Jurnal Ilmu Fisika
Vol. 18, No. 2, September 2026, pp. 210–218
ISSN: 1979-4657 (Print); 2614-7386 (Online)
https://doi.org/10.25077/jif.18.2.210-218.2026

Jurnal Ilmu Fisika
Open Access

Monte Carlo Simulation of Depth-Dose Distribution in Medical Polymers Irradiated by 10 MeV Electron Beam Using PUFFIn

Tiara Sundussiah Andani[1], Sri Oktamuliani[1], Bimo Saputro[2], Fendinugroho[2], Okky Agassay Firmansyah[2], and Nunung Nuraeni[2]

[1] Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Andalas, Padang, 25163, Indonesia
[2] National Research and Innovation Agency, Serpong, Tangerang Selatan, 15314, Indonesia

Article Info

Article History:

Received May 14, 2026
Revised September 28, 2026
Accepted September 29, 2026
Published online September 30, 2026

Keywords:

radiation dose distribution
medical polymers
electron beam sterilization
Monte Carlo simulation
PUFFIn

Corresponding Author:

Sri Oktamuliani,
Email: srioktamuliani@sci.unand.ac.id

ABSTRACT

Polymers are widely used in disposable medical devices that must fulfill strict safety and effectiveness standards, including radiation sterilization. The effectiveness of electron-beam (e-beam) sterilization depends critically on the uniformity of the absorbed radiation dose distribution. This study investigates the absorbed dose depth distribution in 11 industrial polymer materials irradiated by a 10 MeV e-beam accelerator (BRIN specifications) using PUFFIn-based Monte Carlo simulations. Target materials were modeled as 100 × 25.5 × 10 cm blocks with observation points spaced 1 mm along the z-axis. The percentage depth dose (PDD) curves show that maximum dose depth Z_{max} ranges from 1.85 to 3.05 cm across the studied polymers. High-density materials such as Polycarbonate (PC, 1.35 g/cm^3) exhibit shallower penetration (Zmax = 1.85 cm), whereas low-density materials like Polyolefin Elastomer (POE, 0.87 g/cm^3) allow deeper penetration (Zmax = 3.05 cm). At equivalent densities, materials with higher effective atomic numbers (Zeff) tend to show slightly higher maximum doses (Dmax), likely due to enhanced electron interaction and backscattering probabilities. These quantitative insights provide a scientific basis for optimizing industrial e-beam processing parameters and material selection for medical device manufacturing.

Copyright © 2026 Author(s)

1. INTRODUCTION

Irradiation technology plays a crucial role in the medical equipment industry, particularly in the sterilization process, ensuring that products are free from microbial contamination, including bacteria, viruses, parasites, and fungal spores (Danyo et al., 2024; McEvoy et al., 2023; Michaels et al., 2021). This process often utilizes ionizing radiation, such as electron beams from accelerators, to effectively inhibit or kill microorganisms. The effectiveness of sterilization is highly dependent on the distribution of radiation doses absorbed by the material in a device. Uneven dose distribution can reduce sterilization efficiency and potentially damage the material structure at points of high dose (Hansen et al., 2020; Pomatsalyuk et al., 2021; Rahmawati et al., 2024).

Materials used in medical equipment, such as polymers, conductive metals, and composites, exhibit varying characteristics in their ability to absorb radiation. Factors such as thickness, density, and chemical composition affect the dispersion and absorption of radiation energy (Kurudirek & Özdemir, 2011; Yani, 2022). Thicker materials generally absorb more radiation, but produce uneven dose

distribution. Therefore, understanding the interaction of radiation with various types of materials is important for designing efficient irradiation systems and maintaining material resistance to high radiation exposure (Bliznyuk et al., 2022; Spunei et al., 2014).

The need for accuracy in determining dose distribution has led to the use of simulation methods to model the spread of radiation. The Monte Carlo method has become one of the most widely used approaches because it is capable of calculating radiation interactions with materials in detail, including complex geometries and various types of radiation (Fielding, 2023; Miza et al., 2022). One software based on this method is PUFFIn (Penelope-Based User-Friendly Fast Interface), which is designed to model radiation dose distribution with high accuracy and is capable of taking into account variations in density and material composition (Schwarz et al., 2025; Schwarz & Sunderland, 2023).

The present study contributes to the scientific understanding of radiation dose absorption by identifying and analyzing the absorbed dose distribution in materials used in the medical equipment industry through a Monte Carlo method based on the PUFFIn software. Tuan et al. (2019) focused on differences in depth-dose distributions between homogeneous and non-homogeneous materials, particularly in relation to material density. The present study extends this approach by investigating the absorbed dose distribution in medical equipment materials based on their material characteristics and the spatial distribution of radiation dose along the irradiation direction. Schwarz et al. (2024) emphasized the agreement between simulation and experimental results and the use of the Dose Uniformity Ratio (DUR) to evaluate dose uniformity. The present study complements this approach by providing a detailed characterization of absorbed dose distributions within the investigated materials, enabling quantitative analysis of dose variations as a function of position and material characteristics.

Fifield et al. (2021) investigated the effectiveness of electron and X-ray radiation as alternative sterilization methods for polymer materials, with particular emphasis on the relationship between material density and dose uniformity. The present study complements this research by providing a Monte Carlo-based analysis of radiation dose absorption in materials relevant to the medical equipment industry, thereby enabling the interaction between radiation and different material characteristics to be examined through their resulting dose distributions. Liu et al. (2023) investigated the influence of atomic number on the maximum depth-dose distribution, particularly for high-atomic-number materials such as tungsten and tantalum. The present study extends this line of investigation by identifying the absorbed dose distribution characteristics of selected materials using a PUFFIn-based Monte Carlo approach, allowing the relationship between material properties and radiation dose distribution to be examined systematically.

The primary scientific contribution of this study lies in integrating absorbed dose distribution analysis, material characteristics, and PUFFIn-based Monte Carlo simulation within the context of materials used in the medical equipment industry. This approach provides quantitative information on dose variation with depth and irradiation position, thereby offering a more comprehensive understanding of radiation absorption characteristics in the investigated materials. The findings are expected to provide a scientific basis for evaluating the radiation response of materials and to support the selection and development of materials suitable for applications in the medical equipment industry.

2. METHOD

This study employs a Monte Carlo-based simulation method using PUFFIn software to analyze the absorbed radiation dose distribution in various polymer materials used in disposable medical equipment. The geometry of the radiation source and target materials was defined based on a literature review of irradiation processes in Indonesia, particularly the 10 MeV electron-beam (e-beam) irradiation facility operated by the National Research and Innovation Agency (BRIN). The radiation source was defined as a 10 MeV electron beam with an irradiation area of 90 × 20.5 cm. The target material was modeled as a block measuring 100 × 25.5 × 10 cm. The material block was intentionally designed with dimensions larger than the irradiation area to enable observation of the dose distribution in regions that were not directly exposed to the electron beam. Simulations were performed for eleven polymer materials: Acrylonitrile Butadiene Rubber (Buna-N), Polycarbonate (PC), Vinyl Methyl Silicone

(VMQ), Polybutylene Terephthalate (PBT), Polyvinyl Chloride (PVC), High Impact Polystyrene (HIPS), Chlorobutyl Rubber (CIIR), High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Polypropylene Homopolymer (PPH), and Polyolefin Elastomer (POE).

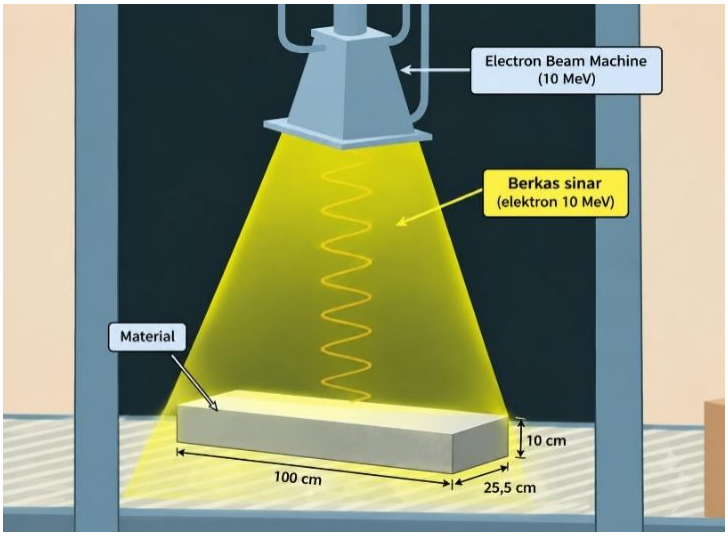


Figure 1 Modification of the radiation source beam design

Each polymer material was defined in PUFFIn by specifying its elemental composition and mass density as material input parameters. The elemental composition determines the constituent atoms present in the material, while the mass density represents the amount of material mass per unit volume. These parameters are incorporated into the Monte Carlo simulation to characterize the interaction of incident electrons with the material. The different densities of the polymer materials therefore influence the transport and energy deposition of electrons within the target volume, resulting in variations in the absorbed dose distribution as a function of depth. For each material, the corresponding density and elemental composition were assigned according to the material properties used in the simulation. This approach enables the absorbed dose distributions of polymers with different physical and compositional characteristics to be compared under identical irradiation conditions.

The radiation source was positioned above the target material, with the electron beam directed perpendicular to the material surface. Absorbed dose data were obtained from 100 observation points along the z-axis, with a spacing of 1 mm between consecutive points. The resulting simulation geometry is presented in Figure 1. The simulated absorbed dose distributions were subsequently processed to determine the maximum absorbed dose (D_{max}) and the corresponding maximum dose depth (Z_{max}). The dose distribution was analyzed using the Percentage Depth Dose (PDD) approach to characterize the variation in absorbed dose as a function of depth within each material. The relationships between material density, effective atomic number (Z_{eff}), and absorbed dose distribution were further evaluated based on the D_{max} values. This analysis was conducted to characterize the radiation absorption behavior of each polymer material and to evaluate its potential relevance to electron-beam irradiation-based sterilization processes.

3. RESULTS AND DISCUSSION

3.1 Modeling of Material Geometry and Radiation Sources

Material geometry and radiation source modeling were performed to analyze radiation dose distribution in the medical equipment sterilization process. The material was modeled as a 100 × 25.5 × 10 cm block and irradiated with a 10 MeV electron beam from a 90 × 20.5 cm source, in accordance with the specifications of a 10 MeV e-beam machine. The selection of materials is based on research by

Fifield et al. (2021) and Li et al. (2025), which highlights the use of polymers as the primary material for disposable medical equipment due to their lightweight, stable, and easy-to-sterilize properties.

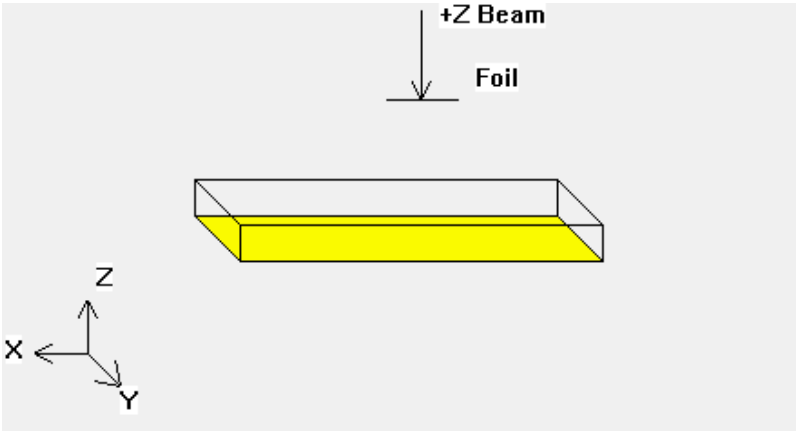


Figure 2 Visualization of material geometry

The geometric model is illustrated in Figure 2, where the radiation source is positioned above the material on the +z axis, and the beam is emitted parallel to the material surface. A thin foil layer is used as an initial radiation filter. The x, y, and z coordinate systems indicate the spatial orientation during the simulation. The model is constructed realistically to represent actual irradiation conditions, with simplifications made to improve computational efficiency without altering the material's important characteristics. The results of this modeling form the basis for analyzing the dose distribution on medical equipment materials.

3.2 Identification of Radiation Dose Distribution Depth

A depth analysis of the absorbed dose distribution was performed along the z-axis using 100 measurement points spaced 1 mm apart. The Percentage Depth Dose (PDD) profile across 11 polymer materials is depicted in Figure 3, the absorbed dose initially increases with penetration depth until reaching a maximum value (Zmax), beyond which it exhibits an exponential decrease.

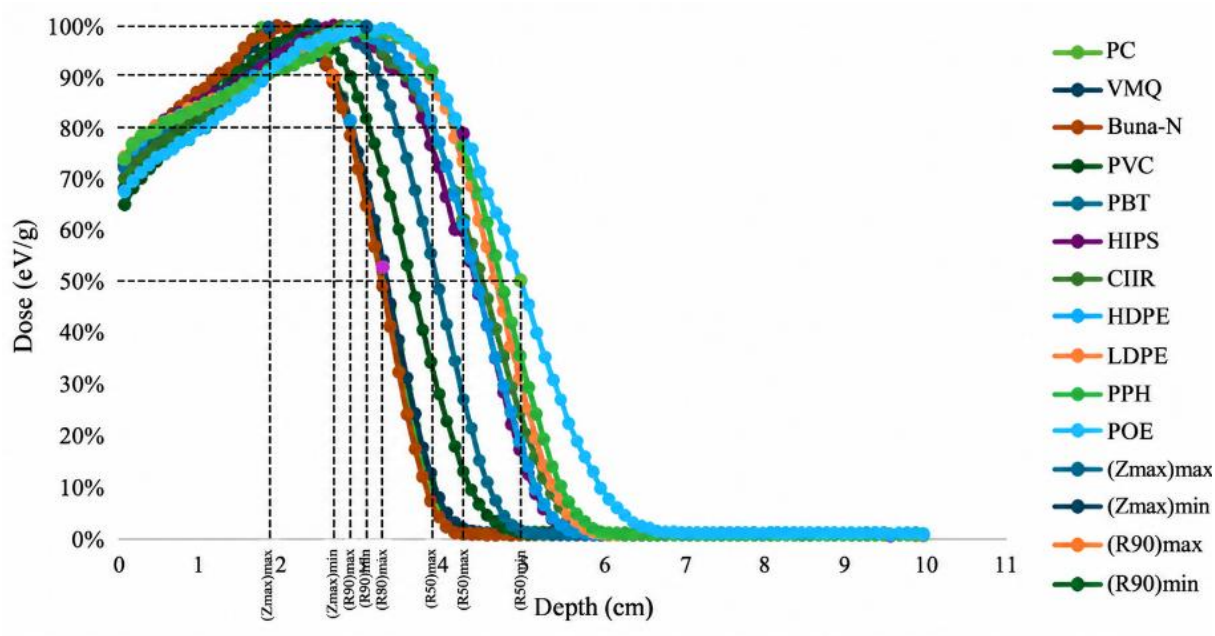


Figure 3 Results of PDD measurements on 11 materials

The initial build-up region occurs due to energy deposition via ionization and excitation processes, accompanied by the generation of energetic secondary electrons (Møller scattering) and forward scattering of primary beam electrons. Beyond Z_{max}, energy deposition diminishes exponentially as both primary and secondary electrons undergo energy degradation and spatial attenuation. This depth-dose profile aligns with fundamental electron-beam dosimetry principles described by Podgorsak (2005).

As listed in Table 1, the peak dose depth (Z_{max}) varies inversely with mass density across the studied range (0.87 - 1.35 g/cm^3). Materials with the highest density (1.35 g/cm^3)—namely Polycarbonate (PC), Vinyl Methyl Silicone (VMQ), and Buna-N—exhibit shallower penetration depths (Z_{max} ranging from 1.85 to 1.95 cm). In contrast, lowest-density polymers such as Polyolefin Elastomer (POE, 0.87 g/cm^3) allow electrons to penetrate deeper, reaching Z_{max} = 3.05 cm. Higher mass density corresponds to increased electron density per unit volume, which accelerates collision stopping power and restricts maximum beam penetration. These observations are consistent with e-beam transport studies reported by Schwarz et al. (2024).

Table 1 PDD value of polymer material at Z_{max}

No.	Material	Density (g/cm^3)	Z_{max} (cm)
1	PC	1.35	1.85
2	VMQ	1.35	1.95
3	Buna-N	1.35	1.95
4	PVC	1.30	2.35
5	PBT	1.30	2.45
6	HIPS	1.03	2.65
7	CIIR	0.94	2.75
8	HDPE	0.94	2.85
9	LDPE	0.92	2.95
10	PPH	0.90	2.95
11	POE	0.87	3.05

The relationship between depth and radiation dose percentage exhibits an increase in dose until it reaches a maximum point (Z_{max}), after which it decreases exponentially. The increase in dose in the build-up region is caused by the interaction of electron beams with atomic electrons, which produces high-energy secondary electrons. After reaching Z_{max}, the dose decreases due to photon attenuation and a reduction in radiation energy at greater depths. This pattern is consistent with the results of research by Wulandari et al. (2022), which shows a decrease in radiation dose with increasing depth.

3.3 Effect of Material Density and Effective Atomic Number (Z_{eff}) on D_{max}

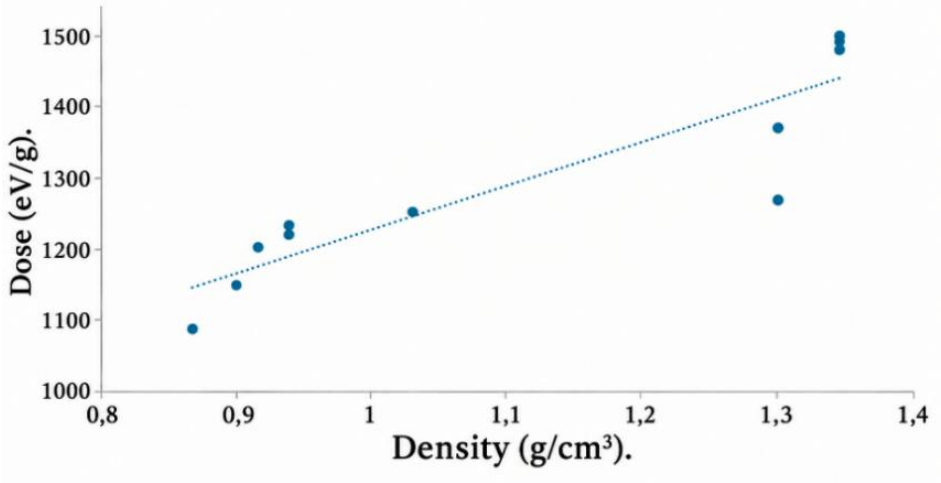


Figure 4 Density versus D_{max} graph for 11 materials.

The relationship between material physical characteristics and maximum absorbed dose (D_{max}) is illustrated in Figure 4. The simulation data demonstrate a clear positive correlation between material density and D_{max}. Lower-density polymers (e.g., POE at 0.87 g/cm^3) register $D_{max} \approx$ 1088.70 eV/g, whereas higher-density polymers (e.g., PC at 1.35 g/cm^3) reach D_{max} = 1502.44 eV/g. Increased density compresses a higher number of target atomic electrons into a given volume, multiplying collisional interaction opportunities per unit path length and concentrating energy deposition near the surface layers. The IAEA (2021) states that radiation absorption depends on the density of the material, where differences in density result in different dose responses in the electron beam irradiation process. Figure 4 shows that materials with high density have greater radiation absorption capacity because electrons lose energy more quickly due to the large number of particles in the same volume. Greening (2017) explains that an increase in the number of particles per unit volume increases the chance of interaction between electrons and the atoms that make up the material, resulting in greater energy absorption. The absorbed dose values for each material density are presented in Table 2.

Table 2 Density, chemical composition, and D_{max} values

No.	Material	Z_{eff}	Density (g/cm^3)	D_{max} (eV/g)
1	PC	7.70	1.35	1502.44
2	VMQ	6.60	1.35	1494.23
3	Buna-N	6.30	1.35	1483.98
4	PVC	10.41	1.30	1373.81
5	PBT	8.73	1.30	1268.70
6	HIPS	6.08	1.03	1252.70
7	CIIR	6.14	0.94	1232.59
8	HDPE	4.67	0.94	1220.88
9	LDPE	4.67	0.92	1202.61
10	PPH	4.67	0.90	1151.91
11	POE	4.67	0.87	1088.70

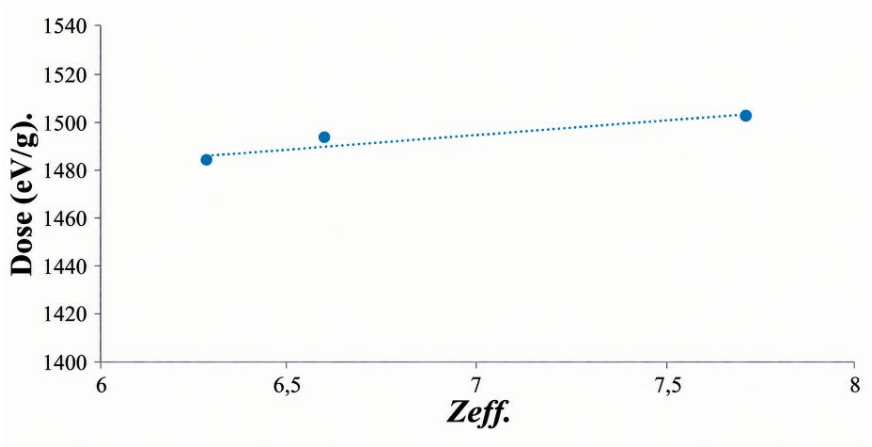


Figure 5 Graph of the relationship between Z_{eff} and D_{max} for materials with a density of 1.35 g/cm^3

Furthermore, comparison of polymers with identical mass densities reveals that the effective atomic number (Z_{eff}) acts as a major secondary driver of energy absorption (Figure 5). For instance, among polymers with ρ = 1.35 g/cm^3, D_{max} increases from 1483.98 eV/g in Buna-N (Z_{eff} = 6.30) to 1494.23 eV/g in VMQ (Z_{eff} = 6.60) and 1502.44 eV/g in PC (Z_{eff} = 7.70). Higher Z_{eff} values enhance atomic electron density and elastic Coulomb scattering probabilities, including electron backscattering. This backscattering component contributes directly to surface dose accumulation and elevates D_{max}. As highlighted by Liu et al. (2023) and IAEA guidelines, mass density governs total mass per unit volume, while Z_{eff} dictates the intrinsic cross-section for electromagnetic radiation interactions. Yani (2022) also emphasizes that material characteristics influence the distribution of doses in electrons and photons.

Materials with higher Z_{eff} have greater radiation energy absorption capacity than materials with lower Z_{eff}. This phenomenon occurs because a high Z_{eff} indicates a greater number of electrons per atom, thereby increasing the likelihood of interaction between radiation and atoms. Electrons lose their energy more quickly over a shorter distance, causing radiation energy to be more concentrated at the surface layer of the material. Additionally, an increase in Z_{eff} also increases the likelihood of backscattering, which contributes to the energy absorbed around the surface and results in a higher D_{max} value.

4. CONCLUSION

This study demonstrates that the PUFFIn-based Monte Carlo method can be effectively used for the identification and analysis of radiation dose distribution in materials with different physical and chemical characteristics. Scientifically, this study contributes to clarifying the relationship between dose distribution, material depth, density, and effective atomic number (Z_{eff}), while demonstrating that material characteristics are important factors in determining the magnitude and position of the maximum dose (Z_{max}). The absorbed dose distribution increases with increasing depth until reaching Z_{max} and subsequently decreases exponentially, consistent with the characteristics of the Percentage Depth Dose (PDD). Materials with higher density tend to exhibit shallower Z_{max} values and higher maximum absorbed doses, whereas lower-density materials demonstrate deeper radiation penetration. The Z_{eff} value also plays a role in enhancing radiation interactions with materials under the same density conditions. The limitation of this study lies in its simulation-based approach, which remains dependent on the parameters and material characteristics used in the modeling process; therefore, the results do not yet fully represent the complexity of experimental conditions and material variations in real-world applications. Experimental validation and testing across a broader range of materials, densities, chemical compositions, and beam energies are required to improve the reliability of the results. Future research should focus on integrating simulation results with experimental measurements, developing models for more diverse and heterogeneous materials, and analyzing the effects of variations in radiation energy and irradiation conditions on dose distribution. These developments are expected to expand the application of the PUFFIn-based Monte Carlo approach in medical dosimetry, material characterization, and industrial irradiation applications. The findings of this study may also provide a foundation for developing more comprehensive and experimentally validated simulation models to support the planning and optimization of irradiation processes.

AUTHOR CONTRIBUTIONS

T.S.A: Methodology, Formal Analysis, Resources, and Writing-Original Draft, Writing-Review and Editing, Data Curation, Conceptualization; S.O: Conceptualization, Validation, Methodology, Investigation, Visualization, Writing-Review and Editing; B.S: Conceptualization, Validation, Methodology, Investigation, Visualization, Writing-Review and Editing; F, O.A.F, and N.N: Methodology, Validation, Visualization.

FUNDING

This research received no external funding.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ARTIFICIAL INTELLIGENCE (AI) USAGE DECLARATION

During the preparation of this work, the author(s) used GPT-6 (GPT-6 Astra, openai.com) for correcting minor grammatical and typographical errors. After using this tool/service, the author(s) reviewed and edited the output as needed and take full responsibility for the content of the publication.

REFERENCES

Bliznyuk, U. A., Borshchegovskaya, P. Y., Zolotov, S. A., Ipatova, V. S., Krusanov, G. A., Nikitchenko, A. D., Studenikin, F. R., & Chernyaev, A. P. (2022). Determining the Electron Beam Spectrum after Passing Through Aluminum Plates. *Moscow University Physics Bulletin*, 77(4), 615–621. https://doi.org/10.3103/S0027134922040038

Danyo, E. K., Ivantsova, M. N., & Selezneva, I. S. (2024). Ionizing Radiation Effects on Microorganisms and Its Applications in the Food Industry. *Foods and Raw Materials*, 12(1), 1–12. https://doi.org/10.21603/2308-4057-2024-1-583

Fielding, A. L. (2023). Monte-Carlo Techniques for Radiotherapy Applications II: Equipment and Source Modelling, Dose Calculations and Radiobiology. *Journal of Radiotherapy in Practice*, 22, e81, 1–6. https://doi.org/10.1017/S1460396923000080

Fifield, L. S., Pharr, M., Staack, D., Pillai, S. D., Nichols, L., McCoy, J., Faucette, T., Bisel, T. T., Huang, M., Hasan, M. K., Perkins, L., Cooley, S. K., & Murphy, M. K. (2021). Direct Comparison of Gamma, Electron Beam and X-ray Irradiation Doses on Characteristics of Low-Density Polyethylene, Polypropylene Homopolymer, Polyolefin Elastomer and Chlorobutyl Rubber Medical Device Polymers. *Radiation Physics and Chemistry*, 186, 109505. https://doi.org/10.1016/j.radphyschem.2021.109505

Greening, J. R. (1985). Fundamentals of Radiation Dosimetry (2nd ed.). CRC Press.

Hansen, J. M., Fidopiastis, N., Bryans, T., Luebke, M., & Rymer, T. (2020). Radiation Sterilization: Dose Is Dose. *Biomedical Instrumentation & Technology*, 54(S3), 45–52. https://doi.org/10.2345/0899-8205-54.s3.45

International Atomic Energy Agency. (2021). Radiation Effects on Polymer Materials Commonly Used in Medical Devices (Coordinated Research Project F23035, 1st RCM Report). IAEA.

Kurudirek, M., & Özdemir, Y. (2011). Energy Absorption and Exposure Build-up Factors for Some Polymers and Tissue Substitute Materials: Photon Energy, Penetration Depth and Chemical Composition Dependence. *Journal of Radiological Protection*, 31(1), 117–128. https://doi.org/10.1088/0952-4746/31/1/008

Li, D., Bisel, T. T., Cooley, S. K., Ni, Y., Murphy, M. K., Spencer, M. P., Hasan, M. K., Fifield, L. S., Pharr, M., Staack, D., Huang, M., Pillai, S. D., Nichols, L., Parker, R., & Gustin, E. (2025). Gamma, Electron Beam and X-ray Irradiation Effects on Polymers in an Advanced Bone Cement Mixer Device. *Radiation Physics and Chemistry*, 226, 112188. https://doi.org/10.1016/j.radphyschem.2024.112188

Liu, M., He, C., Feng, J., Xun, M., Sun, J., Li, Y., & Guo, Q. (2023). Analysis of Difference in Areal Density Aluminum Equivalent Method in Ionizing Total Dose Shielding Analysis of Semiconductor Devices. *Electronics*, 12(19), 4181. https://doi.org/10.3390/electronics12194181

Malinowski, M. (2021). Using X-ray Technology to Sterilize Medical Devices. *American Journal of Biomedical Science & Research*, 12(3), 272–276. https://doi.org/10.34297/AJBSR.2021.12.001755

McEvoy, B., Maksimovic, A., Howell, D., Reppert, P., Ryan, D., Rowan, N., & Michel, H. (2023). Studies on the Comparative Effectiveness of X-Rays, Gamma Rays and Electron Beams to Inactivate Microorganisms at Different Dose Rates in Industrial Sterilization of Medical Devices. *Radiation Physics and Chemistry*, 208, 110915. https://doi.org/10.1016/j.radphyschem.2023.110915

Osman, N. M., Mohamad Tajudin, S., Aminordin Sabri, A. H., Mohd Noor, A. F., & Abdul Aziz, M. Z. (2022). Evaluation of Scattering Effects for Radiation Shielding or Filter Materials by Using Monte Carlo Simulation. *IOP Conference Series: Materials Science and Engineering*, 1231(1), 012007. https://doi.org/10.1088/1757-899X/1231/1/012007

Podgorsak, E. B. (Ed.). (2005). Radiation Oncology Physics: A Handbook for Teachers and Students. International Atomic Energy Agency.

Pomatsalyuk, R. I., Titov, V. Y., Titov, D. V., Uvarov, V. L., Shevchenko, V. A., & Zakharchenko, A. A. (2021). Monitoring of Critical Parameters of Radiation Sterilization Process at an Industrial Electron Accelerator. *RAP Conference Proceedings*, 6, 39–43. https://doi.org/10.37392/RapProc.2021.08

Rahmawati, I., Jumpeno, B. Y. E. B., Mellawati, J., & Ramlan. (2023). Analisis Tingkat Absorpsi Berkas Sinar-X pada Sintesis Komposit Kaktus (Opuntia spp.) dan Timbal (II) Asetat (Pb(CH3COO)2) sebagai Material Apron. *Ganendra: Majalah IPTEK Nuklir*, 26(2), 82–90. https://doi.org/10.55981/gnd.2023.6870

Schwarz, R. A., Azuma, M., Boutros, C., Murphy, M. K., & Pagh, J. R. (2025). PUFFIn Software Modeling for Quality Management (PNNL-37351). Pacific Northwest National Laboratory.

Schwarz, R., Salvat, F., Sunderland, D., Azuma, M., Boutros, C., Pillai, S. D., Kuntz, F., Nasreddine, A., Pagh, J., Wootan, D., & Murphy, M. K. (2024). PUFFIn – A User Friendly Fast Interface for Calculating and Visualizing the Dose Distribution in Materials. *Radiation Physics and Chemistry*, 222, 111774. https://doi.org/10.1016/j.radphyschem.2024.111774

Schwarz, R. A., & Sunderland, D. J. (2023). PUFFIn User's Manual: Penelope User Friendly Fast Interface (PNNL-34009). Pacific Northwest National Laboratory.

Spunei, M., Malaescu, I., Mihai, M., & Marin, C. N. (2014). Absorbing Materials with Applications in Radiotherapy and Radioprotection. *Radiation Protection Dosimetry*, 162(1–2), 167–170. https://doi.org/10.1093/rpd/ncu252

Tuan, N. A., Van Tao, C., & Rangacharyulu, C. (2019). The Depth-Dose Curve Depends on the Inhomogeneity of the Material Irradiated by Electron Beam. *Radiation Physics and Chemistry*, 163, 22–25. https://doi.org/10.1016/j.radphyschem.2019.05.001

Wulandari, I., Shafii, M. A., Adrial, R., & Diyona, F. (2022). Distribusi Dosis Radiasi Foton Berdasarkan Variasi Kedalaman dan Luas Lapangan Penyinaran pada Fantom Menggunakan Pesawat Linac Tipe Clinac CX. *Jurnal Fisika Unand*, 11(1), 89–96. https://doi.org/10.25077/jfu.11.1.89-96.2022

Yani, S. (2022). Analisis Performa Timbal dan Besi Meredam Radiasi Foton 2 MeV dengan Simulasi Monte Carlo. *Journal Online of Physics*, 7(2), 13–18. https://doi.org/10.22437/jop.v7i2.18224