURE 3. The a) LAC, b) MAC, c) HVL and d) TVL value for the PMMA-Bismuth nanocomposites at 80 kVp

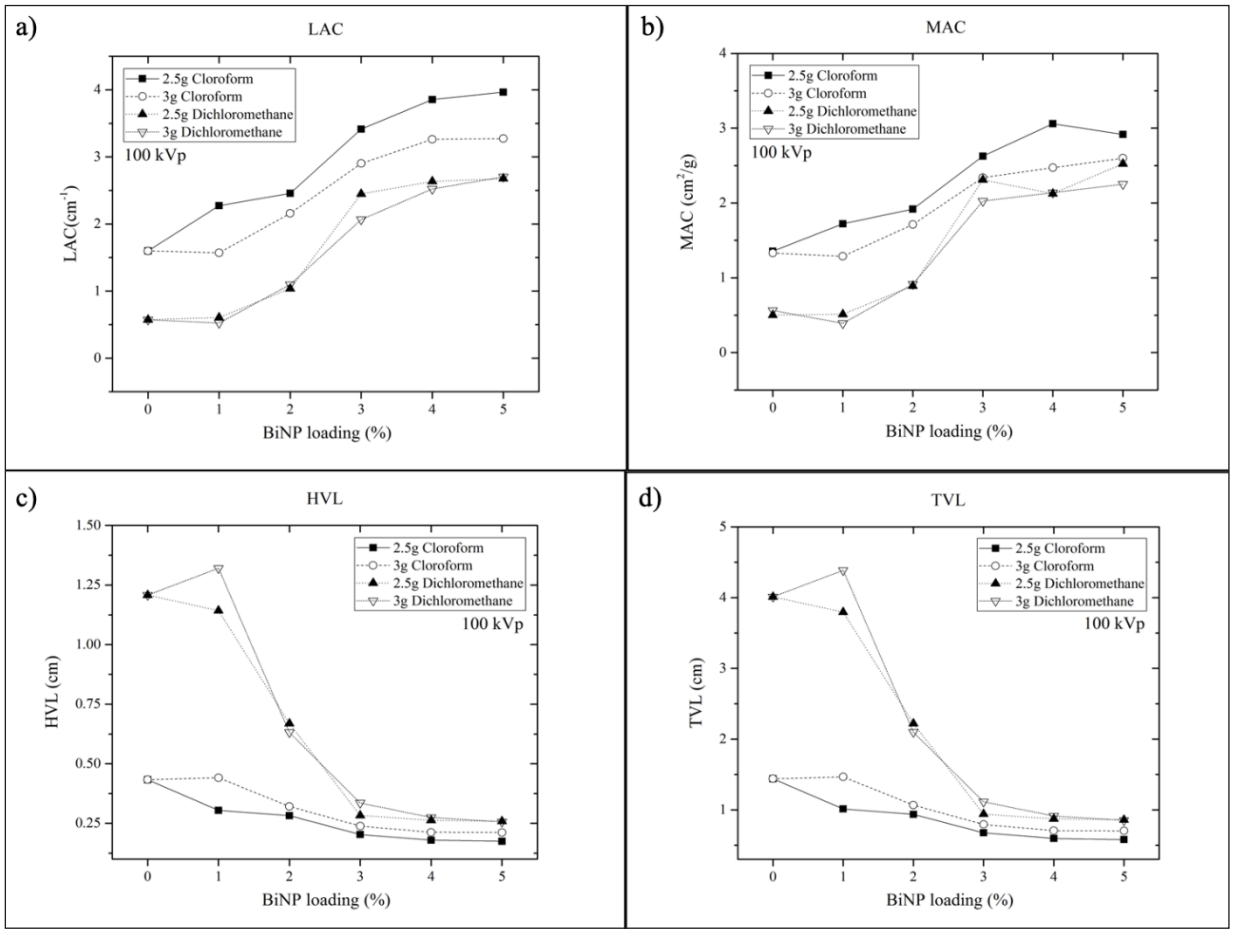


FIGURE 4. The a) LAC, b) MAC, c) HVL and d) TVL value for the PMMA-Bismuth nanocomposites at 100 kVp

CONCLUSION

This study investigated the influence of solvent type (chloroform and DCM), solvent mass (2.5 g and 3.0 g), bismuth loading (1%-5 wt%), and X-ray energy (80 kVp and 100 kVp) on the radiation attenuation performance of PMMA/BiNP shields as a non-toxic alternative to conventional shielding materials. Particular emphasis was placed on the role of solvent selection in determining shielding efficiency. The radiation attenuation parameters showed that the LAC and MAC increased with increasing bismuth loading for both X-ray energies, while the HVL and TVL decreased accordingly. Notably, films prepared using chloroform exhibited superior attenuation performance compared to those synthesized with DCM, indicating that solvent type significantly influences nanoparticle dispersion and shielding effectiveness. The highest LAC and MAC values were achieved using 2.5 g of chloroform at 80 kVp, accompanied by the lowest HVL and TVL values. These results demonstrate that PMMA–BiNP nanocomposites fabricated with 2.5 g chloroform, particularly at 5% bismuth loading, provide enhanced attenuation of diagnostic X-rays, confirming their strong potential as efficient and lead-free radiation shielding materials.

REFERENCES

AbuAlRoos, N.J., Baharul Amin, N.A. & Zainon, R. 2019. Conventional and new lead-free radiation shielding materials for radiation protection in nuclear medicine: A review. *Radiation Physics and Chemistry* 165: 108439.

Adlienė, D., Gilys, L. & Griškonis, E. 2020. Development and characterization of new tungsten and tantalum containing composites for radiation shielding in medicine. *Nuclear Instruments & Methods in Physics Research Section B-beam Interactions with Materials and Atoms* 467: 21-26.

Alabsy, M.T., Abbas, M.I., El-Khatib, A.Y. & El-Khatib, A.M. 2024. Attenuation properties of poly methyl methacrylate reinforced with micro/nano ZrO_2 as gamma-ray shields. *Scientific Reports* 14(1): 1279.

Almuqrin, A.H., Sayyed, M.I., Elsafi, M. & Khandaker, M.U. 2022. Comparison of radiation shielding ability of Bi_2O_3 micro and nanoparticles for radiation shields. *Radiation Physics and Chemistry* 200: 110170.

Almutery, A., Rahman, W.N., Mohamed, F., Hua, C.C., Razak, K.A., Rashid, R.A., Rilwan, U., Sayyed, M.I. & Maghrbi, Y. 2025a. Enhancing the gamma radiation shielding performance: The impact of Bi_2O_3 and MgO nanoparticles on PMMA. *Radiation Physics and Chemistry* 237: 113070.

Almutery, A.A., Rahman, W.N., Mohamed, F., Hua, C.C. & Ab Rashid, R. 2025b. SiO_2-modified lead-free poly (methyl methacrylate) (PMMA) transparent nanocomposites: Structural, optical, and radiation shielding enhancements. *The European Physical Journal Plus* 140: 1258.

Almutery, A.A., Mohamed, F., Hua, C.C., Rahman W.N. & Al'-Kamali, M.F.S.H. 2026. Fabrication and optimization of the morphological, structural, and optical features of PMMA/MgO as promising nanocomposites for radiation shielding application: An experimental approach. *Applied Radiation and Isotopes* 231: 112525.

Alsaab, A.H. & Zeghib, S. 2023a. Study of prepared lead-free polymer nanocomposites for X- and gamma-ray shielding in healthcare applications. *Polymers* 15(9): 2142.

Alsaab, A.H. & Zeghib, S. 2023b. Analysis of X-ray and gamma ray shielding performance of prepared polymer micro-composites. *Journal of Radiation Research and Applied Sciences* 16(4): 100708.

Alshahri, S., Alsuhybani, M., Alosime, E., Almurayshid, M., Alrwais, A. & Alotaibi, S. 2021. LDPE/Bismuth oxide nanocomposite: Preparation, characterization and application in X-ray shielding. *Polymers* 13(18): 3081.

Bawazeer, O., Albakri, H., Makkawi, K., Aga, Z.B., Alomari, A., Adil, S.F., Algethami, M., Assiri, N., Alsubhi, A., Qutub, M., Alotaibi, E., Khan, S.A., Althagafy, K., Al-Qahtani, S., Althomali, M. & Ajlouni, A.W. 2025. Evaluation of X-ray shielding performance of Bi/PMMA andBi/PMMA–TiO_2/PMMA nanocomposites. *Radiation Physics and Chemistry* 231: 112596.

Charkiewicz, A.E. & Backstrand, J.R. 2020. Lead toxicity and pollution in Poland. *International Journal of Environmental Research and Public Health* 17(12): 4385.

Hazim, A., Abduljalil, H.M. & Hashim, A. 2020. Analysis of structural and electronic properties of novel (PMMA/Al_2O_3, PMMA/Al_2O_3-Ag, PMMA/ZrO_2, PMMA/ZrO_2-Ag, PMMA-Ag) Nanocomposites for low cost electronics and optics applications. *Transactions on Electrical and Electronic Materials* 21(1): 48-67.

Hedaya, A., Elsafi, M., Al-Saleh, W.M. & Saleh, I.H. 2024. Effect of Bi_2O_3 particle size on the radiation-shielding performance of free-lead epoxide materials against ionizing radiation. *Polymers* 16(15): 2125.

Johnson, T.E. & Cember, H. 2017. *Introduction to Health Physics.* Fifth Edition. McGraw-Hill Education.

Klein, L.W., Miller, D.L., Balter, S., Laskey, W., Haines, D., Norbash, A., Mauro, M.A. & Goldstein, J.A. 2009. Occupational health hazards in the interventional laboratory: Time for a safer environment. *Radiology* 250(2): 538-544.

Marshall, S.K., Boonpeng, K., Buapud, N., Chimhashat, S., Chuaymuang, J., Kwandee, P. & Songphum, N. 2025. Bismuth oxide nanoparticle-enhanced poly(methyl methacrylate) composites for I-131 radiation shielding: A combined simulation and experimental investigation. *Polymers* 17(5): 590.

Mazrani, W., McHugh, K. & Marsden, P.J. 2007. The radiation burden of radiological investigations. *Archives of Disease in Childhood* 92(12): 1127-1131.

Muthamma, M.V., Prabhu, S., Bubbly, S.G. & Gudennavar, S.B. 2021. Micro and nano Bi_2O_3 filled epoxy composites: Thermal, mechanical and γ-ray attenuation properties. *Applied Radiation and Isotopes* 174: 109780.

Ortaç, B., Baskan, T., Mutlu, S., Yilmaz, S.S. & Yilmaz, A.H. 2025. Gamma radiation shielding efficiency of cross-linked polystyrene-b-polyethyleneglycol block copolymer nanocomposites doped arsenic (III) oxide and boron nitride nanoparticles. *Polymers* 17(24): 3330.

Sayyed, M.I., Hanan Al-Ghamdi, Almuqrin, A.H., Yasmin, S. & Elsafi, M. 2022. A study on the gamma radiation protection effectiveness of nano/micro-MgO-reinforced novel silicon rubber for medical applications. *Polymers* 14(14): 2867.

Zulkifli, Z.A., Razak, K.A. & Rahman, W.N.W.A. 2017. Effect of hydrothermal reaction time on size of bismuth oxide nanoparticles synthesized via hydrothermal method. *AIP Conference Proceedings* 1901: 020011.

Zulkifli, Z.A., Razak, K.A., Rahman, W.N.W.A. & Abidin, S.Z. 2018. Synthesis and characterisation of bismuth oxide nanoparticles using hydrothermal method: The effect of reactant concentrations and application in radiotherapy. *Journal of Physics: Conference Series* 1082: 012103.