



Emerging Fabrication Strategies and Multiscale Characterisation of Radiation Shielding Materials: A Review

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Abstract

Ionizing radiation presents significant hazards in medical radiology, aerospace, and nuclear power systems, necessitating effective shielding for the protection of people and equipment. Conventional shielding materials such as lead remain widely used; however, concerns regarding toxicity, excessive weight, and limited adaptability have accelerated the search for alternative materials. This review examines recent developments in polymer-based materials, composites, nanocomposites, ceramics, concrete, and hybrid systems for radiation shielding applications. The disparity from existing reviews that largely treat material classes independently, this work integrates fabrication approaches, microstructural tailoring, characterization techniques, and application-driven shielding performance. Emphasis is placed on the role of advanced processing methods and nanoscale fillers in enhancing attenuation efficiency. Key characterization tools, including X-ray diffraction, scanning electron microscopy, mechanical testing, and radiation attenuation measurements, are critically assessed. By providing a multiscale comparative perspective and highlighting sustainability considerations, this review identifies current limitations and outlines future directions for the development of effective, lightweight, and environmentally responsible radiation shielding materials.

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1.0 Introduction

The demand for effective radiological protection has intensified with the widespread application of ionizing radiation in medical diagnostics and therapy, nuclear power generation, industrial processes, and research laboratories (Kaika *et al.*, 2025; Almuqrin *et al.*, 2022; Alsalsi *et al.*, 2024; Almuqrina *et al.*, 2024; Sayyed *et al.*, 2024). Exposure to ionizing radiation poses significant biological and environmental risks, necessitating the implementation of shielding strategies to protect radiation workers, sensitive equipment, and surrounding environments.

Lead has historically been employed as a primary shielding material owing to its high density and atomic number, which confer excellent photon attenuation capability. However, increasing concern regarding its toxicity, environmental impact, and regulatory constraints has prompted sustained research interest in alternative shielding materials (Mirji & Lobo, 2017; Verma & Srivastava, 2024). In response, various material classes, including locally sourced bricks and lead-based alloys, have been investigated for radiation shielding applications. Several studies have demonstrated their effectiveness in attenuating gamma radiation across different energy ranges (Kurudirek *et al.*, 2010; Sathish *et al.*, 2021).

Polymers and polymer-based composites have emerged as a highly attractive class of shielding materials, particularly for applications requiring lightweight, corrosion resistance, ease of fabrication, and design flexibility. These materials are well suited for portable and wearable radiation protection systems. Nevertheless, their inherently low atomic number limits their intrinsic attenuation efficiency, necessitating reinforcement with high atomic number fillers. Consequently, extensive research has focused on polymer

composites incorporating materials such as bismuth, barite, and rare-earth compounds, which have demonstrated significant improvements in radiation attenuation while preserving favorable processing and mechanical characteristics (Drobný, 2012; Shahzad *et al.*, 2022; Zeng *et al.*, 2023).

Recent advances in composite and nanocomposite shielding materials have highlighted the role of matrix–filler interactions in controlling attenuation performance through tailored microstructural dispersion and homogeneity. Multifunctional composites capable of providing radiation shielding alongside mechanical strength and thermal stability have been reported, particularly for long-term radiation exposure scenarios (Okafor *et al.*, 2021; Bawazeer *et al.*, 2023). In addition, conventional materials such as concrete, as well as polymer-modified concretes, remain essential for shielding applications in nuclear and medical facilities, where structural integrity and material optimization are critical considerations (Abdullahi *et al.*, 2022).

Fabrication methodology and Characterisation techniques play a decisive role in determining shielding effectiveness. Processing routes such as melt compounding, solution casting, additive manufacturing, and nanofiller functionalization significantly influence attenuation behavior. Accurate assessment of shielding performance across a broad energy spectrum requires a combination of experimental attenuation measurements, microstructural Characterisation, and computational modelling (Wu & Wang, 2024). Despite substantial progress at the laboratory scale, the translation of advanced shielding materials into practical applications remains limited by inconsistencies in testing standards,

insufficient benchmarking, and a lack of systematic comparison across material classes.

Monte Carlo simulation techniques, in conjunction with experimental Characterisation, have been widely employed to evaluate the radiation attenuation capabilities of emerging materials, thereby supporting efforts to reduce reliance on lead-based shielding systems (Aral *et al.*, 2020; Kaika *et al.*, 2025). Current research increasingly emphasizes materials that combine adequate density and mechanical strength with flexibility and environmental compatibility.

Despite the growing body of literature, existing reviews largely examine individual material systems in isolation, with limited integration of fabrication methods, Characterisation techniques, and application-driven performance metrics. Furthermore, comparative and multiscale analyses

across lead-based, polymeric, composite, and concrete shielding materials remain insufficiently addressed. Accordingly, this review critically examines the current state of research on lead-based, polymeric, nanocomposite, and concrete-based radiation shielding materials, with particular emphasis on fabrication approaches, Characterisation methodologies, and attenuation mechanisms. By providing a comparative and integrative perspective, this work aims to identify existing limitations and outline future research directions for the development of effective, sustainable, and application-oriented radiation shielding materials. Figure 1 presents a schematic overview of the major radiation shielding material classes, their fabrication routes, characterization techniques, and application domains considered in this review.

Schematic Overview of Radiation Shielding Materials and Processes

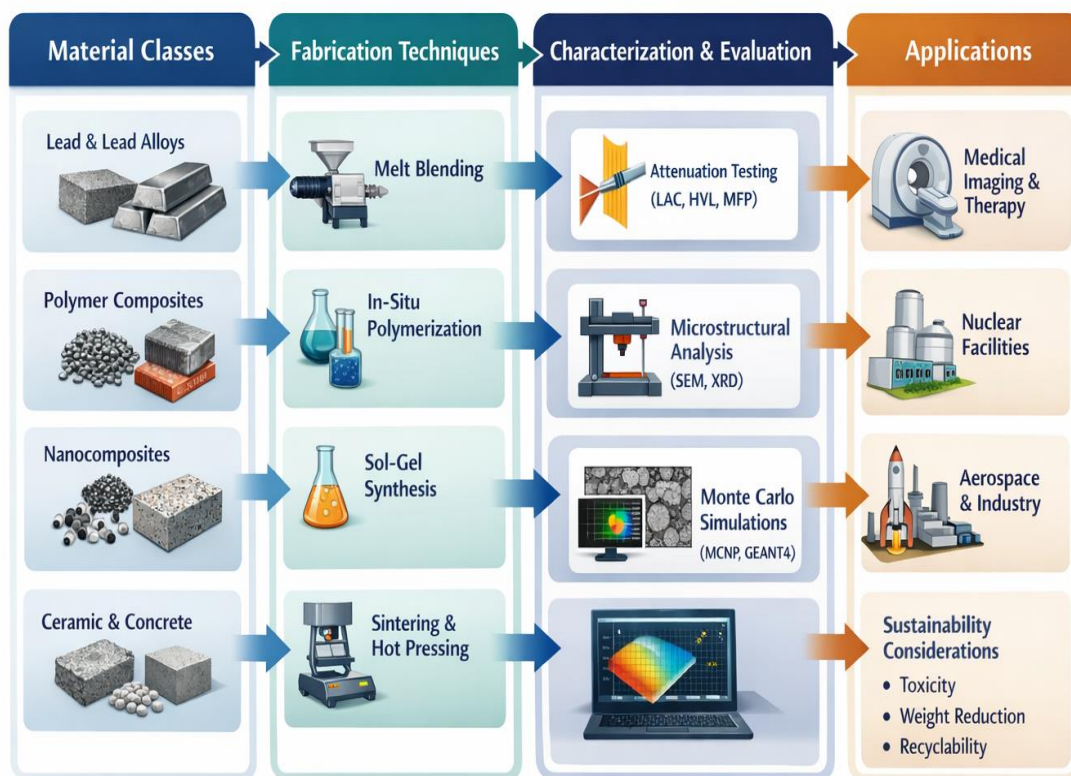


Figure 1: Schematic representation of radiation shielding material classes, fabrication techniques, characterization methods, and application domains. Adapted from concepts reported in Chaitali *et al.* (2021), Aral *et al.* (2020) and Wu & Wang (2024).

2.0 Materials and Method

This study employed narrative literature review aimed at amplifying the present knowledge on

radiation shielding, fabrication and characterisation of diverse materials. Secondary data were collected from peer-reviewed journal

articles published between 2019 and 2025. Sources were identified through searches on databases such as Google Scholar, and research gate using keywords including “fabrication,” “characterisation,” “radiation protection,” “lead,” and “Shielding Materials.” Studies that aligned with the keywords were automatically considered and three of most suitable for every keyword was selected while non-English studies, and those lacking practical applications were excluded. A total of 65 sources were selected, including 62 journal articles, and 3 published books. Data were analyzed thematically to identify fabrication, characterisation, and testing techniques.

2.1 Fabrication and Characterisation Techniques of Radiation Shielding Materials

Fabrication techniques for polymer-based and nanocomposite radiation shielding materials require precise control over filler dispersion and microstructural homogeneity to maximize attenuation efficiency and suppress nanoparticle agglomeration (Qiru Chang *et al.*, 2023). Methods such as sol–gel synthesis enable the production of nanoscale fillers with controlled size and morphology, facilitating uniform incorporation into polymer matrices (Bawazeer *et al.*, 2023). Melt blending offers a scalable approach for dispersing nanoparticles within polymer melts, whereas in situ polymerization enhances filler distribution and interfacial bonding by forming the polymer matrix in the presence of dispersed nanoparticles. Electrospinning further allows spatial and orientation control, producing nanofibrous structures with aligned fillers that improve directional shielding performance. A key challenge in these fabrication routes lies in maintaining filler–polymer compatibility and optimizing filler loading to balance mechanical integrity with attenuation efficiency. The spatial arrangement of fillers within the matrix is particularly critical, as controlled or orientation-dependent dispersion enhances radiation–matter interactions while reducing the material volume required for effective shielding (Muzata *et al.*,

2023). For metallic and ceramic shielding materials, fabrication commonly involves hot pressing, sintering, and powder metallurgy techniques. In tungsten carbide–boride composite systems, carefully blended powders undergo reactive sintering to produce dense microstructures with controlled phase distribution, which directly influences attenuation behavior and mechanical robustness (Surakasi *et al.*, 2022). Cement-based shielding composites are typically produced by incorporating lead oxide nanoparticles or other high atomic number fillers into Portland cement matrices, followed by controlled curing to ensure filler immobilization and structural stability. Also, metal foam-based shielding systems are fabricated through physical foaming or gas injection processes to generate porous frameworks that can be subsequently infiltrated with neutron-absorbing agents such as hydrogen-rich polymers, boron-containing compounds, or heavy metal particulates. Precise control of porosity, filler homogeneity, and interfacial integrity is essential in these systems to preserve both mechanical strength and shielding performance (Zhao *et al.*, 2021).

2.2 Advanced Manufacturing and Simulation-Assisted Design

Advanced radiation shielding materials are complicated and multifunctional, which has prompted the use of computational simulation techniques to support experimental production (Ribeiro *et al.*, 2021). During composite synthesis, the CALPHAD approach provides predictive control over phase equilibria, allowing for exact component proportion optimization for improved performance. Radiative transport within suggested material layouts is modeled using Monte Carlo simulations like MCNP and GEANT4, which offer insights into ideal thickness, filler distribution, and layering techniques prior to physical fabrication (Kaika *et al.*, 2025). This simulation-guided design approach speeds up development cycles, minimizes trial-and-error, and improves material qualities to satisfy

application-specific needs. The development of advanced, geometrically complicated shielding structures with customized compositional gradients and internal architectures is made possible by emerging additive manufacturing processes, which integrate computational data to ensure maximum efficacy and material economy (Braun, 2021).

2.3 Radiation Attenuation Testing

Mahmoud & Marashdeh (2023) report that radiation attenuation assessments, which measure gamma, X-ray, and neutron shielding capacities, are the main method used to quantitatively to characterize the efficiency of shielding materials. To assess the intensity of transmitted radiation after it has passed through material samples, experimental setups frequently use scintillation spectrometers, such as NaI(Tl) detectors, in conjunction with calibrated radioactive sources. Direct measures of shielding performance are provided by parameters such as the linear attenuation coefficient and half-value layer (HVL), which is the thickness needed to cut radiation intensity in half. By simulating the intricate interactions and scattering events within materials, Monte Carlo simulation algorithms such as MCNP enhance empirical testing by facilitating correlation with physical data (Kaika *et al.*, 2025). Another crucial factor that is frequently assessed to determine neutron shielding capacity is the neutron mass removal cross-section. When combined, these techniques offer thorough and exacting insights on material performance under pertinent radiation settings (Sayyed *et al.*, 2024a).

2.4 Structural and Morphological Characterisation

According to Kaika *et al.* (2025) and Sayyed *et al.* (2024b) detailed structural and morphological characterisation of shielding materials, in addition to attenuation testing, provides information on the interior architecture that directly influences mechanical and shielding capabilities. Nanoparticle dispersion,

agglomeration states, and interface morphology within composites can be seen using electron microscopy techniques including Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM). For ceramics and metal composites, X-ray diffraction (XRD) methods are essential because they show crystalline phases and how they change during processing. Particularly in foams and cured cement composites, microcomputed tomography (microCT) offers high-resolution 3D imaging to evaluate porosity, material density, and crack formation that may jeopardize shielding effectiveness. Such characterisation is crucial for connecting microstructure to macroscopic shielding behavior because these morphologies determine interaction cross-sections and energy dissipation mechanisms (Almuqrina *et al.*, 2024; Rilwan *et al.*, 2024).

2.5 Mechanical and Thermal Properties Evaluation

For radiation shielding materials to last a long period, especially in harsh settings like nuclear reactors or medical equipment, their mechanical strength and thermal stability are essential. To evaluate load-bearing capacity and resistance to mechanical deformation, tests of compressive and flexural strength are performed (Galehdari & Kelkar, 2017). For metal foams, ceramics, and composite concretes intended for structural purposes, these tests are essential. Measurements of thermal conductivity and thermal expansion, which affect a material's performance in temperature gradients brought on by radiation heating or environmental exposure, are part of thermal Characterisation. To ensure safety in the event of an unintentional fire, fire resistance and flame retardant qualities are assessed in accordance with regulatory procedures. The selection of materials that satisfy the demanding specifications of radiation shielding applications while guaranteeing durability and safety is made possible by these combined mechanical and thermal evaluations (Kavun & Eken, 2024; El-Samrah *et al.*, 2018).

3.0 Result and Discussion

Based on recent scholarly and empirical studies, the emerging fabrication strategies and multiscale Characterisation of radiation shielding materials were

discussed in this section. Table 1 and Table 2 presents the Summary of Materials Class and their Attenuation Characteristics and Summary of Fabrication and Characterisation Method.

Table 1: Summary of Materials Class and their Attenuation Characteristics

Material Class	Density (g/cm ³)	Energy (MeV)	MAC (cm ² /g ⁻¹)	LAC (cm ⁻¹)	TF (1–2 cm thickness)	Source
Lead (Pb) & Pb-based Composites	11.3	0.662–1.25	0.070–0.115	0.80–1.30	0.02–0.10	Aral <i>et al.</i> (2020); Kurudirek <i>et al.</i> (2010)
Polymer Nanocomposites (PbO/Bi₂O₃-filled)	1.2–2.0	0.662–1.25	0.030–0.085	0.05–0.18	0.45–0.75	More <i>et al.</i> (2021); Chang <i>et al.</i> (2023); Gouda <i>et al.</i> (2024)
Metal Foams & Metal–Ceramic Foams	2.0–4.5 (effective)	0.662–1.25	0.040–0.090	0.12–0.35	0.30–0.60	Araz <i>et al.</i> (2024); Abramovskis <i>et al.</i> (2023)
Ceramics & Glass-Ceramics (PbO, BaO, Bi₂O₃ based)	3.5–6.0	0.662–1.25	0.060–0.100	0.20–0.55	0.20–0.50	Alasali <i>et al.</i> (2024); Selvam <i>et al.</i> (2024); Kurudirek <i>et al.</i> (2010)
Radiation Shielding Concrete	2.3–3.8	0.662–1.25	0.050–0.090	0.12–0.32	0.35–0.65	Abdullah <i>et al.</i> (2022); El-Samrah <i>et al.</i> (2018)

3.1 Comparative Radiation, Fabrication, Characterisation and Attenuation Performance across Material Classes

Aral *et al.* (2020) and Kurudirek *et al.* (2010) reported that lead (Pb) and Pb-based composites remain the most effective gamma-ray shielding materials within the 0.662–1.25 MeV energy range due to their very high density (~11.3 g cm⁻³). The high mass attenuation coefficients (0.070–0.115 cm² g⁻¹) translate into large linear attenuation coefficients (0.80–1.30 cm⁻¹), resulting in extremely low transmission factors (0.02–0.10) for thicknesses of only 1–2 cm. These findings confirm the dominance of lead as a benchmark shielding material, while also highlighting the persistent challenges of toxicity, excessive weight, and limited design flexibility that restrict its use in modern and portable

radiation protection systems. More *et al.* (2021), Chang *et al.* (2023), and Gouda *et al.* (2024) demonstrated that polymer nanocomposites reinforced with high-Z fillers such as PbO and Bi₂O₃ offer a lightweight alternative to traditional metallic shields. With densities ranging from 1.2 to 2.0 g cm⁻³, these materials exhibit lower MAC (0.030–0.085 cm² g⁻¹) and LAC (0.05–0.18 cm⁻¹) values, leading to comparatively higher transmission factors (0.45–0.75). Although their shielding efficiency is reduced relative to lead, the studies emphasize that improved filler dispersion, higher loading fractions, and nanoscale engineering can significantly enhance attenuation performance while maintaining flexibility, low toxicity, and ease of fabrication. Abramovskis *et al.* (2023) investigated metal foams and metal–ceramic

foams and showed that their effective densities ($2.0\text{--}4.5\text{ g cm}^{-3}$) place them between dense metals and polymer systems in terms of shielding capability. The reported MAC ($0.040\text{--}0.090\text{ cm}^2\text{ g}^{-1}$) and LAC ($0.12\text{--}0.35\text{ cm}^{-1}$) values correspond to moderate transmission factors ($0.30\text{--}0.60$), indicating a favorable compromise between attenuation efficiency and weight reduction. Araz *et al.* (2024) further noted that the porous architecture of these foams enables multifunctional performance, combining radiation shielding with mechanical strength and energy absorption, which is advantageous for aerospace and structural applications. Alasali *et al.* (2024), Selvam *et al.* (2024), and Kurudirek *et al.* (2010) reported enhanced gamma-ray attenuation in ceramics and glass-ceramics containing heavy metal oxides such as PbO , BaO , and Bi_2O_3 . Owing to their relatively high densities ($3.5\text{--}6.0\text{ g cm}^{-3}$), these materials exhibit MAC values of $0.060\text{--}0.100\text{ cm}^2\text{ g}^{-1}$ and LAC values ranging from 0.20 to 0.55 cm^{-1} , resulting in lower transmission factors (0.20--

0.50) compared to polymers and some metal foams. In addition to their shielding effectiveness, these studies highlight the thermal stability, chemical durability, and optical transparency of certain glass-ceramic systems, supporting their suitability for radiation-resistant windows and high-temperature environments. El-Samrah *et al.* (2018) examined radiation shielding concrete and found that, despite its moderate density range ($2.3\text{--}3.8\text{ g cm}^{-3}$), it provides reliable attenuation for large-scale shielding applications. The reported MAC ($0.050\text{--}0.090\text{ cm}^2\text{ g}^{-1}$) and LAC ($0.12\text{--}0.32\text{ cm}^{-1}$) values correspond to transmission factors between 0.35 and 0.65 , which are higher than those of lead and heavy-oxide ceramics. Abdullah *et al.* (2022) emphasized that shielding concrete remains indispensable due to its low cost, structural functionality, and adaptability through the incorporation of heavy aggregates and industrial by-products to improve radiation attenuation performance.

Table 2: Summary of Fabrication and Characterisation Method

Material Class	Fabrication Route	Key Processing Methods	Characterisation Techniques Commonly Used	Representative Sources
Lead (Pb) & Pb-based Systems	Conventional metallurgical processing	Casting, alloying, lamination, PbO –glass melting	XRD, SEM/EDS, γ -ray spectrometry (LAC, MAC, HVL), Monte Carlo simulations	Aral <i>et al.</i> (2020); Sathish <i>et al.</i> (2021); Kurudirek <i>et al.</i> (2010); Mortazavi <i>et al.</i> (2024)
Polymer Nanocomposites	Filler-reinforced composite fabrication	Melt blending, solution casting, hot pressing, extrusion	SEM/TEM, FTIR, TGA/DSC, γ -ray attenuation tests, MCNP	More <i>et al.</i> (2021); Chang <i>et al.</i> (2023); Gouda <i>et al.</i> (2024)
Metal Foams / Metal–Ceramic Foams	Porosity-controlled fabrication	Powder metallurgy, space-holder foaming, sintering	SEM, micro-CT, density/porosity analysis, γ -ray attenuation measurements	Araz <i>et al.</i> (2024); Abramovskis <i>et al.</i> (2023); Ensarioglu <i>et al.</i> (2022)
Ceramics & Glass-Ceramics	High-temperature consolidation	Melt quenching, sintering, sol–	XRD, SEM/EDS, DSC, UV–Vis, γ -ray	Alasali <i>et al.</i> (2024); Selvam <i>et al.</i>

Radiation Shielding Concrete	Aggregate-modified cement processing	gel, oxide doping	shielding parameter evaluation	(2024); Kurudirek <i>et al.</i> (2010)
		Mechanical mixing, vibration casting, curing control	Density & porosity tests, SEM, compressive strength, γ -ray attenuation experiments	Abdullah <i>et al.</i> (2022); El-Samrah <i>et al.</i> (2018); Shi <i>et al.</i> (2024)

Aral *et al.* (2020), Sathish *et al.* (2021), Kurudirek *et al.* (2010), and Mortazavi *et al.* (2024) described lead (Pb) and Pb-based shielding systems as being predominantly fabricated through conventional metallurgical routes. These studies commonly employed casting, alloying, lamination, and PbO–glass melting techniques to achieve dense and homogeneous shielding structures. Characterisation was largely centered on crystallographic and microstructural evaluation using XRD and SEM/EDS, complemented by γ -ray spectrometry to determine key shielding parameters such as MAC, LAC, and HVL. Monte Carlo simulation tools were frequently integrated to validate experimental attenuation results, reflecting the maturity and standardisation of fabrication and evaluation approaches for lead-based systems. More *et al.* (2021), Chang *et al.* (2023), and Gouda *et al.* (2024) reported that polymer nanocomposites are fabricated through filler-reinforced composite processing routes aimed at achieving uniform dispersion of high-Z additives. Melt blending, solution casting, hot pressing, and extrusion were identified as the dominant processing techniques, each influencing filler distribution and interfacial bonding. The characterisation framework combined SEM and TEM for morphological assessment, FTIR for chemical interactions, and TGA/DSC for thermal stability, alongside γ -ray attenuation experiments and MCNP simulations. These studies collectively demonstrate a multidisciplinary approach linking processing–structure–property relationships to radiation shielding efficiency. Araz *et al.* (2024), Abramovskis *et al.* (2023), and Ensarioglu *et al.* (2022) focused on metal foams and metal

ceramic foams fabricated via porosity-controlled routes such as powder metallurgy, space-holder foaming, and sintering. These methods enable precise control over pore size, distribution, and overall density, which are critical parameters influencing attenuation performance. Characterisation techniques frequently included SEM and micro-computed tomography (micro-CT) to visualise pore architecture, as well as density and porosity measurements correlated with γ -ray attenuation experiments. The authors emphasized that this combination of structural and radiological analyses is essential for optimizing lightweight yet effective shielding materials. Alasali *et al.* (2024), Selvam *et al.* (2024), and Kurudirek *et al.* (2010) investigated ceramics and glass-ceramics produced through high-temperature consolidation routes such as melt quenching, sintering, sol–gel processing, and oxide doping. These fabrication strategies allow precise tailoring of composition and network structure, particularly through the incorporation of heavy metal oxides. Characterisation commonly involved XRD for phase identification, SEM/EDS for microstructural and compositional analysis, DSC for thermal behavior, UV–V is spectroscopy for optical properties, and systematic evaluation of γ -ray shielding parameters. This comprehensive methodology highlights the multifunctional nature of ceramic-based shielding systems. Abdullah *et al.* (2022), El-Samrah *et al.* (2018), and Shi *et al.* (2024) examined concrete and cement-based composites fabricated through aggregate-modified cement processing routes. Mechanical mixing, vibration casting, and controlled curing were identified as key processing steps

influencing density, porosity, and mechanical integrity. Characterisation approaches typically combined density and porosity measurements with SEM microstructural analysis, compressive strength testing, and γ -ray attenuation experiments. These studies show the importance of coupling structural performance with radiological assessment, particularly for large-scale and load-bearing radiation shielding applications.

5.0 Conclusion

This review highlights the shift from conventional dense and toxic shielding materials toward lightweight, multifunctional systems. Polymer-based composites reinforced with high-atomic-number fillers offer a combination of flexibility, processability, and improved attenuation efficiency, while ceramic and hybrid composites provide the thermal stability and mechanical robustness required for extreme environments. Nanostructural optimization has further enhanced shielding performance by increasing attenuation coefficients and reducing material weight. The novelty of this work lies in its integrated assessment of fabrication methods, Characterisation techniques, and application-oriented performance across multiple material classes. By adopting a multiscale comparative framework, this research bridges gaps between material development, functional evaluation, and sustainability considerations that are often treated independently in existing reviews. Nevertheless, progress toward real-world implementation is constrained by non-standardized testing methodologies, limited cross-material benchmarking, and unresolved trade-offs between attenuation efficiency, mechanical durability, and environmental impact. Future research should prioritize standardized evaluation protocols, scalable fabrication routes, and coupled experimental computational modeling, alongside life-cycle and sustainability assessments. Addressing these challenges will be critical for advancing next-generation radiation shielding materials from

laboratory studies to reliable and sustainable applications.

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Conflict of Interest

The authors declared no conflict of interest exist.

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