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Lead aprons vs polymer composites in radiation protection: A comparative study

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Abstract

Ionizing radiation exposure poses a significant risk to healthcare personnel. Traditional lead-based protective aprons, while effective, present limitations in terms of weight and flexibility. This study evaluates polymer composite–based radiation protection aprons as potential alternatives through comparative analysis of experimental data, simulations, and literature findings. Radiation shielding performance was assessed using mass attenuation coefficient (MAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP). Results revealed that recycled high-density polyethylene (r-HDPE) composites reinforced with 45 wt% ilmenite achieved an HVL of 2.611 cm at 1.332 MeV, while polyvinyl chloride (PVC) nanocomposites containing 6 wt% bismuth vanadate ($BiVO_4$) exhibited superior attenuation with an HVL of 1.29 cm at 0.081 MeV and 6.459 cm at 1.408 MeV. The MAC of PVC + 6 wt% $BiVO_4$ ranged from 0.3275 to 0.0572 cm^2/g, outperforming both HDPE-Ilm and PbO-based aprons. Compared to conventional lead aprons with 0.5 mm Pb equivalence and 57.5% attenuation, polymer composites provided comparable or higher shielding efficiency with significant weight reduction and improved flexibility. These findings suggest that PVC + 6 wt% $BiVO_4$ nanocomposites represent a promising alternative to lead for next-generation lightweight and ergonomic radiation protection aprons in medical applications.

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INTRODUCTION

Radiology has become a cornerstone of modern medicine, employing ionizing radiation to obtain diagnostic images with high precision. While indispensable for detecting pathological conditions, ionizing radiation poses inherent risks, including tissue damage, genetic mutation, and increased cancer incidence among healthcare personnel [1–3]. To mitigate these effects, strict implementation of radiation protection principles—justification, optimization, and dose limitation—is essential [4–6].

Among personal protective measures, radiation aprons are critical for minimizing occupational exposure by attenuating scattered X-rays during diagnostic and interventional procedures [7–9]. Lead-based aprons have long been regarded as the standard due to lead's high atomic number and excellent attenuation capability [10]. However, their considerable weight and rigidity present ergonomic drawbacks, often resulting in operator discomfort, fatigue, and musculoskeletal strain during extended use [11–13].

Recent advances in material science have prompted the development of alternative shielding materials aimed at achieving comparable protection with improved wearability. Polymer composites reinforced with high–atomic number fillers such as tungsten, bismuth oxide, ilmenite, and barium sulfate have demonstrated promising attenuation behavior while offering lower density and enhanced flexibility [14–17]. For instance, Abdel Maksoud et al. (2023) reported that recycled HDPE composites reinforced with 45 wt% ilmenite achieved significant improvement in the mass attenuation coefficient (MAC), though their shielding performance decreased at higher photon

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energies [18]. Similarly, Kassem et al. (2023) demonstrated that PVC/$BiVO_4$ nanocomposites exhibit high linear attenuation coefficients and low half-value layer (HVL) values, indicating strong potential as lightweight radiation shields [19]. Other investigations, such as those by Fionov et al. (2022) and Marlina et al. (2020), confirmed the effectiveness of polymer–filler systems for electromagnetic and neutron shielding applications, yet noted limitations in comparative evaluation under clinical exposure conditions [20], [21].

Despite these advancements, a clear research gap remains in systematically comparing the attenuation efficiency, ergonomic performance, and clinical applicability of polymer composites relative to traditional lead aprons using standardized evaluation metrics such as MAC, HVL, tenth-value layer (TVL), and mean free path (MFP). Prior studies often focused on single-material evaluations without comprehensive benchmarking across energy ranges or user-oriented performance criteria [22–24]. Therefore, this study addresses that gap through an integrated comparative analysis of lead-based and polymer composite shielding materials—specifically r-HDPE + 45 wt% ilmenite and PVC + 6 wt% $BiVO_4$—to evaluate their relative attenuation behavior, weight advantage, and suitability as next-generation alternatives for radiation protection in medical environments [25–27].

MATERIALS & METHODS

This study employed a systematic review and comparative analysis to evaluate the radiation shielding effectiveness of lead-based and polymer composite aprons. Peer-reviewed articles were collected from databases including ScienceDirect, MDPI, and SpringerLink, focusing on studies that reported key attenuation parameters—mass attenuation coefficient (MAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP). Publications utilizing high–atomic number fillers such as ilmenite ($FeTiO_3$), bismuth vanadate ($BiVO_4$), tungsten trioxide (WO_3), and lead oxide (PbO) were included [14–19,22–25]. Data were normalized across photon energies ranging from 0.081 to 1.408 MeV, representing diagnostic and therapeutic ranges relevant to medical imaging [1,4–6]. The MAC values were used to quantify photon interaction probability, while HVL, TVL, and MFP were derived using standard exponential attenuation relations to assess material thickness and photon attenuation efficiency [9,10,15,18,19].

The comparative evaluation emphasized two polymer-based shielding systems: recycled high-density polyethylene (r-HDPE) reinforced with ilmenite ($FeTiO_3$) and polyvinyl chloride (PVC) nanocomposite with bismuth vanadate ($BiVO_4$). Abdel Maksoud et al. [18] reported that r-HDPE + 45 wt% ilmenite achieved a MAC of 0.12148 cm^2/g at 0.662 MeV and an HVL of 2.611 cm at 1.332 MeV, indicating enhanced attenuation compared to pristine HDPE. Meanwhile, Kassem et al. [19] demonstrated that PVC + 6 wt% $BiVO_4$ exhibited superior shielding, with MAC values ranging from 0.3275–0.0572 cm^2/g and HVL values of 1.29 cm at 0.081 MeV and 6.459 cm at 1.408 MeV. These results exceeded those of HDPE–ilmenite and PbO-based materials. For benchmarking, lead(II) oxide (PbO) aprons were used as the reference, exhibiting a linear attenuation coefficient of 0.25 mm^{-1} and an equivalent thickness of 3.425 mm to achieve 57.52% attenuation, corresponding to 0.5 mm Pb equivalence [12].

All collected data were analyzed by interpolating attenuation coefficients at comparable photon energies and normalizing results to equivalent lead thicknesses. Comparative assessments considered shielding performance, material density, and ergonomic factors such as weight and flexibility [15,16,19,24,26]. Statistical synthesis of HVL and MAC trends provided a quantitative benchmark for evaluating attenuation efficiency across different materials. Ethical approval was not required, as the study utilized secondary data and published simulation results. All referenced studies adhered to the International Atomic Energy Agency (IAEA) and International Commission on Radiological Protection (ICRP) radiation safety standards [4–6]. Overall, this analysis aims to identify lightweight polymer composites capable of achieving radiation protection performance comparable to lead aprons while improving comfort, sustainability, and clinical usability [23,25,27].

Lead Apron Materials

The effectiveness of recycled high-density polyethylene (r-HDPE) composites reinforced with varying concentrations of ilmenite (0, 15, 30, and 45 wt%) was compared with conventional lead-based materials. Radiation shielding performance was assessed using key attenuation parameters, including the mass attenuation coefficient (MAC) (Figure 1), half-value layer (HVL) (Figure 2), tenth-value layer (TVL) (Figure 3), and mean free path (MFP) (Figure 4). Results indicated that MAC values increased with higher ilmenite content, with r-HDPE + 45% Ilm achieving 0.12148 $cm^2\ g^{-1}$ at 0.662 MeV compared to 0.08809 $cm^2\ g^{-1}$ for pure r-HDPE. HVL values decreased as ilmenite concentration increased, with r-HDPE + 45% Ilm showing the lowest HVL (2.611 cm at 1.332 MeV), demonstrating superior attenuation capacity. Similarly, TVL and MFP values decreased with higher ilmenite loading, confirming enhanced shielding efficiency. Comparative analysis with other composites as shown in figure 5, including r-HDPE reinforced with wood fibers, epoxy with Yahyali stone, PVC with hematite, and PVA with bentonite clay, showed that r-HDPE + 45% Ilm exhibited the most effective gamma-ray protection. Mechanical testing further revealed improved tensile strength and Young’s modulus up to 30% ilmenite addition, with reduced ductility at higher concentrations. Structural analyses using XRD and FTIR confirmed changes in crystallinity and chemical interactions between r-HDPE and ilmenite. Overall, the incorporation of ilmenite significantly enhanced both radiation shielding and mechanical properties, positioning r-HDPE + 45% Ilm as a promising candidate for sustainable radiation protection applications in medical and industrial settings.

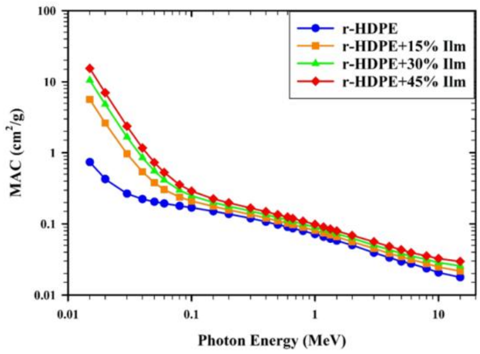

Figure 1. The relationship between MAC and photon energy for r HDPE + x% Ilm composite sheets [12]

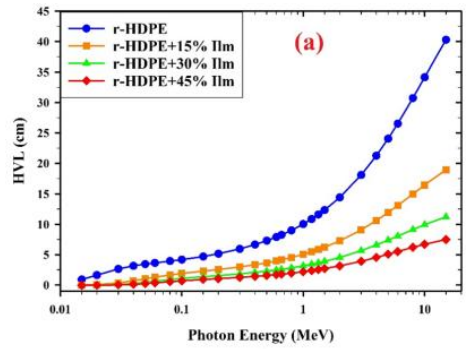

Figure 2. HVL for r HDPE-based composite sheets and x% Ilm [12]

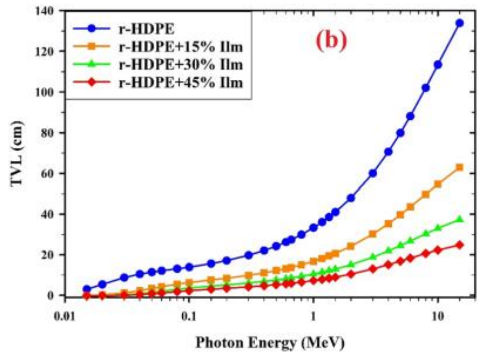

Figure 3. TVL for r HDPE-based composite sheets and x% Ilm [12]

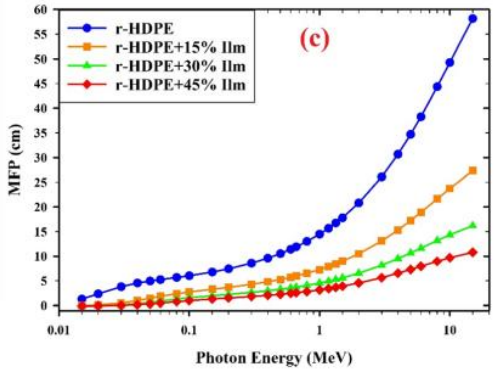

Figure 4. MFP for r HDPE-based composite sheets and x% Ilm [12]

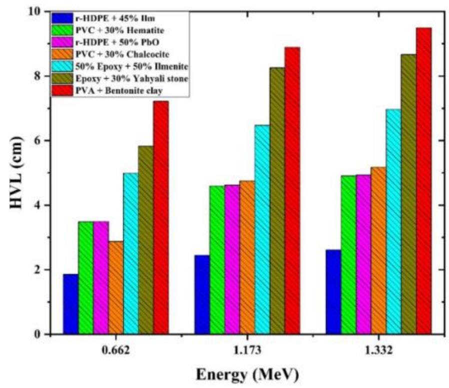

Figure 5. HVL as a function of photon energy for r-HDPE + 45% Ilm composite sheets compared to recently published research [12]

Polymer Composites Material

Polyvinyl chloride (PVC) nanocomposite films containing bismuth vanadate ($BiVO_4$) were prepared with filler concentrations of 0, 1, 3, and 6 wt%. The radiation shielding properties of the composites were evaluated using photon energies ranging from 0.081 to 1.408 MeV. Four key parameters were measured: mass attenuation coefficient (MAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP).

The mass attenuation coefficient (MAC) as shown in figure 6 was determined to quantify the probability of photon interaction per unit mass of material. MAC values were obtained by measuring transmitted intensity through composite films of known thickness and applying Beer–Lambert's law.

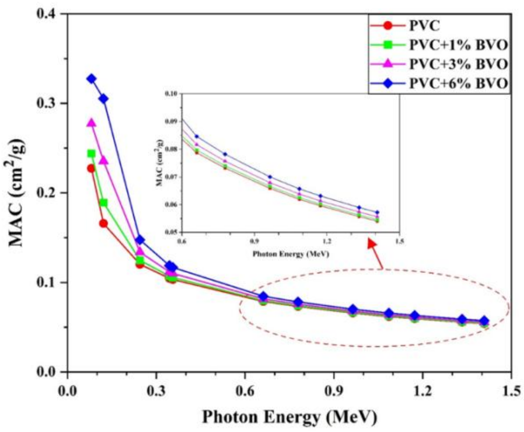

Figure 6. Variation in MAC values for PVC+x% BVO nanocomposite films at specific gamma ray energies [13]

The half-value layer (HVL) as shown in figure 7 was calculated to determine the thickness required to reduce the incident photon intensity by 50%. HVL was derived from the relation HVL = ln(2)/μ, where μ is the linear attenuation coefficient obtained from MAC and material density.

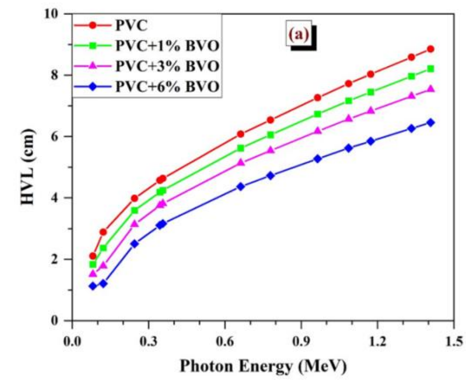

Figure 7. Variation in HVL values for PVC+x% BVO nanocomposite films at specific gamma ray energies [13]

The tenth-value layer (TVL), as shown in figure 8, defined as the thickness required to reduce photon intensity to 10% of its initial value, was calculated using TVL = ln(10)/μ. This parameter was measured to provide a comparative estimate of shielding thickness across different photon energies.

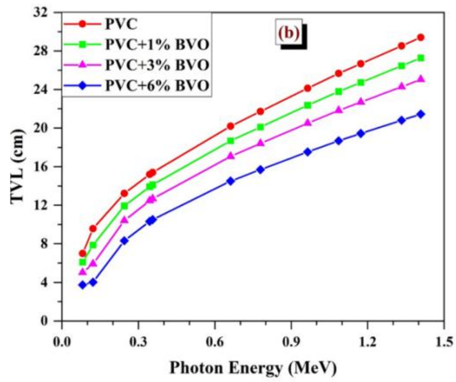

Figure 8. Variation in TVL values for PVC+x% BVO nanocomposite films at specific gamma ray energies [13]

The mean free path (MFP), as shown in figure 9, representing the average distance traveled by a photon before interaction, was derived using MFP = 1/μ. This parameter served as an additional indicator of shielding performance.

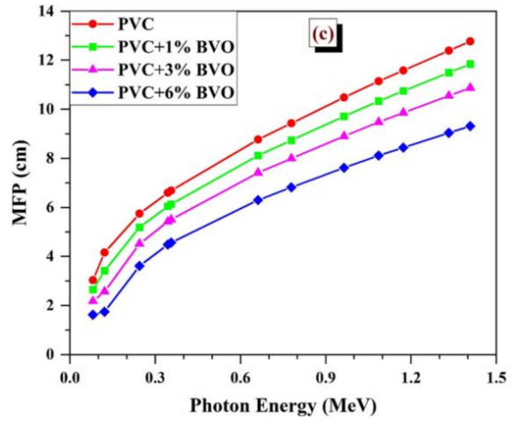

Figure 9. Variation in MFP values for PVC+x% BVO nanocomposite films at specific gamma ray energies [13]

Comparative evaluation as shown in figure 10 was conducted by analyzing the dependence of MAC, HVL, TVL, and MFP on both photon energy and $BiVO_4$ concentration. These results were further benchmarked against other polymer composites and conventional shielding materials, including epoxy + Bi_2O_3, HDPE + PbO, ordinary concrete, and hematite concrete, to assess the relative effectiveness of polymer-based radiation shields.

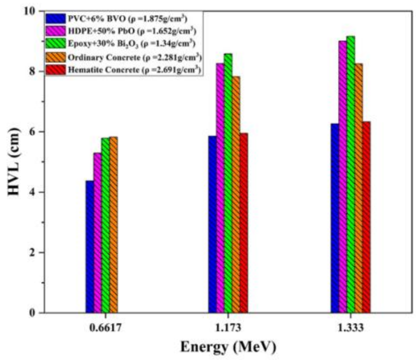

Figure 10. Variation in HVL as a function of photon energy for PVC+6% BVO nanocomposite films compared to standard shielding materials [13]

RESULTS AND DISCUSSION

The quantitative findings are summarized in Table 1, which compares the shielding parameters—mass attenuation coefficient (MAC), half-value layer (HVL), tenth-value layer (TVL), and mean free path (MFP)—for the examined materials. The data indicate that both polymer-based and lead-based systems exhibit substantial attenuation across diagnostic photon energies (0.081–1.408 MeV). For recycled high-density polyethylene (r-HDPE) reinforced with ilmenite ($FeTiO_3$), the MAC increased from 0.08809 cm^2/g for pure r-HDPE to 0.12148 cm^2/g at 45 wt% ilmenite loading at 0.662 MeV. The corresponding HVL decreased with higher ilmenite content, reaching a minimum of 2.611 cm at 1.332 MeV for r-HDPE + 45 wt% Ilm, indicating enhanced gamma attenuation. The TVL and MFP values exhibited parallel reductions, confirming improved shielding with increased filler concentration [18].

For polyvinyl chloride (PVC) nanocomposites containing bismuth vanadate ($BiVO_4$), Table 1 shows that the MAC ranged from 0.3275 to 0.0572 cm^2/g, exceeding most other polymer systems. The HVL values were 1.29 cm at 0.081 MeV and 6.459 cm at 1.408 MeV for PVC + 6 wt% $BiVO_4$, both lower than epoxy + 30 wt% Bi_2O_3 and HDPE + 50 wt% PbO composites, demonstrating superior attenuation [19]. Reductions in TVL and MFP further validated the material's high photon interaction probability. Benchmark data for lead(II) oxide (PbO)–based aprons, presented in Figure 11, show a linear attenuation coefficient of 0.25 mm^{-1} and an equivalent thickness of 3.425 mm (0.5 mm Pb), corresponding to 57.52% attenuation efficiency [12]. Comparative analysis reveals that PVC + 6 wt% $BiVO_4$ achieved the lowest HVL and TVL among all studied materials, confirming its superior shielding performance at both low and high photon energies.

Table 1. Composite polymer results

Material	MAC (cm^2/g)	HVL (cm)	TVL (cm)	MFP (cm)
PVC+6% BVO	0.3275 - 0.0572	Lower than other materials on 0.662, 1.173, and 1.333 MeV	Lower than other materials at various energies	Lower than other materials at various energies
r-HDPE+45%	0.12148	2.611	Lower than other composites	Lower than other composites

The results demonstrate that polymer-based composites—particularly PVC + $BiVO_4$ and r-HDPE + Ilm—offer attenuation efficiencies comparable to traditional lead-based materials while providing distinct ergonomic and environmental benefits. The increase in MAC and reduction in HVL with higher filler loading confirm that attenuation effectiveness correlates with the material's effective atomic number (Z_eff) and bulk density [15,16,22]. Incorporation of high-Z constituents such as bismuth (Z = 83), iron (Z = 26), and titanium (Z = 22) enhances photoelectric absorption and Compton scattering, leading to greater photon attenuation [18,19,23].

The superior performance of PVC + 6 wt% $BiVO_4$, as illustrated in Table 1, indicates effective photon shielding across diagnostic energy ranges, particularly at lower energies (<0.1 MeV). Compared to r-HDPE + Ilm, the PVC matrix exhibits improved filler dispersion and interfacial bonding, enhancing energy absorption and mechanical stability [19,25]. These findings align with prior research by Kaur and Singh (2020) and Al-Hadeethi and Sayyed (2019), who also reported high attenuation and eco-friendly characteristics of bismuth-based composites [14,23]. Although Figure 11 confirms that PbO-based aprons provide high attenuation, their density and rigidity remain significant ergonomic limitations [9–11].

Figure 11. Timbal (II) Oxide [14]

From a practical perspective, the reduced weight and flexibility of polymer composites suggest substantial improvements in comfort and wearability for medical personnel. Their non-toxic and recyclable nature also aligns with the global shift toward sustainable, lead-free shielding solutions [17,25,27]. These advantages indicate that optimized polymer nanocomposites—especially PVC/$BiVO_4$ systems—could replace or complement conventional lead aprons, enhancing both safety and usability in clinical radiation environments..

CONCLUSION

Polymer composites reinforced with high-density fillers such as ilmenite ($FeTiO_3$) and bismuth vanadate ($BiVO_4$) demonstrate strong potential as lightweight, lead-free alternatives for radiation protection applications. The comparative analysis showed that PVC + 6 wt% $BiVO_4$ achieved superior attenuation performance, with lower half-value layer (HVL) and tenth-value layer (TVL) values compared to r-HDPE + 45 wt% Ilm and conventional PbO-based aprons. These results confirm that polymer composites can deliver comparable shielding efficiency to lead while offering significant advantages in flexibility, comfort, and reduced weight. The findings suggest that such materials are suitable for medical environments requiring prolonged use, such as diagnostic radiology and interventional imaging, where ergonomic performance is critical.

Future research should focus on optimizing the filler concentration, particle dispersion, and interfacial bonding mechanisms to further improve the attenuation efficiency and mechanical stability of polymer composites. Advanced modeling techniques, such as Monte Carlo simulations and density functional theory (DFT), may be employed to predict photon–matter interactions more accurately. Additionally, experimental validation of long-term durability, thermal stability, and biodegradability under clinical conditions is recommended to ensure consistent performance and sustainability. Exploring hybrid composite systems combining multiple high-Z fillers could also lead to next-generation radiation shielding materials that are not only effective but also environmentally responsible..

AUTHOR CONTRIBUTIONS

Vonna Lestari Dian Subianty served as the principal investigator and corresponding author. She conceptualized the study design, conducted the data collection and analysis, interpreted the results, and prepared the initial draft of the manuscript. Sovian Aritonang contributed to data validation, literature review, and manuscript refinement, ensuring the scientific accuracy and clarity of presentation. Mikael Syväjärvi provided senior supervision, critical guidance on the research direction, and contributed to the final review and interpretation of the data. All authors participated in the interpretation of findings, reviewed and edited the final version of the paper, and approved it for submission.

REFERENCES

[1] Aryawijayanti S, Susilo, Sutikno. Analisis dampak radiasi sinar-X pada mencit melalui pemetaan dosis radiasi di laboratorium fisika medik. Jurnal MIPA. 2015;38(1):25–30.

[2] Bandunggawa P, Sandi I, Merta I. Bahaya radiasi dan cara proteksinya. Medicina (B. Aires). 2009;40:47–51.

[3] Ayu MSK. Proteksi radiasi pada pasien, pekerja, dan lingkungan di dalam instalasi radiologi. Anatomi Klinis Dasar. 2018;236–239.

[4] International Commission on Radiological Protection (ICRP). ICRP Publication 146: Radiological protection of people and the environment in the event of a large nuclear accident. Ann ICRP. 2020;49(4).

[5] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources, Effects and Risks of Ionizing Radiation. New York: United Nations; 2022.

[6] International Atomic Energy Agency (IAEA). Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards. Vienna: IAEA; 2014.

[7] Damayanti O. Hasil uji kebocoran alat pelindung diri di instalasi radiologi rumah sakit umum Karawang. J Teras Kesehatan. 2021;4(1):22–28.

[8] Maslebu G, Muninggar J, Hapsara SA. Estimasi risiko radiasi janin pada pemeriksaan radiografi pelvis. Jurnal Fisika. 2017;4(2):40–47.

[9] He X, Zhao R, Rong L, Yao K, Chen S, Wei B. Answers to if the Lead Aprons are Really Helpful in Nuclear Medicine from the Perspective of Spectroscopy. Radiat Prot Dosimetry. 2017;174(4):558–564.

[10] Kartikasari Y, Alif M, Fathoni N, Indrati R. Uji fungsi alat pelindung radiasi (*lead apron*) di instalasi radiologi rumah sakit. Publication Ethics. 2021;25(2).

[11] Marlina R, Engberg AR, Eriksson O, Dalgliesh RM. Understanding neutron absorption and scattering in polymer composite materials. Nucl Instrum Methods Phys Res A. 2020;984:164613.

[12] Abidin Z, Alkrytania D, Indrajati IN, Besar Kulit B, Plastik Yogyakarta K, Yogyakarta S. Analisis bahan apron sintetis dengan filler timbal (II) oksida sesuai SNI untuk proteksi radiasi sinar-X. J Forum Nuklir. 2015;9(2).

[13] Rahmawati I, Jumpeno BYEB, Mellawati J, Ramlan R. Analisis pengaruh densitas terhadap potensi komposit apron proteksi radiasi sinar-X dengan bahan kaktus centong dan timbal (II) asetat. Publication Ethics. 2023;25(2).

[14] Akman, F, Ogul H, Kaçal MR, Polat H, Dilsiz K, Agar O. Eco/Friendly Polymer-Based Composites for Nuclear Shielding Applications. In: Ikhmayies, S.J. (eds) Advanced Composites. Advances in Material Research and Technology. Springer, Cham. 2024.

[15] Jayakumar S, Saravanan T, Philip J. A review on polymer nanocomposites as lead-free materials for diagnostic X-ray shielding: Recent advances, challenges and future perspectives. Hybrid Advances. 2023;4:100100.
[16] Kavaz, E., Ekinci, N. Energy Absorption and Exposure Buildup Factors in Polymers by Nuclear Track Detectors. ajc 2016, 28, 1673-1681.
[17] Kharita MH, Takeyeddin M, Alnassar M, Yousef S. Development of special radiation shielding concretes using natural local materials and evaluation of their shielding characteristics. Prog Nucl Energy. 2008;50(1):33–36.
[18] Abdel Maksoud MIA, Kassem SM, Ashour AH, Awed AS. Recycled high-density polyethylene reinforced with ilmenite as a sustainable radiation shielding material. RSC Adv. 2023;13(30):20698–20708.
[19] Kassem SM, Abdel Maksoud MIA, El Sayed AM, Ebraheem S, Helal AI, Ebaid YY. Optical and radiation shielding properties of PVC/$BiVO_4$ nanocomposites. Sci Rep. 2023;13(1):1–19.
[20] Fionov A, Kraev I, Yurkov G, Solodilov V, Zhukov A, Surgay A, et al. Radio-absorbing polymer composites and their applications in electromagnetic compatibility. Polymers. 2022;14(15).
[21] Marlina R. Analisis kepatuhan penggunaan alat pelindung diri (APD) dalam pelaksanaan cegah tangkal penyakit COVID-19 di pintu negara pada negara pada petugas kesehatan kantor pelayanan pelabuhan kelas 1 Makassar. Universitas Hasanuddin; 2020.
[22] Chang L, Zhang Y, Liu Y, Fang J, Luan W, Yang X, Zhang W. Preparation and characterization of tungsten/epoxy composites for γ-rays radiation shielding. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 2015; 356-357: 88-93.
[23] Almuqrin, AH, Elsafi M, Yasmin S, Sayyed MI. Morphological and Gamma-Ray Attenuation Properties of High-Density Polyethylene Containing Bismuth Oxide. Materials 2022;15, 6410.
[24] Elsafi M, Hedaya AM, Abdel-Gawad EH. et al. Experimental Investigation of the Radiation Shielding Performance of a Newly Developed Silicon-Epoxy Resin Doped with WO3 Micro/Nanoparticles. Silicon. 2024;16, 5439–5446.
[25] Bayoumi EE, Attia NF, Elshehy EA, Abd El-Magied MO, Atia BM, Galhoum AA, Manjunatha HC, Sridhar KN, Khalil LH, Mohamed AA. Tungsten-based hybrid nanocomposite thin film coated fabric for gamma, neutron, and X-ray attenuation. Surfaces and Interfaces. 2023; 39:102883.
[26] Nayak NG, Vijaya MG, Siddappa K. Effective atomic numbers of some polymers and other materials for photoelectric process at 59.54keV. Radiation Physics and Chemistry. 2001;61(3-6): 559-561.
[27] More CV, Alsayed Z, Badawi MS, et al. Polymeric composite materials for radiation shielding: a review. Environ Chem Lett. 2021:19: 2057–2090.