A SYSTEMATIC LITERATURE REVIEW ON FABRICATION TECHNIQUES OF METAL-POLYMER COMPOSITES AS RADIATION SHIELDING MATERIAL

Nurul Syafiqah Roslan[1], Nur Maizatul Azra Mukhtar[2a,2b,2c*], Ainorkhilah Mahmood[3], Nor Aimi Abdul Wahab[4], Hanisah Zainal Abidin[5]

[1]Department of Applied Sciences, Universiti Teknologi MARA Cawangan Pulau Pinang, Malaysia
✉ syafiqah01701@gmail.com ⓘD https://orcid.org/0009-0000-6752-5475

[2a]Department of Applied Sciences, Universiti Teknologi MARA Cawangan Pulau Pinang, Malaysia
[2b]Faculty of Health Sciences, Universiti Teknologi MARA Cawangan Pulau Pinang, Malaysia
[2c]Department of Biomedical Imaging, Advanced Medical and Dental Institute, Universiti Sains Malaysia, Malaysia
✉ nurmaizatul038@uitm.edu.my ⓘD https://orcid.org/0000-0002-9578-0438

[3]Department of Applied Sciences, Universiti Teknologi MARA Cawangan Pulau Pinang, Malaysia
✉ ainorkhilah_sp@uitm.edu.my ⓘD https://orcid.org/0000-0001-6764-3084

[4]Department of Applied Sciences, Universiti Teknologi MARA Cawangan Pulau Pinang, Malaysia
✉ noraimi108@uitm.edu.my ⓘD https://orcid.org/0000-0002-7143-2535

[5]Department of Applied Sciences, Universiti Teknologi MARA Cawangan Pulau Pinang, Malaysia
✉ Hanisahzainal2000@gmail.com ⓘD https://orcid.org/0009-0008-8032-9100

*Corresponding Author

Article Info:

Abstract:

Lead-based materials have long been used for radiation shielding in medical and industrial applications due to their high attenuation capacity. However, their toxicity, heaviness, and handling difficulties raise significant health and environmental concerns. This Systematic Literature Review (SLR) evaluates recent advancements in lead-free metal–polymer composites as safer alternatives for radiation protection.

The review followed the PRISMA methodology, analysing studies published between 2019 and 2024 across five databases: Google Scholar, Scopus, PubMed, ScienceDirect, and Web of Science. From 95 initial records, only 13 studies met the inclusion criteria and were thoroughly reviewed. Seven fabrication techniques were identified, such as pencil beam spray coating, layer-by-layer (LBL), hot pressing, electrospinning, 3D printing, mixing and curing, and metal doping, each offering unique advantages in structure and performance. The findings revealed that composites containing high atomic number (Z) fillers such as bismuth (Bi) and tungsten (W) achieved the highest shielding efficiencies, with RPE values exceeding 99% and Z_{eff} up to 83. Techniques such as LBL and doping demonstrated superior attenuation and flexibility, while electrospinning and pencil beam spray coating enabled lightweight shields with up to 45% weight reduction. In contrast, hot pressing and 3D printing produced dense, durable composites ideal for structural shielding, and mixing and curing methods provided sustainable, non-toxic alternatives using materials such as red mud and Bi_2O_3. This review concludes that metal–polymer composites are strong candidates to replace lead in radiation shielding. Nevertheless, further research is needed to assess long-term durability, toxicity, and cost-effectiveness, supporting the advancement of lightweight, flexible, and eco-friendly shielding materials for medical, industrial, and environmental applications.

Keyword:

Lead-Free Composite, Metal-Polymer Fabrication, Radiation Shielding Performance

Introduction

When handling high-energy gamma rays and X-rays, medical personnel and patients must wear suitable personal protective equipment (PPE) to protect vital organs from ionising radiation. High-density materials are particularly effective, as they have a higher probability of interaction with these rays, resulting in greater energy absorption and shielding efficiency (More et al., 2021). PPE functions primarily to absorb and scatter high-energy photons, thereby reducing exposure to critical organs such as the kidneys, heart, and lungs (El-Khatib et al., 2024; J. A. Kamarolzeman & N. M. A, 2020). Radiation, whether emitted as particles (alpha, beta) or electromagnetic waves (gamma, X-rays) poses significant health risks due to its ionising capability, which can damage biological tissues and DNA (N. M. A. Mukhtar et al., 2024; Nur Maizatul Azra Mukhtar et al., 2024.; Sobczak & Żyła, 2024).

Traditionally, lead-based materials have been the standard PPE for radiation shielding in diagnostic and therapeutic applications due to their high atomic number and density, which enable excellent attenuation of ionising radiation (Al-Balushi et al., 2021; Elsafi et al., 2022).

However, their use presents several drawbacks. Lead aprons are extremely heavy, malleable, and prone to chemical degradation, making them uncomfortable and difficult to inspect for structural integrity. More critically, prolonged use of lead aprons contributes to severe musculoskeletal disorders (MSDs) and spinal injuries among healthcare workers.

Recent studies report that 50–82% of physicians and radiologic technologists experience musculoskeletal pain due to wearing lead aprons, with 21 to 44% suffering activity-limiting back or shoulder pain (Hartung et al., 2025). Similarly, a Japanese survey found that 54.5% of radiologic technologists reported work-related MSDs, significantly correlated with frequent lead apron use (Akebi et al., 2022). These findings are supported by multiple reviews highlighting chronic lumbar, cervical, and shoulder strain among radiation workers due to the ergonomic burden of lead PPE (Monaco et al., 2020); (Şahin et al., 2024).

Consequently, ergonomic and health concerns have driven research toward lead-free, lightweight shielding materials that can offer equivalent radiation protection. Among these alternatives, metal–polymer composites have attracted significant attention. These materials combine high atomic number metal fillers with flexible polymer matrices. The metal fillers enhance radiation attenuation due to their atomic number and density, while the polymer matrix contributes flexibility, lightness, and biocompatibility. The atomic number (Z) and density (ρ) of the filler materials are key parameters influencing radiation attenuation, and the higher these values, the better the shielding performance.

Polymers such as medical-grade silicone are particularly suitable as matrix materials because they are inert, biocompatible, and easily sterilized. Advances in composite fabrication techniques have enabled precise dispersion of metal fillers, optimizing the effective atomic number (Zeff), linear attenuation coefficient (LAC), mass attenuation coefficient (MAC), half-value layer (HVL), tenth-value layer (TVL), and radiation protection efficiency (RPE).

Therefore, this review systematically evaluates the performance and fabrication techniques of metal polymer composites fabricated for radiation shielding applications. It aims to compare their physical, mechanical, and radiation attenuation characteristics with conventional lead-based PPE, offering insights into sustainable, ergonomic, and high-performance lead-free alternatives for medical and industrial radiation protection.

Literature Review

Radiation can be classified as ionising radiation and non-ionising radiation. Ionising radiation is a high-energy form of electromagnetic radiation capable of removing electrons from atoms and molecules, thereby producing charged ions (Velásquez et al., 2024a). It arises from the spontaneous disintegration of unstable atomic nuclei, releasing energy in the form of photons or particles such as gamma rays (γ-rays), X-rays, beta particles, and neutrons. Due to their high energy and penetrative capability, ionising radiations pose significant biological risks, including cellular and DNA damage. Therefore, efficient radiation shielding is essential, particularly in medical, nuclear, and industrial environments (Alanazi et al., 2024a; Y. Wang et al., 2020).

The interaction of ionising radiation with matter primarily occurs through three mechanisms: the photoelectric effect, Compton scattering, and pair production. The photoelectric effect predominates at lower photon energies (10–100 keV), where incoming photons are completely

absorbed by tightly bound inner-shell electrons, leading to photoelectron emission. This process is highly dependent on the atomic number of the shielding material, where higher atomic number materials exhibit a greater probability of photoelectric absorption (Aldawood et al., 2024), (Alanazi et al., 2024; B. Wang et al., 2023).

Secondly, Compton scattering dominates at intermediate photon energies (100 keV to 10 MeV) and involves partial energy transfer between a photon and an outer-shell electron, resulting in reduced photon energy and ejection of the electron (Chang et al., 2023; Jreije et al., 2024). This interaction is inelastic scattering in which the photon interacts with an electron, and its energy will be reduced after transferring some of its energy to the electron of the radiated materials. During this interaction, an electron will be ejected from its orbital position (Dekker et al., 2020).

Thirdly, at photon energies above 1.02 MeV, pair production occurs, where a photon's energy is converted into an electron–positron pair upon interaction with an atomic nucleus. These interactions collectively define the attenuation characteristics of materials exposed to ionising radiation (Aldawood et al., 2024; Chang et al., 2023). In this interaction, the Coulomb interaction will slow down the ejected electron and antiparticle. As a result, bremsstrahlung X-ray photons will be released. Gamma photons with an energy of at least 0.511 MeV will be produced as the antiparticle reunites with its pair, the electron (Y. Wang et al., 2020). The destroyed photons travel in the opposite direction to preserve the linear momentum (Saleem et al., 2023). The atomic number influenced the cross-section of pair production.

The effectiveness of a radiation shielding material is quantified by parameters such as the MAC, LAC, HVL, TVL, Zeff, and RPE. These parameters describe how effectively a material can attenuate radiation intensity as photons traverse it. Generally, materials with a higher atomic number and density provide superior attenuation due to increased photon interaction probability. For example, lead (Z = 82) has long been the standard material for radiation shielding because of its high density and excellent photon absorption capacity. However, its toxicity, rigidity, and significant weight (density ~11.34 g cm^{-3}) impose serious occupational and ergonomic concerns. Prolonged use of lead-based protective equipment, such as aprons, has been shown to cause chronic musculoskeletal disorders (MSDs) among healthcare workers, especially in the lumbar and cervical regions. Recent studies report MSD prevalence rates ranging from 50 to 82% among professionals who regularly wear lead aprons, with up to 44% experiencing work-limiting pain (Hartung et al., 2025); (Akebi et al., 2022). These ergonomic limitations highlight the urgent need for lightweight, lead-free shielding alternatives with comparable radiation attenuation performance.

In this context, metal–polymer composites have emerged as a promising class of lead-free shielding materials. These composites integrate high atomic number (Z) metallic fillers—such as tungsten (W), bismuth (Bi), or tin (Sn)—within lightweight polymer matrices like silicone, epoxy, or polyethylene. The metal fillers enhance the material's photon absorption capability, while the polymer matrix imparts flexibility, processability, and chemical stability. This combination allows for the development of shielding materials that are not only efficient in radiation attenuation but also ergonomically superior and safer for human use.

The performance of metal–polymer composites is strongly influenced by several factors, including the atomic number and density of the metal filler, filler dispersion uniformity, and the fabrication technique used. Fabrication processes such as solution casting, melt blending,

hot pressing, and additive manufacturing determine the microstructural distribution of fillers within the polymer matrix, which in turn affects the composite's attenuation efficiency and mechanical properties. Optimising these fabrication parameters can enhance the overall shielding effectiveness, achieving protection levels equivalent to or surpassing those of lead-based materials while significantly reducing weight and toxicity.

Therefore, this manuscript aims to systematically evaluate the radiation attenuation performance of metal–polymer composites fabricated using different processing techniques. The review synthesises existing studies on the relationships between filler type, filler loading, fabrication method, and resulting shielding performance. Through this analysis, the study provides comprehensive insight into the current advancements and challenges in developing lightweight, flexible, and environmentally sustainable alternatives to lead-based radiation shielding materials.

Material and Method

This systematic literature review (SLR) was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework. The PRISMA flow diagram shown in Figure 1 illustrates the step-by-step process of identifying, screening, and selecting studies that met the inclusion criteria. The search strategy was designed to ensure comprehensiveness, transparency, and reproducibility.

Identification

The first stage involved identifying potentially relevant studies through comprehensive database searches. Five major scientific databases were systematically queried: Google Scholar, ScienceDirect, Web of Science, Scopus, and PubMed. These databases were chosen for their broad coverage across materials science, engineering, and biomedical research. The following Boolean search string was applied: "Metal" AND "Polymer" AND "Radiation Shielding" OR "Lead-Alternative". This combination of keywords was selected to capture studies focusing on metal–polymer composite materials and their radiation attenuation performance as potential lead-free alternatives for shielding applications. A total of 95 records were initially retrieved across the five databases. Duplicate records (n = 20) were then removed, resulting in 75 unique studies proceeding to the screening stage. The removal of duplicates ensured that the same study was not counted multiple times, which maintains the validity of data representation and prevents redundancy.

Screening

The screening phase aimed to exclude studies that were not directly relevant to the research objectives. A two-level screening approach was used: Title and abstract screening – Studies were excluded if they did not focus on metal–polymer composites, radiation shielding, or lead-free materials. Out of the 75 screened studies, 23 records were excluded due to irrelevance or insufficient alignment with the scope of the review. Full-text screening – The remaining 52 studies underwent detailed evaluation. However, 21 records could not be retrieved due to access restrictions or incomplete publication details. Consequently, 31 studies were advanced to the eligibility assessment phase for further appraisal of methodological quality and relevance.

Eligibility

During the eligibility assessment, the full texts of the remaining 31 studies were reviewed thoroughly to determine whether they met the inclusion criteria. The inclusion criteria required that studies must focus on metal–polymer composites used for gamma-ray or X-ray attenuation, report at least one radiation shielding performance parameter (e.g., mass attenuation coefficient (MAC), half-value layer (HVL), or effective atomic number, include quantitative or experimental data derived from laboratory measurements or validated simulations, published in peer-reviewed journals between 2019 and 2024. Studies were excluded if the paper focused only on pure metals or ceramics without polymer matrices, or addressed unrelated applications such as electronics, corrosion, or energy storage and lacked sufficient experimental or numerical data for comparison. As a result, 17 papers were excluded at this stage: six (6) for being outside the targeted research area and eleven (11) for insufficient data or incomplete methodology. This left 13 high-quality studies that fulfilled all eligibility requirements and were included in the final synthesis (Figure 1).

Data Abstraction and Analysis

Data from the 13 included studies were systematically extracted and organised in Table 1 to ensure consistency and traceability. Extracted data elements included author(s) and publication year, database source, type of metal filler and polymer matrix, fabrication technique (e.g., hot pressing, melt blending, solution casting, electrospinning), radiation type and photon energy range tested, reported shielding parameters (MAC, HVL, Z_eff, RPE) and key findings with comparative performance against lead or standard shielding materials The analysis focused on identifying trends across fabrication techniques and their effect on shielding performance. Quantitative data such as MAC and HVL were compared where available, and qualitative patterns were synthesised across studies. The database breakdown as shown in Table 1, five papers were obtained from the Web of Science, three from PubMed, two from Google Scholar, one from ScienceDirect, and two from Scopus. The most common fabrication techniques identified across these studies included metal doping, electrospinning, multi-layer hot pressing, and solution blending. These diverse techniques reflect ongoing efforts to optimise the interfacial dispersion of metal fillers and improve the attenuation efficiency of polymer composites while maintaining flexibility and lightweight characteristics.

Table 1: Data Extraction of Published Papers from Five Databases

Databases	Keywords	Total references	Excluded	Included
Google Scholar		19	17	2
ScienceDirect		6	5	1
Web of Science	"Metal" AND " polymer" AND "radiation shielding"	60	55	5
Scopus	OR "lead - alternative"	13	10	3
PubMed		12	9	3
Google Scholar		19	17	2

Quality Appraisal

Quality assessment was conducted to evaluate the methodological rigour and reliability of the included studies. Each paper was appraised based on the following criteria of experimental clarity, completeness of fabrication and measurement methods, reproducibility – Presence of sufficient detail for replication of results, data integrity includes transparency in reporting shielding parameters and energy levels, comparative analysis, inclusion of control or benchmark materials, and peer-review status – Confirmation that all studies were published in peer-reviewed scientific journals. All 13 included studies met a satisfactory standard in methodological transparency and data reporting. However, a few studies lacked full energy-dependent attenuation profiles, which limited direct quantitative comparison. Nonetheless, the overall quality of evidence was deemed adequate to support the synthesis and discussion of fabrication-performance relationships. The PRISMA-based methodology ensured a systematic and transparent selection process, as illustrated in Figure 1. The multi-database approach, supported by structured inclusion and exclusion criteria, ensured that only the most relevant and reliable studies were incorporated into the review. The final dataset of 13 high-quality studies provides a robust foundation for evaluating how different fabrication techniques influence the radiation shielding performance of metal–polymer composites.
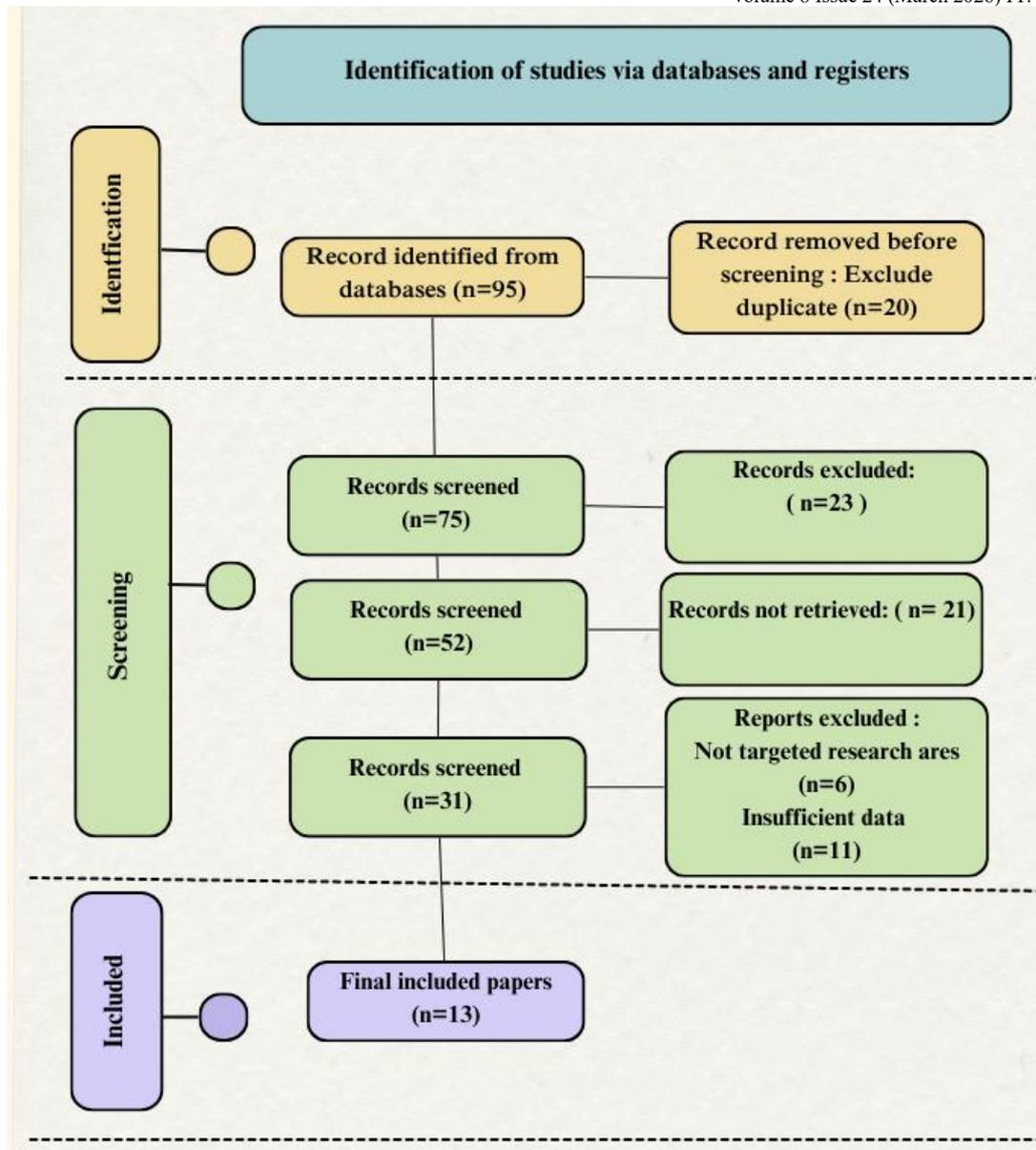
Figure 1: PRISMA Flow Diagram for Systematic Review

Result and Finding

This systematic literature review analysed 13 studies that investigated various lead-free metal–polymer composites for radiation shielding applications. Seven primary fabrication techniques were identified: pencil beam spray coating, layer-by-layer (LBL), hot pressing, electrospinning, 3D printing, mixing and curing, and doping of polymers with metals. Each technique was evaluated based on its effectiveness in photon attenuation, as determined by key parameters such as effective atomic number, LAC, MAC, HVL, TVL, and RPE. The findings consistently indicate that composite materials containing high-Z fillers such as bismuth (Bi), tungsten (W), tin (Sn), cadmium (Cd), and barium (Ba) embedded within polymer matrices (PDMS, HDPE, TPU, PLA, PVA, or epoxy) can achieve radiation-shielding performance comparable to conventional lead-based materials while offering significant advantages in weight reduction, flexibility, and environmental safety.

Pencil Beam Spray Coating Technique

The pencil beam spray coating method [Ref. (Kim, 2023)] was applied to fabricate high-density tungsten–HDPE (high-density polyethylene) composites for lightweight radiation-shielding applications. In the pencil beam spray coating method, tungsten–HDPE composites were fabricated with 70%, 80%, and 85% W concentrations. The increase in filler content resulted in improved particle uniformity, density, and attenuation efficiency. The RPE increased from 72.21% (W70%) to 92.54% (W85%) within the energy range of 22.5–53.8 keV. The performance improvement was directly linked to higher tungsten loading, which increased both Zeff and LAC. Although this method produced uniform, flexible coatings ideal for wearable radiation shields, its low production rate (~2 hours/m²) limits scalability. Overall, the W85% composite demonstrated the best shielding behaviour, achieving a high attenuation rate and low transmitted photon intensity, with HVL below 0.05 cm, suitable for diagnostic energy applications.

Figure 2 illustrates the spraying process of the tungsten mixture solution, where a continuous stream of the tungsten–polyethylene mixture is deposited onto a nonwoven substrate under controlled pressure and nozzle velocity. The constant-speed spraying allows for an even coating thickness, which is essential to maintain consistent attenuation characteristics across the shield. Despite the advantages of this method, it remains time-intensive, requiring approximately two hours per square meter of coated sheet. The study suggests that process improvements, such as multi-line spray systems or self-stirring injection devices, could enhance scalability for industrial applications.
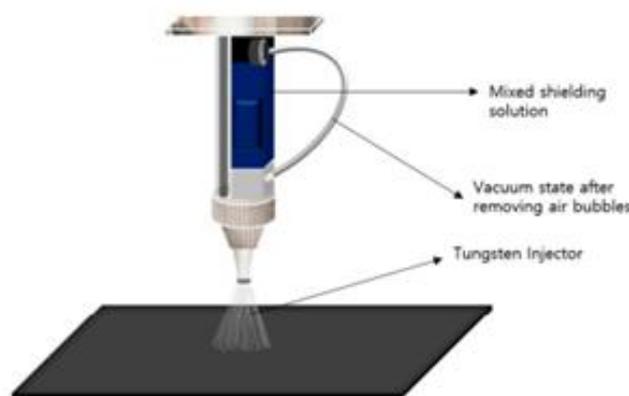

Figure 2: Spraying of Tungsten Mixture Solution (S.C. Kim, 2023)

Layer-by-Layer Technique

The Layer-by-Layer (LBL) or sandwich-structured approach produced multilayered composites composed of alternating polymer and metal oxide layers (Sn, CeO₂, WO₃, and Bi). This structure enhanced photon attenuation through multiple scattering and interfacial reflection. The Zeff ranged from 50 (Sn-based) to 83 (Bi-based), showing strong energy dependence on metal type and filler loading.

In the diagnostic range of 40 to 141 keV, multilayered structures with higher filler concentrations achieved RPE values of 99.68% (50 keV), 97.74% (70 keV), and 95.53% (90 keV). The LAC reached up to 0.4 cm⁻¹, with low HVL and TVL values, confirming excellent

attenuation at minimal thickness. Compared with single-phase composites, LBL structures displayed enhanced mechanical stability and flexibility, making them highly suitable for lead-free medical aprons and flexible shielding panels (Galehdari, n.d.) (Gilys et al., 2022).

Hot Pressing Technique

Hot-pressed composites based on HDPE, EVA, or epoxy resin reinforced with SiC, MoC, and BaO exhibited high density and strong filler–matrix bonding. The LAC values ranged between 0.15–3.70 cm^{-1} and MAC between 2.60–3.89 cm²/g, measured over 32.5–64.5 keV energy ranges.

The corresponding RPE values were 30–92%, depending on filler concentration, with SiC- and MoC-filled composites showing the best attenuation performance. BaO–epoxy composites achieved Zeff ≈ 51, demonstrating effective attenuation across 276–1408 keV, confirming their suitability for structural shielding applications (Türkaslan et al., 2022). Hot pressing produced dense, void-free composites with consistent mechanical strength, though their rigidity limits use in flexible PPE applications. Figure 3 illustrates the hot-pressing setup used to synthesise the composites (Lyutyy et al., 2024).
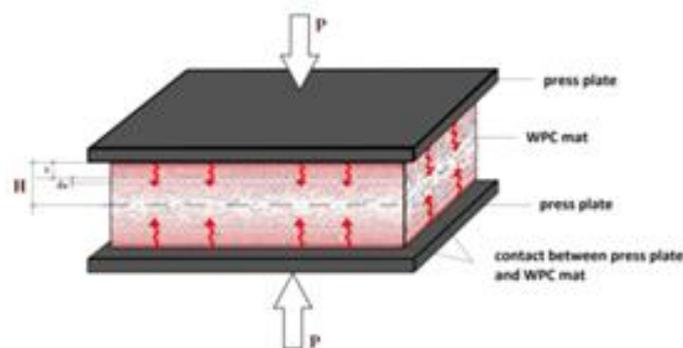

Figure 3: Hot Pressing of The Composite (Lyutyy et al., 2024)

Electrospinning Technique

Electrospun TPU composites incorporating tungsten (W), bismuth (Bi), tin (Sn), and tellurium (Te) were developed for lightweight radiation-shielding films, particularly for paediatric diagnostic imaging (60 to 90 kV). Monte Carlo simulations using GATE and Geant4 optimised layer composition and thickness.

Double-layer configurations combining Bi–Sn or Bi–Te fillers exhibited superior attenuation compared to monolayer designs. At 60 kV, a configuration of 30% W + 65% Bi achieved a 40.8% weight reduction, while maintaining high attenuation. Densities ranged from 6.24 g/cm³ (TPU–Te) to 19.25 g/cm³ (TPU–W), with HVL between 0.007 to 0.002 cm (Kwon et al., 2023). The high Zeff values (50 to 83) and consistent RPE (15 to 70%) confirm effective attenuation at minimal material thickness. The electrospinning method thus provides a viable pathway for lightweight, flexible, and patient-safe shielding materials.

Figure 4 illustrates the schematic setup of the electrospinning process, which was specifically applied for developing radiation-shielding materials used in paediatric diagnostic X-ray imaging. This imaging range typically operates between 60 kV and 90 kV, where the balance

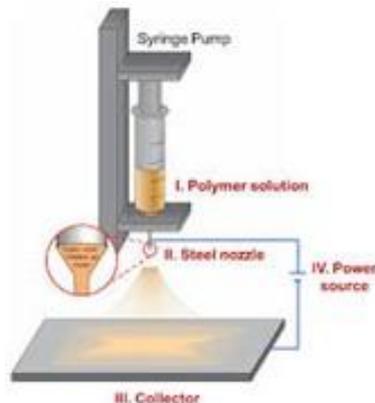between effective attenuation and lightweight flexibility is critical for ensuring both patient safety and comfort.

Figure 4: An Electrospinning Technique (Kwon et al., 2023)

3D Printing Technique

The 3D print fabrication technology for PLA polymeric composites filled with tungsten powder involves the use of the Rapid 3D Shield model developed in Virtual Foundry for radiation oncology medical applications, as shown in Figure 5. Additive manufacturing enabled the precise fabrication of PLA–tungsten composites for radiation shielding. The printed material composition consisted of 6.9% PLA and 93.1% tungsten, achieving a density of 7.51 g/cm³.

The composites exhibited LAC values of 0.7773–0.1996 cm⁻¹, MAC = 0.0432 cm²/g, and an HVL of 2.138 cm, with RPE ≈ 50% across 10–2000 keV photon energies. Although attenuation efficiency was lower than that of LBL or hot-pressed materials, 3D printing provided superior precision, uniformity, and design flexibility, making it ideal for customised shielding geometries and patient-specific protection devices in radiation oncology (Y. Wang et al., 2023), (Velásquez et al., 2024). The fabrication process used the PRUSA i3 MK3S printer, which was appropriate for the specific extrusion that determines the composite's dimensional correctness.
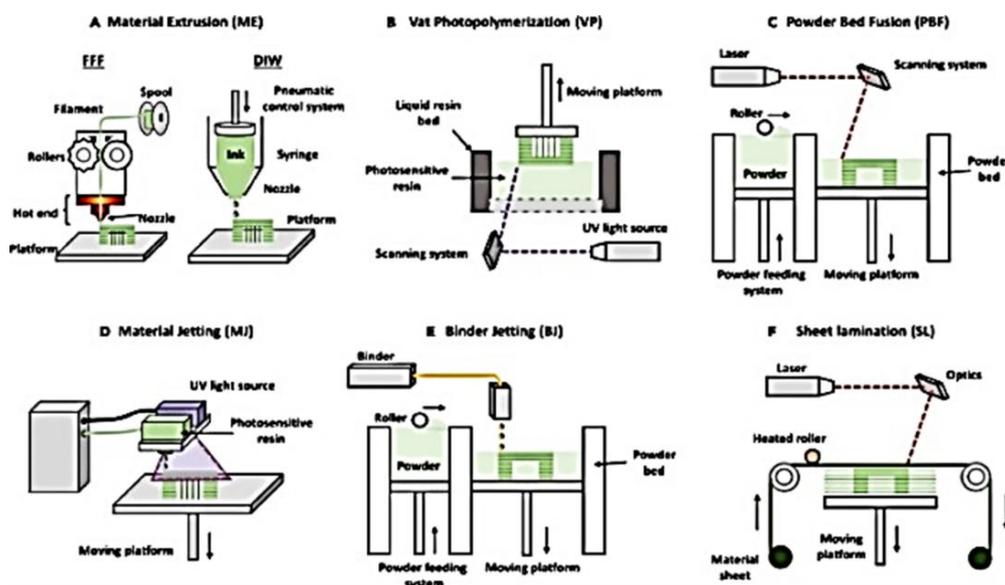

Figure 5: 3D Printing Fabrication of Metal-Polymer (Zheng et al., 2024)

Mixing and Curing Technique

Mixing and curing methods were used to prepare composites such as PDMS–Bi_2O_3, PDMS–SnO_2, and Red Mud–PVA (RM–PVA) (Shivani et al., 2024). These studies demonstrated that the particle size and concentration of Bi_2O_3 strongly influenced attenuation properties. For DMPS–Bi_2O_3 composites, Zeff = 63.28, LAC = 0.977 to 5.516 cm^{-1}, and RPE = 15 to 99% were achieved over 60 to 1333 keV photon energies. Nano-sized Bi_2O_3 particles provided greater attenuation than micro-sized ones, confirming the effectiveness of nanoscale dispersion in improving photon interaction probability.

Similarly, RM–PVA composites showed LAC = 0.24 to 0.26 cm^{-1} and HVL = 0.32 to 0.14 cm, validating their potential as environmentally sustainable lead alternatives. The results demonstrate that optimized filler distribution can yield efficient shielding while reducing material cost and toxicity. Figure 6 illustrates the mixing method (Almuqrin et al., 2024).
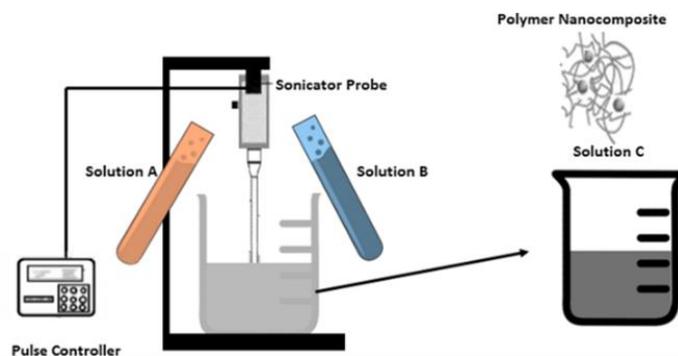

Figure 6: Mixing and Curing Fabrication of Metal-Polymer (Almuqrin Et Al., 2024)

Doping of Polymer with Metal Technique

This fabrication method focuses on the creation and characterisation of a novel composite material for gamma radiation protection (Gouda et al., 2023). The doping approach involved direct incorporation of SnO_2, CdO, Bi_2O_3, SiC, MoC, and WC into polymers such as PDMS, HDPE, and TPV. These composites achieved Zeff values between 18 and 34, LAC from 9 to 100 cm^{-1}, and MAC between 0.07 to 98 cm^2/g for energies 59.54 to 1408 keV.

Composites containing bismuth and tungsten exhibited the best results, achieving RPE ≈ 99.9% and HVL as low as 0.17 cm, confirming superior shielding performance comparable to lead-based materials. Nano-sized fillers enhanced interfacial bonding and reduced porosity, improving both thermal stability and radiation attenuation. These results indicate that metal-doped polymers such as Bi_2O_3–TPV and W–HDPE that offer high-efficiency, flexible, and non-toxic alternatives for medical radiation PPE and low-energy X-ray shielding (B. Wang et al., 2023) (Almuqrin et al., 2024).

The comparative analysis of all seven fabrication techniques, as shown in Table 2, indicates that the radiation attenuation efficiency of polymer–metal composites is strongly influenced by the type of filler, its atomic number (Zeff), and distribution uniformity, rather than the fabrication method alone. The Layer-by-Layer (LBL) and doping techniques achieved the highest RPE values (>99%) due to the effective use of high-Z fillers such as bismuth oxide

(Bi_2O_3) and tungsten (W), providing excellent shielding at reduced thickness and weight. The electrospinning and pencil beam spray methods demonstrated significant weight reduction (up to 40–45%) while maintaining good photon attenuation, making them suitable for flexible and lightweight PPE applications. In contrast, hot pressing and 3D printing produced dense, mechanically robust composites ideal for structural shielding, though less flexible. Meanwhile, mixing and curing techniques incorporating eco-friendly fillers like red mud and Bi_2O_3 offered a balance between performance and sustainability, achieving LAC up to 5.516 cm^{-1} and RPE up to 99%.

Overall, the data in Table 2 confirm that bismuth- and tungsten-based composites, regardless of fabrication method, consistently provide superior radiation protection, demonstrating their strong potential as lead-free shielding alternatives for both medical and industrial applications.

Table 2: Data Extraction from Published Studies on Metal–Polymer Composite Fabrication and Radiation Shielding Performance

Reference	Method fabrication	Materials	Zeff	Energy (keV)	LAC (cm^{-1})	MAC (cm^{2}g^{-1})	HVL (cm)	TVL (cm)	RPE (%)
(El-Khatib et al., 2024)	Doping polymer with metal	SnO$_2$, CdO, Bi$_2$O$_3$ PDMS	34 - 18	59.54 - 1408	100 - 9.0	98 - 0.07	0.03 - 100	0.03 - 80	-
(B. Wang et al., 2023)	Doping polymer with metal	TPV, CaCO$_3$, Bi, BiWO PDMS	-	80 - 120	0.178 - 0.347	0.0182 - 0.0355	0.17 - 1.54	-	99.90
(Al-mugren et al., 2024)	Doping of polymer with metal	HDPE, SiC, MoC, WC	-	30-50	0.165 - 1.801	0.25 - 2.25	4.44 - 0.61	-	63.58 - 91.73
(Velásquez et al., 2024)	3D printing	PLA, W	72.85	10 - 2000	0.7773 - 0.1996	0.0432	2.138	7.10	50
(Almuqrin et al., 2024)	Mixing, curing	DPMS, Bi$_2$O$_3$	63.28	60 - 1333	0.977 - 5.516	-	0.752	-	15 - 99
(Alanazi et al., 2024)	Hot pressing	HDPE, SiC, MoC	-	32.5 - 64.5	0.15 - 3.70	-	2.60 - 3.89	-	30 - 92
(Bagheri et al., 2024)	Hot pressing	HDPE, LDPE, PP, PVA, PMMA, Epoxy resin, Bi$_2$O$_3$	51.113 – 51.118	276 - 1408	0.12 - 0.55	1.0 - 0.38	-	-	-
(Nakamura et al., 2024)	Layering	Barium sulfate Tungsten Silicon rubber	-	50 70 90 110	-	0.4	-	-	99.68 97.74 95.53 93.66

Reference	Method	Material							
(Shivani et al., 2024)	Mixing, curing	Red mud (RM) PVA binder	-	60 - 120	0.24 - 0.26	-	-	0.32 - 0.14	- - -
(Gouda et al., 2023)	Mixing, curing.	Tin oxide PDMS	10 – 47	60 - 1408	0.25 - 6.40	0.25 - 6.40	0.25 - 10.2	0.20 - 32.5	6 - 100
(Kim, 2023)	Pencil beam laser	Tungsten HDPE	-	22.5 - 53.8	-	-	-	-	92.54 - 72.21
(Kwon et al., 2023)	Electrostatic spinning method	W, Bi, Sn, Te, TPU	-	10 - 90	12.60 - 266.53	-	0.007 - 0.002	-	15 - 70
(Gilys et al., 2022)	Layering	Sn, CeO$_2$, WO$_3$, Bi, PDMS	50 - 83	30 - 90	0 - 50	-	-	-	-

Conclusion

This systematic literature review examined 13 studies that explored the development of lead-free metal–polymer composites fabricated through seven distinct techniques—pencil beam spray coating, layer-by-layer (LBL), hot pressing, electrospinning, 3D printing, mixing and curing, and metal doping—for use in radiation shielding applications. Collectively, these findings establish a growing scientific foundation for lead-alternative materials that combine high attenuation efficiency with lightweight and flexible characteristics suitable for both medical and industrial use.

The review contributes significantly to advancing knowledge in the field of lead-free radiation shielding by systematically comparing performance metrics such as effective atomic number (Zeff), linear attenuation coefficient (LAC), half-value layer (HVL), and radiation protection efficiency (RPE) across different fabrication techniques and material compositions. Results from the reviewed studies confirm that composites incorporating bismuth (Bi) and tungsten (W) consistently exhibit the highest photon attenuation efficiencies, with RPE values exceeding 99% and Zeff up to 83, positioning them as viable substitutes for traditional lead-based materials. Moreover, techniques such as layer-by-layer (LBL) fabrication and metal doping have shown the most promising outcomes, achieving superior shielding with reduced thickness and improved flexibility, making them particularly suitable for PPE in radiology and nuclear medicine.

The findings of this SLR have several practical implications. For medical applications, these composites offer a pathway to developing lightweight, non-toxic protective gear that reduces musculoskeletal strain in healthcare workers while maintaining high shielding effectiveness. In industrial and nuclear environments, dense polymer–metal composites produced through hot pressing or 3D printing can serve as durable, customisable shielding barriers. From an environmental standpoint, the use of recyclable polymers and eco-friendly fillers such as red mud demonstrates potential for sustainable manufacturing practices that mitigate the ecological impact of traditional lead usage.

However, this review also highlights several limitations and research gaps. The small number of studies included (13) restricts the generalisability of findings across different radiation energy ranges and application contexts. Additionally, long-term durability, toxicity, and ageing behaviour of these composites remain underexplored, particularly under repeated radiation exposure or extreme environmental conditions. Cost-effectiveness and large-scale manufacturing feasibility also require deeper investigation to enable industrial adoption.
Future research should therefore focus on comprehensive durability and lifecycle studies, toxicity assessments to confirm biocompatibility, and cost–performance optimisation for large-scale production. Advanced computational modelling and multi-objective optimisation could further guide material selection and fabrication parameters to achieve the optimal balance between attenuation efficiency, weight, and sustainability. Collaborative efforts between materials scientists, medical physicists, and industrial engineers will be essential to translate laboratory findings into practical lead-free shielding technologies that meet global safety standards.

In summary, this review reinforces that metal–polymer composites, when properly engineered and fabricated, hold strong potential to replace lead as the standard in radiation protection. By consolidating and comparing existing evidence, this SLR provides a critical reference

framework for future research and development of lightweight, durable, and environmentally sustainable radiation-shielding materials, advancing the ongoing transition toward safer and greener shielding solutions for the medical, industrial, and environmental sectors.

Conflict of Interest Statement:	The authors declare that there is no conflict of interest regarding the publication of this paper. All authors have contributed to this work and approved the final version of the manuscript for submission to the International Journal of Innovation and Industrial Revolution (IJIREV).
Ethics Statement:	This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that the research was conducted in accordance with accepted academic integrity and ethical publishing standards.
Author Contribution Statement:	All authors contributed significantly to the development of this manuscript. [Authors 2, 3, and 4] were responsible for the conceptualization, methodology, and overall supervision of the study. [Author 1, 2 and 5] handled data collection, analysis, and interpretation of results. [Author 1] contributed to the literature review, drafting, and critical revision of the manuscript. All authors read and approved the final version of the manuscript prior to submission.

References

Alanazi, S. F., Alotaibi, N. M., Alsuhybani, M., Alnassar, N., Almasoud, F. I., & Almurayshid, M. (2024). Fabrication, Structural Characterization, and Photon Attenuation Efficiency Investigation of Polymer-Based Composites. Polymers, 16(9), 1212. https://doi.org/10.3390/polym16091212

Al-Balushi, M. A., Ahmed, N. M., Zyoud, S. H., Mohammed Ali, M. K., Akhdar, H., Aldaghri, O. A., & Ibnaouf, K. H. (2021). Ionization Radiation Shielding Effectiveness of Lead Acetate, Lead Nitrate, and Bismuth Nitrate-Doped Zinc Oxide Nanorods Thin Films: A Comparative Evaluation. Materials, 15(1), 3. https://doi.org/10.3390/ma15010003

Aldawood, S., Asemi, N. N., Kassim, H., Aziz, A. A., Saeed, W. S., & Al-Odayni, A.-B. (2024). Gamma radiation shielding by titanium alloy reinforced by polymeric composite materials. Journal of Radiation Research and Applied Sciences, 17(1), 100793. https://doi.org/10.1016/j.jrras.2023.100793

Al-mugren, K. S., Almalki, L., Alshehri, R., Alamri, S., Almurayshid, M., Alsuhybani, M., Alharbi, R., & Khandaker, M. U. (2024). Development of lead-free metal carbides and ceramic decorated HDPE composites for low energy X-ray shielding applications. Radiation Physics and Chemistry, 220, 111688. https://doi.org/10.1016/j.radphyschem.2024.111688

Almuqrin, A. H., Sayyed, M. I., Khandaker, M. U., & Elsafi, M. (2024). Exploring the impact of Bi2O3 particle size on the efficacy of dimethylpolysiloxane for medical gamma/X-rays shielding applications. Radiation Physics and Chemistry, 220. https://doi.org/10.1016/j.radphyschem.2024.111629

Bagheri, S., Khalafi, H., Tohidifar, M. R., & Bagheri, S. (2024). Thermoplastic and thermoset polymer matrix composites reinforced with bismuth oxide as radiation shielding materials. Composites Part B: Engineering, 278. https://doi.org/10.1016/j.compositesb.2024.111443

Chang, Q., Guo, S., & Zhang, X. (2023). Radiation shielding polymer composites: Ray-interaction mechanism, structural design, manufacture and biomedical applications. In Materials and Design (Vol. 233). Elsevier Ltd. https://doi.org/10.1016/j.matdes.2023.112253

Dekker, H., Schulten, E. A. J. M., van Ruijven, L., van Essen, H. W., Blom, G. J., Bloemena, E., ten Bruggenkate, C. M., Kullaa, A. M., & Bravenboer, N. (2020). Bone microarchitecture and turnover in the irradiated human mandible. Journal of Cranio-Maxillofacial Surgery, 48(8), 733–740. https://doi.org/10.1016/j.jcms.2020.05.015

El-Khatib, A. M., Zard, K., Abbas, M. I., & Gouda, M. M. (2024). Novel composite based on silicone rubber and a nano mixture of SnO2, Bi2O3, and CdO for gamma radiation protection. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-51965-0

Elsafi, M., Al-Ghamdi, H., Sayyed, M. I., Antar, A., Almuqrin, A. H., Mahmoud, K. A., Cornish, K., Shalaby, T. I., & El-Khatib, A. M. (2022). Optimizing the gamma-ray shielding behaviors for polypropylene using lead oxide: a detailed examination. Journal of Materials Research and Technology, 19, 1862–1872. https://doi.org/10.1016/j.jmrt.2022.05.128

Galehdari, N. A. (n.d.). Fabrication of Nanoengineered Radiation Shielding Multifunctional Polymeric Sandwich Composites. https://www.researchgate.net/publication/308746084

Gilys, L., Griškonis, E., Griškevičius, P., & Adlienė, D. (2022). Lead Free Multilayered Polymer Composites for Radiation Shielding. Polymers, 14(9). https://doi.org/10.3390/polym14091696

Gouda, M. M., Abbas, M. I., Hammoury, S. I., Zard, K., & M.El-Khatib, A. (2023). Nano tin oxide/dimethyl polysiloxane reinforced composite as a flexible radiation protecting material. Scientific Reports, 13(1), 210. https://doi.org/10.1038/s41598-023-27464-z

J. A. Kamarolzeman, & N. M. A, M. (2020). A Review on The Personal Protective Equipment (PPE) Used in Occupational Radiation Protective. Virtual Science Invention Innovation Conference (SIIC), 9, 299–300. https://ir.uitm.edu.my/id/eprint/81553/1/81553.pdf

Jreije, A., Keršienė, N., Griškevičius, P., & Adlienė, D. (2024). Properties of irradiated Bi2O3 and TiO2 enriched 3D printing polymers for fabrication of patient specific immobilization devices in radiotherapy. Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 549. https://doi.org/10.1016/j.nimb.2024.165298

Kim, S.-C. (2023). Metal Particle Pencil Beam Spray-Coating Method for High-Density Polymer–Resin Composites: Evaluation of Radiation-Shielding Sheet Properties. Materials, 16(18), 6092. https://doi.org/10.3390/ma16186092

Kwon, D. E., Han, D. H., Kim, J. O., Jung, K. H., & Baek, C. H. (2023). Multi-layered structures for lightweight providing shielding from unintended radiation exposure for pediatric patients. Radiation Physics and Chemistry, 204. https://doi.org/10.1016/j.radphyschem.2022.110720

Lyutyy, P., Bekhta, P., Protsyk, Y., & Gryc, V. (2024). Hot-Pressing Process of Flat-Pressed Wood–Polymer Composites: Theory and Experiment. Polymers, 16(20), 2931. https://doi.org/10.3390/polym16202931

More, C. V., Alsayed, Z., Badawi, M. S., Thabet, A. A., & Pawar, P. P. (2021). Polymeric composite materials for radiation shielding: a review. In Environmental Chemistry Letters (Vol. 19, Issue 3, pp. 2057–2090). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s10311-021-01189-9

N. M. A. Mukhtar, A. Mahmood, A. N. Suhaimi, N. F. H. Noor Azman, J. A. Kamarolzerman, I. J. Boniface, & A. Safian. (2024). The Effects of Educational Level on Radiation Professionals' Knowledge and Implementation of ALARA Principles For Occupational Radiation Protection. Journal of Islamic, Social, Economics and Development (JISED), 9(60), 82–92. https://doi.org/10.55573/jised.096010

Nakamura, K., Kubo, K., Hirata, M., Sakai, Y., Nakamura, Y., Kosaka, H., & Monzen, H. (2024). Evaluation of the shielding effectiveness of a non-toxic, double-layered BaSO4/W composite against diagnostic X-rays. Radiation Physics and Chemistry, 219. https://doi.org/10.1016/j.radphyschem.2024.111684

Nur Maizatul Azra Mukhtar, Ainorkhilah Mahmood, Aina Nafisya Suhaimi, Nur Fatma Husna Noor Azman, Jawidah Adiba Kamarolzeman, Ivy June Boniface, & Azlan Safian. (n.d.). Education Level And ALARA Principles In Occupational Radiation Protection.

Saleem, A., Agada, F., Ayoub, M. H., Khan, A. M., Sarwar, R., Bukhari, S. M., Zaidi, A., Farooq, U., & Shaikh, A. J. (2023). The synergistic effect of electron lone pairs and aromaticity on the binding affinity towards metal surfaces. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 664, 131127. https://doi.org/10.1016/j.colsurfa.2023.131127

Shivani, Vishwakarma, J., Dhand, C., M, M. S., Salammal, S. T., Gupta, G. K., Mishra, A., & Dwivedi, N. (2024). "Red-Mud, A Golden Waste for Radiation Shielding": Red-Mud Polymer Composites for High-Performance Radiation-Shielding Components. Journal of Hazardous Materials Advances, 13, 100394. https://doi.org/10.1016/j.hazadv.2023.100394

Sobczak, J., & Żyła, G. (2024). Nano and microcomposites as gamma and X-ray ionizing radiation shielding materials — A review. Energy, 290. https://doi.org/10.1016/j.energy.2023.130210

Türkaslan, S. S., Ugur, Ş. S., Türkaslan, B. E., & Fantuzzi, N. (2022). Evaluating the X-ray-Shielding Performance of Graphene-Oxide-Coated Nanocomposite Fabric. Materials, 15(4). https://doi.org/10.3390/ma15041441

Velásquez, J., Fuentealba, M., & Santibáñez, M. (2024). Characterization of Radiation Shielding Capabilities of High Concentration PLA-W Composite for 3D Printing of Radiation Therapy Collimators. Polymers, 16(6). https://doi.org/10.3390/polym16060769

Wang, B., Qiu, T., Yuan, L., Fang, Q., Wang, X., Guo, X., Zhang, D., Lai, C., Wang, Q., & Liu, Y. (2023). A comparative study between pure bismuth/tungsten and the bismuth tungsten oxide for flexible shielding of gamma/X rays. Radiation Physics and Chemistry, 208. https://doi.org/10.1016/j.radphyschem.2023.110906

Wang, Y., Wang, G., Hu, T., Wen, S., Hu, S., & Liu, L. (2020). Enhanced photon shielding efficiency of a flexible and lightweight rare earth/polymer composite: A Monte Carlo simulation study. Nuclear Engineering and Technology, 52(7), 1565–1570. https://doi.org/10.1016/j.net.2019.12.028

Wang, Y., Zhang, X., Su, R., Chen, M., Shen, C., Xu, H., & He, R. (2023). 3D Printed Antennas for 5G Communication: Current Progress and Future Challenges. Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers, 2(1), 100065. https://doi.org/10.1016/j.cjmeam.2023.100065

Zheng, S., Wang, Y., Wang, X., & Lu, H. (2024). Research progress on high-performance electromagnetic interference shielding materials with well-organized multilayered structures. Materials Today Physics, 40, 101330. https://doi.org